

**Medium-term Impact of Conservation Agriculture on Soil fertility in Dryland
Millet fields in Northeast Namibia**

Thomas Haundjangi Sikoka

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**NAMIBIA UNIVERSITY
OF SCIENCE AND TECHNOLOGY**

Supervisor: Dr H. Amwele

(Namibia University of Science and Technology)

Co-Supervisor: Brian Mhango

(Namibia University of Science and Technology)

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List of Acronyms

Al	Aluminium
Ca	Calcium
CA	Conservation Agriculture
CAN	Conservation Agriculture Namibia
CEC	Cation Exchange Capacity
CT	Conventional Tillage
ECF	European Conservation Agriculture Federation
Exch.	Exchangeable
FAO	Food and Agriculture Organisation of the United Nations
Fe	Iron
g Kg ⁻¹	Gram per Kilogram
GAPs	Good Agriculture Practices
GIZ	(German cooperation) Deutsche Gesellschaft für Internationale Zusammenarbeit
IFAD	The International Fund for Agricultural Development
K	Potassium
KE	Kavango East
KW	Kavango West
MAWF	Ministry of Agriculture, Water and Forestry
MAWLR	Ministry of Agriculture, Water and Land Reform
MET	Ministry of Environment and Tourism Namibia
mg kg ⁻¹	Milligram per kilogram
Mg	Magnesium
mmol Kg ⁻¹	Millmole per kilogram
N	Nitrogen
NGO	Non-Governmental Organization
NNFU	Namibia National Farmers Union
NUST	Namibian University of Science and Technology
P	Phosphorus
SCORE	Scaling up Community Resilience to Climate variability and Climate Change in Northern Namibia

Si	Silicium/silicon
SOC	Soil Organic Carbon
SOM	Soil Organic Mater
SSA	Sub-Saharan Africa
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
USDA	United State Department of Agriculture
Zn	Zinc

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Dedication

“Whatever we plant in our subconscious mind and nourish with repetition and emotion will one day become a reality.”

Earl Nightingale

I dedicate this work to my mother and late father who never had the opportunity to live and see me graduate. This work is also dedicated to all friends and colleagues who contributed directly and indirectly to the success of the thesis. Special dedication to Milka who has always been by my side and supported me in every step.

Abstract

Smallholder farmers in Northern Namibia have been experiencing poor crop production in recent years, making it difficult to meet household consumption demand. The poor crop output is attributed to poor soil fertility, sporadic rainfall, and high temperature. To address this issue, MAWF and GIZ collaborated to train small-scale farmers on Conservation Agriculture (CA) practices in the northern regions of Namibia. CA is being considered as a farming system having the potential to improve soil fertility and providing stable yields. However, there are concerns raised about the shortage of evidence of the advantages of CA for small-scale farmers in Southern Africa, specifically on soil fertility. A study was therefore conducted in KE and KW to evaluate the medium term (6 years) impact of CA on soil fertility from 2016/2017 to 2021/2022 seasons. Prior to CA implementation soil samples were collected in designated CA fields at a depth of 5-30cm and soil samples were continuously collected at least after every season. Soil samples were taken to the soil laboratory for analysis of physicochemical properties such as pH, OC, N, K, P, Ca, Mg, Zn, Fe, CEC, Al, Si and soil texture, using the Bruker Alpha I spectrometer. The study analysed data for 17 farms from 2016 to 2022. The study findings indicated that there was no significant impact of CA on soil fertility in a period of 6 years. It was observed that, soil elements remained relatively low while the potential toxic elements remain relatively higher over the years. There was statistically significant difference ($p < .002$) in soil pH under CA. However, the average pH in the 6th year, (5.76 ± 1.00) was lower than the threshold and that of the first year (6.55 ± 0.70). CA did not have any significant improvement on SOC/SOM ($p > 0.05$) K ($p > 0.05$), P ($p > 0.05$), Ca ($p > 0.05$), and Fe ($p > 0.05$). There was a significant decrease in N ($p < .001$) from a mean value of $0.40 \pm 0.22 \text{ g Kg}^{-1}$ in 2016 to $0.27 \pm 0.18 \text{ g Kg}^{-1}$ in 2022. Zn was also significantly decreasing ($p < .001$) over the years. Si remained relatively high while Al levels remained consistently low. CEC was low and decreased significantly ($p < .001$). Mg was high in first years, but it reduced significantly ($p < .001$) to the required range. The correlation analysis revealed positive relationship between pH and various nutrients, including N, K, Ca, Mg, CEC, Zn, Fe, and Al. OC showed a positive correlation with N and CEC, and there was a weak positive correlation between OC, Ca and Mg. CEC exhibited a positive and significant relationship with OC, N, K, Ca, and Mg. In conclusion, the research findings indicated that there was no significant improvement in soil fertility under CA over a period of six years in Northeast Namibia.

Keywords: Smallholder farmers, conservation agriculture, crop rotation, permanent soil cover, minimum tillage, soil fertility

Chapter 1: General Introduction

1.1 Background

Namibia's population is expected to grow from 2.5 million to 3 million by 2031, with the majority of the population concentrated in the northern regions of Omusati, Oshana, Ohangwena, Oshikoto, Kavango East, Kavango West, and Zambezi (MAWF, 2015). The projected increase in rural population is expected to put more pressure on agricultural land, resulting in smaller farms and lower agricultural production per household (UNDP, 2012). As land becomes scarce, farmers cultivate on the same piece of land year after year without shifting cultivation, resulting in the soil losing its fertility when no conservation is practised. Inappropriate farming practices and management are frequently attributed for low and variable production levels and declining crop yields. This includes mono-cropping without adequate soil nutrient replenishment, crop residue burning or removal, and frequent topsoil disturbance by ploughing and disking (Shifiona et al., 2016).

Namibia's subsistence-based smallholder sector is also highly susceptible to climate change and variability, as small scale farmers directly depend on rainfall and weather conditions (MAWF, 2015). Weather patterns are frequently changing and climate change will exacerbate this dependence, reducing crop yields and agricultural income (Amakali, 2019; GIZ, 2020). The Namibia meteorological services predict higher atmospheric temperatures, with 2.5°C to 3°C increase in southern Africa by 2050. Also rainfall variability is expected to increase, resulting in more frequent and intense extreme events like droughts and floods (Dirkx et al., 2008). Given these obstacles, rainfall patterns and poor soil fertility have proven to be the most significant obstacles for maize and pearl millet production, of which both are required for food security and economic development in Namibia (Shifiona et al., 2016). Due to Namibia's low and erratic annual rainfall, which ranges from 350 to 700 mm on average, and summer temperatures that can reach 40 degrees Celsius, crop production activities are restricted, primarily due to dry conditions and poor soil fertility (Shifiona et al., 2016). Agricultural production in Namibia varies in response to climatic conditions, resulting in food shortage ranging from 35% to 75% of total demand (Frøystad et al., 2008). Maize and pearl millet production in Namibia is possible in the north and north-eastern parts of the country. However, the country's rapidly changing environmental conditions is currently making farming difficult, and crop variety is limited. The major crops include millets, maize and sorghum (GIZ, 2020). Shifiona et al., (2016), further pointed out that only 1% of the country's total surface area is suitable for seasonal and

permanent crop production, and there are few opportunities to increase staple crop production. As a result, the country's domestic consumption needs are likely to remain reliant on imports of all major cereals crops (GIZ, 2020).

Pearl millet (*Pennisetum glaucum*) locally known as Mahangu is a major cereal crops grown by many farmers across Northeast Namibia (Thomas & Mpofu, 2013). Pearl millet is mostly produced under rain fed conditions at a subsistence level (Macauley, 2015). The crop production in Namibia have decreased drastically in the recent years and the yield gap- (the difference between potential and actual yields) of pearl millet is extremely wider and farmers struggle to meet household consumption demand (Oosterveld & Galand, 2012). This is due to poor soil fertility, sporadic rainfall, climate change, pests, inadequate weed management practices and unsustainable agricultural practice (Amakali, 2019) . Furthermore farmers cultivate their crops in traditional/conventional systems which is cereal-based mono-cropping systems, with little/no practice of crop rotation, heavy tillage and removal of crop residue, and subsequent overgrazing of crop fields by domestic animals, leaving the soil bare and vulnerable to erosion (Thierfelder et al., 2012)

Soil degradation is one of the key issue that concerns the long-term viability of crop and livestock productivity systems around the world (Zingore et al., 2010). Soil degradation is most severe in sub-Saharan Africa (SSA), and about 65% of the agriculture land area is classified as degraded (Zingore et al., 2010). Soil degradation in cropping systems is mainly caused by poor soil management methods that cause losses in soil biological, chemical, and physical quality, lowering the soil's potential to support plant growth and environmental service (Nkonya et al., 2015). Since smallholder farmers in African societies rely on subsistence farming to meet their daily needs, land degradation puts their socioeconomic and physical well-being at risk (Tully et al., 2015).

Tillage is also one of the most important agricultural practices, it is primary done to loosen the soil, initially control weeds, and provide a good seedbed for seed germination and plant growth. However tillage practices affects the physical and biological features of the soil, resulting in changes in plant development and productivity (Alam et al., 2014; Khan et al., 2017). Soil tillage influence soil characteristics and contributes up to 20% of crop production variables and has an impact on the sustainable use of soil resources due to its influence on soil qualities(Khan et al., 2017).

According to Alam *et al.*, (2014), conventional tillage practices changes soil structure by altering soil bulk density and moisture content of the soil. Frequent disturbance by conventional tillage produces a finer, looser-setting soil structure. Which results in breaking down soil aggregates, sealing of pores, dispersion of soil particles, compaction and reduced root penetration (Alam et al., 2014). Soil chemical depletion is not easily observed by naked eyes, but it can be observed in crop development and soil analysis. Soil erosion is accelerated by steep slope cultivation, clearing of vegetation especially leaving land bare between cultivation cycles, and poorly managed grazing (Tully et al., 2015). Bergtold and Sailus, (2020) pointed out that reduced tillage has a favourable impact on numerous characteristics of the soil, but excessive and unnecessary tillage have the opposite effect, which is destructive to the soil. Soil erosion is common on smallholder farms, and nitrogen (N), phosphorus (P), and potassium (K) balances are all below average (Mupangwa et al., 2017). This scenario has been exacerbated by climate change effects, which have increased the frequency of drought periods, as well as shifts and unpredictability in rainfall patterns. As a result, there is currently a lot of attention and focus on the transition from excessive tillage to conservation and no-tillage practices for managing soil quality and erosion (Bergtold & Sailus, 2020). Conservation Agriculture (CA) is one of the smart farming practice promoted global as sustainable and economical farming system (Thierfelder et al., 2012).

According to FAO (2016), conservation agriculture is a resource-conserving agricultural crop production concept that aims to achieve acceptable profits while maintaining high and consistent production levels and simultaneously conserving the environment. The concept of CA is to improve natural biological processes both above and below ground (FAO, 2016c). Mechanical soil tillage are minimized and external inputs such as agrochemicals and mineral or organic nutrients are applied at the optimum level, in a way and quantity that does not interfere with or disrupt biological processes (Nyamangara et al., 2013).

Conservation Agriculture is based on three principles.

- I. Reduced soil disturbance with minimum tillage
- II. Permanent organic soil cover (retaining crop remaining on the land and incorporated as part of soil improvement) and,
- III. Diversification of crop species (in sequences and/or associations) (Friedrich et al., 2009)

Currently CA adoption is highest in the southern parts of South America and the north-western parts of North America, with adoption rates exceeding 50% in both regions. In Latin America, countries

such as; Argentina, Paraguay, Uruguay, and Brazil are approaching 100% adoption of no-till farming (Friedrich et al., 2017). CA has been promoted in Europe by the European Conservation Agriculture Federation (ECAAF) since 1999, and adoption is visible in Spain, Finland, France, and the United Kingdom, with some farmers in Ireland, Portugal, Germany, Switzerland, and Italy at the proof-of-concept stage. In Spain, Portugal, and Italy adoption of CA in perennial crops such as fruit orchards, vineyards, and olive plantations has outpaced that in annual crops (Friedrich et al., 2017).

In sub-Saharan Africa, conservation agriculture has received a lot of research and promotion support from various organizations over the last few decades (Amakali, 2019; FAO, 2013b; Mango et al., 2017; Thierfelder et al., 2018). Conservation agriculture is widely promoted as one of the few win-win technologies available to farmers, in the sense that it has the potential to increase farmer's yield while also conserving the environment over time (Nyathi, 2020). At least 14 African countries (Kenya, Uganda, Tanzania, Sudan, Swaziland, Lesotho, Malawi, Madagascar, Mozambique, South Africa, Zambia, Zimbabwe, Ghana and Burkina Faso) are now at the fast pace to adopt conservation agriculture practices (Friedrich et al., 2017; Mango et al., 2017). In African context some of CA practices such as; direct seeding and hand hoe basin builds on indigenous knowledge (Nyathi, 2020). In Namibia Conservation agriculture is promoted by the Ministry of Agriculture, Water and Land Reform, with the assistance of non-governmental organisations (NGOs) and institutions. Conservation Agriculture Namibia (CAN) is a Namibian non-governmental organisation that was founded with the goal of enhancing agricultural production in Namibia (Amakali, 2019). CAN is also supported by other projects such as Scaling up community resilience to climate variability and climate change (SCORE), the Namibia National Farmers Union (NNFU), and international NGOs such as the Food and Agriculture Organisation (FAO), Germany Cooperation (GIZ), and the Red Cross of Namibia.

Conservation Agriculture have been reported to have the potential to assist farmers in maintaining and increasing yields and earnings while also reversing land degradation, safeguarding the environment, and reacting to the growing problems of climate change (FAO, 2016c; Giller et al., 2015; Jayaraman et al., 2021b; Laghrour et al., 2016; Sommer et al., 2013; Vercauteren, 2013). Minimum soil disturbance with residue cover conserves water, progressively enhances soil organic matter, and controls weeds while lowering the expenses of machinery, fuel, and time spent tilling. Furthermore leaving the soil undisturbed enhances water infiltration, retains soil moisture, and aids in the prevention of topsoil erosion (Verma, 2021).

Permanent soil cover protect the soil from physical harm of wind and rain which causes soil erosion(Ahmed et al., 2017; FAO, 2016b). Crop residues left on the soil surface increase infiltration and enhanced water holding capacity. Mulches also protect the soil surface from extreme temperatures and reduce evaporation, which is important in tropical and subtropical climates (Carbonell-Bojollo et al., 2019).

Crop diversification/rotation is the practice of growing different crops in different sequences on the same piece of land (Friedrich et al., 2009). By including smothering crop species such as cowpeas or green manure cover crops in the rotation, pests and diseases in the cropping system are reduced, and weeds are controlled(Clark, 2015). Legume crops improve soil quality, through nitrogen fixation and enhances different root systems which increase biological activity, and improve nutrient distribution in the soil profile (Naab et al., 2017).

According to MAWF (2015), CA can be used in conjunction with other Good Agricultural Practices (GAPs) like; timely farm operations, the use of improved seed, targeted applications of both mineral and organic fertilizers, and integrated pest management. CA with GAPs can assist increase and stabilize yields, reduce production costs (labour, machinery, fuel, fertilizer), adapt to and mitigate climate change, reduce land degradation, and conserve water. CA principles apply to all crop-production systems and levels of mechanization, though different techniques and practices apply in different circumstances (Nyathi, 2020). In sub-Saharan African were problems of poor agricultural productivity and soil degradation is highly experienced CA can be an alternative solution to address these problems (Thierfelder & Mhlanga, 2022).

However, CA's feasibility and applicability in the specific circumstances of southern African farmers is debatable. There is a need for locally generated quantitative data to improve understanding of the benefits and challenges of various CA systems, as well as to demonstrate that CA is feasible in southern African farming systems (Thierfelder et al., 2013).

According to Rusinamhodzi *et al.*, (2011), implementing conservation agriculture in Africa particularly in semi-arid locations provides challenges that differ from those encountered in the United States. Conservation agriculture success in semi-arid regions (300-500 mm annual rainfall), particularly in Southern Africa, is dependent on farmers' capacity to conserve crop residues and maintain effective weed control. While Farmers in Southern Africa, particularly in northeast Namibia farm in communal areas where resources is shared, after harvesting all farmers let go of their

animals to freely graze everywhere even in fields without control, this has made keeping crop residues on the ground difficult unless the farmer have strong fence round the field.

Poor soil fertility is identified as one of the setbacks encountered during crop production in sub-Saharan Africa, and a major reason for insufficient harvest experience by subsistence farmers (Ndah et al., 2014). CA is one of the farming practices that is proposed to have the potential to improve soil fertility, enhance crop yield and maintain ecological systems. However, there have been concerns raised about a lack of evidence of CA's benefits for small-scale farmers in Southern Africa, particularly in terms of soil fertility (Thierfelder, Mwila and Rusinamhodzi, 2013). Subsistence farmers lack the inputs, skills, and knowledge needed to maintain and improve their soil fertility, whereas commercial farmers have turned to artificial fertilizer to make up for the lacking nutrients (Amakali, 2019).

Plants, like all living things, require food to grow and develop. Plants require about 16 different elements to survive (Hall et al., 2022; Sharma et al., 2022). The atmosphere and soil water provide carbon, hydrogen, and oxygen. The other essential elements; nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, zinc, manganese, copper, boron, molybdenum, and chlorine are obtained from soil minerals and organic matter, as well as from organic and inorganic fertilizers (Brown et al., 2022).

The objective of the study was to evaluate the medium term (6 years) effects of CA on soil fertility that is based on minimum tillage, crop rotation, and retention of crop stalks, on smallholder farmer's field in Kavango West (KW) and Kavango East (KE), Northeast Namibia. The study investigated the build-up of soil chemical elements (pH, Organic Carbon, Nitrogen, Phosphorus, Potassium, calcium, magnesium, sulfur, iron, zinc, manganese, copper, and Cation Exchange Capacity (CEC).

1.2 Statement of the problem

Smallholder farmers in Northeast Namibia have been experiencing poor crop production in recent years, making it difficult to meet household consumption demand, leading to reliance on government for draught relief to survive. Farmers cultivate their crops in cereal-based mono-cropping systems with little/no practice of crop rotation, with a combination of repeatedly ploughing, removal of crop residue, and subsequent overgrazing of crop fields by domestic animals, leaving the soil bare and vulnerable to erosion (Thierfelder et al., 2012). As a result of this practice, soil nutrients have been depleted and organic

matter has decreased resulting to poor soil fertility in crop fields. Furthermore, climate change with its inconsistent rainfall patterns in Namibia have worsen the situation whereby heavy rainfall is experienced once, resulting in waterlogging and washing away planted crops followed by a long dry spell that burn planted crops, resulting in poor plant development and poor crop output (MAWF, 2015). These has necessitated the need to look for various ways of farming that improves soil healthy and improve crop production. The Ministry of Agriculture, Water and Land Reform (MAWLR) and various non-governmental organizations have thus came together to train and educate small-scale farmers on sustainable way of farming, which ought to combat climate change and land degradation (MAWF, 2015). Conservation agriculture (CA) is one of the potential cropping system promoted in Northeast Namibia as a possible farming system that ought to help small-scale farmers to improve crop production and soil quality (MAWF, 2015). However, there are concerns raised about the shortage of evidence of the advantages of CA for small-scale farmers in Southern Africa, specifically on soil fertility (Thierfelder et al., 2013). Poor soil fertility is identified as one of the setbacks encountered during crop production and a major reason for insufficient harvest experience by subsistence farmers (Zingore et al., 2010). This study examined the effect of conservation agriculture on soil fertility in dryland fields in Northeast Namibia over a period of six years, (2016/2017 to 2021/2022 seasons).

1.3 Research Objective(s)

The overall objective is to evaluate the effectiveness of Conservation Agriculture (CA) on amending/improving soil fertility over a period of six years (2016/2017 to 2021/2022 seasons).

1.3.1 Specific objective(s)

1. To determine the effect of the combined CA principles (minimum tillage, crop rotation and permanent soil cover) on soil fertility in a period of six years (2016/2017 to 2021/2022 seasons).
2. To identify elements that are responsive to the principles of conservation agriculture.
3. To evaluate the relationship between soil chemical elements

1.3.2 Research question

Can Conservation Agriculture improve soil fertility within six years?

1.3.3 Hypothesis

H_0 = Conservation agriculture will not improve soil fertility within 6 years of practice

H_a = Conservation agriculture will improve soil fertility within 6 years of practice

1.4 Significance of the Study

The significance of this study lies in its valuable contributions to the understanding of conservation agriculture and its impact on soil fertility and crop production. The study will provide insights into the benefits of implementing CA practices, such as minimal soil disturbance, crop rotation, and permanent soil cover, which ultimately enhance crop yield.

One noteworthy aspect of the study is its emphasis on the role of cowpea (Bira/Shindimba/Nakare) as legume in improving soil fertility, as well as the advantages of retaining crop residue on the soil. By providing farmers with this knowledge base, the study empowers them to make informed decisions regarding their agricultural practices, potentially leading to more sustainable and productive farming methods.

Furthermore, the study's findings hold relevance at both the regional and national levels. The information the study provides is of particular importance to the Ministry of Agriculture and other projects focused on promoting conservation agriculture in Namibia.

Also, by raising awareness of the potential of CA principles to improve soil fertility and crop yield, it fosters a deeper understanding of sustainable farming practices among farmers. This increased awareness can drive support for initiatives that prioritise soil health and food security.

Additionally, the significance of this study is in its focus on a region that has received limited attention in terms of CA research. While various studies have been conducted on the effects of CA in different countries, there is a lack of comprehensive research specific to Northeast Namibia. Therefore, this study fills an important knowledge gap by investigating the impact of CA on soil fertility in the region over a six-year period (2016-2022), considering the unique characteristics of soils and climate in Namibia.

In conclusion, the study will enhance the understanding of conservation agriculture and its positive effects on soil fertility and crop production. By providing valuable information, empowering farmers, informing policymakers, and shedding light on a region-specific context, this research paves the way for more sustainable agricultural practices and improved food security in Namibia and beyond.

1.5 Theoretical framework

The Namibian government's strategy to poverty mitigation tries to alleviate the declined agricultural output and provide benefits to people, particularly smallholder farmers (MAWF, 2015). Some of the major key factors identified as a challenge to soil fertility management in Namibia is the: expansion of cultivated areas to compensate for low yields, the exploitation of low nutrient status soil without restoration of soil fertility, changing climatic patterns, including low and erratic rainfall, and the lack of well-adopted technologies. Soil fertility conservation and maintenance are thus critical for improving input efficiency while increasing productivity (MAWF, 2015).

The Food and Agriculture Organization (FAO) of the United Nations (2016) defines conservation agriculture as a resource-conserving agricultural crop production concept that aims to achieve acceptable profits while maintaining high and consistent production levels and simultaneously conserving the environment, through the adherence to three core principles: minimal tillage, maintaining a permanent soil cover of at least 30%, and implementing crop rotation or intercropping involving leguminous plants. The simultaneous implementation of these principles offers various advantages, such as the reduction of soil erosion and decreased labour demands, particularly when mechanized techniques are employed (Hermans et al., 2020). Over the long term, the application of these principles leads to increased and more consistent yields, enhanced soil quality, and the development of greater resilience among farmers against unfavourable climatic conditions (FAO, 2013a; Jayaraman et al., 2021b; Johnson et al., 2019; Kolady et al., 2021).

Minimal Soil Disturbance (No-Till or Reduced Tillage):

Within conservation agriculture (CA) systems, the conventional method of intensive soil ploughing is reduced or eliminated. Instead, minimal tillage techniques are adopted to minimize soil disturbance, thus supporting soil structure maintenance, erosion prevention, and the preservation of natural microbial and organic components (Verma, 2021).

Permanent Soil Cover

Maintaining soil cover through crop residues, cover crops, or mulch constitutes an important element within the CA framework. This protective cover shields against water and wind erosion, curbs evaporation, stabilizes soil temperature, and introduces organic matter during decomposition, thereby enhancing soil structure and fertility (Rusinamhodzi et al., 2011).

Diversified Crop Rotations and Intercropping

Conservation Agriculture encourages the rotation of different crops over time and the intercropping of different species on the same plot. This diversity helps break pest and disease cycles, reduces the risk of soil nutrient depletion, and enhances nutrient cycling. Intercropping leguminous plants, which can fix atmospheric nitrogen into the soil, is particularly beneficial for maintaining soil fertility (Kolady et al., 2021)

The primary goals of Conservation Agriculture are to:

Improve Soil Health: By minimizing soil disturbance and maintaining soil cover, CA helps preserve soil structure, prevent erosion, and enhance microbial activity. This results in healthier and more productive soils.

Enhance Water Management: Soil cover reduces evaporation, conserving soil moisture and making water use more efficient. This is especially important in areas prone to drought.

Increase Crop Productivity: CA practices can lead to more stable and increased crop yields over the long term due to improved soil conditions and nutrient availability.

Reduce Environmental Impact: By preventing soil erosion, minimizing chemical runoff, and promoting sustainable practices, CA contributes to a reduced ecological footprint of agriculture.

Conservation agriculture in Namibia will address the problem of low and erratic rainfall by reducing water losses and increasing infiltration, as well as low soil nutrient status by increasing soil carbon and nitrogen through the use of organic soil cover and legumes in rotation. CA has been shown to facilitate sustainable intensification of agriculture by conserving and improving soil quality, resulting in excellent yields and the protection of the local environment and ecosystem services.

As a result, the Ministry of Agriculture, Water, and Forestry has designated CA as a critical agricultural production system foundation for increasing crop and animal productivity, livelihood, and farmer quality throughout the country.

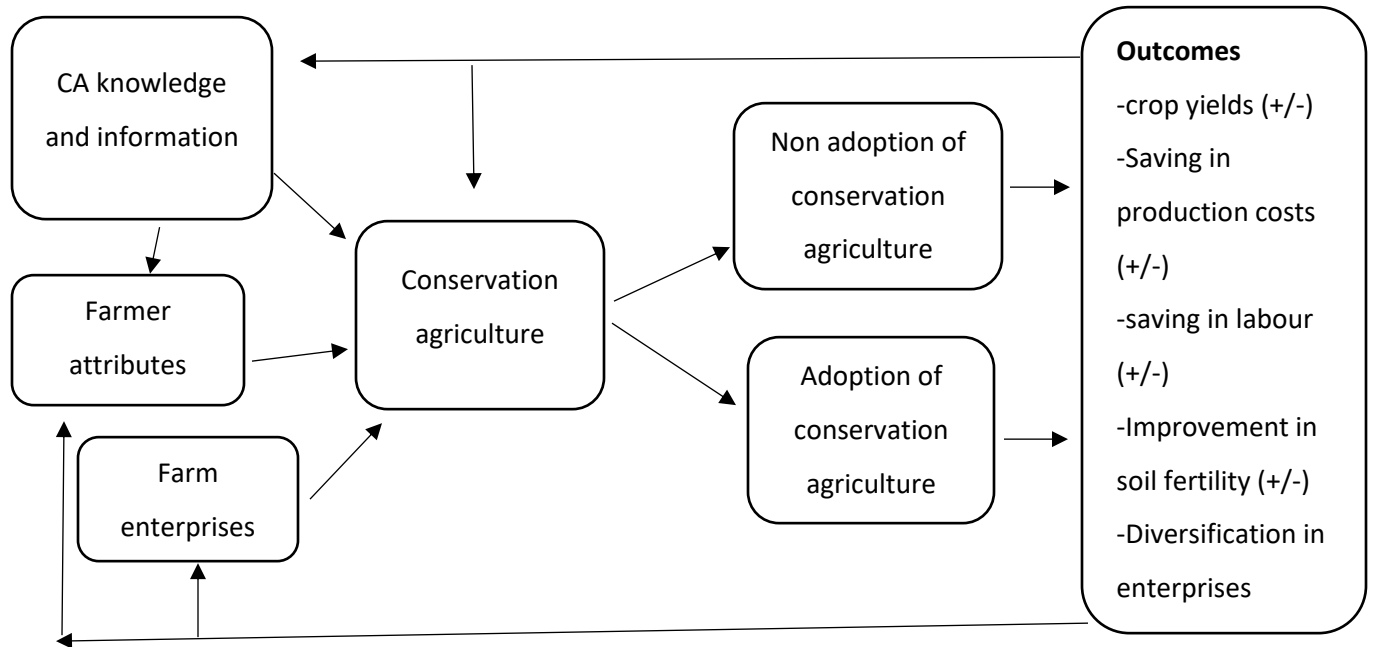


Figure 1: Theoretical framework for CA practice.

Source: Taapopi et al., 2018

1.6 Thesis Outline

This thesis comprises of 6 chapters.

Chapter 1 provides background information to agriculture in Namibia and introduces the concepts of conservation agriculture as well as the research objectives, hypothesis, significance of the study and the theoretical framework. Chapter 2 presents a review of the literature from a variety of studies relevant to this study and expands on the theoretical foundation of the study. It also discusses soil fertility, land degradation in Sub-Saharan Africa, and small-scale farming in Namibia. Furthermore, chapter 2 looks into CA practises and adoptability in the world and SSA and the effect of CA on soil fertility. Chapter 3 presents the methods used for data collection, the study area and statistical analysis applied. Chapter 4 is the presentation of the results. Chapter 5 discusses the results, and Chapter 6 conclude and provide recommendation for further research.

Chapter 2: Literature Review

This chapter is a review of the literature from a number of studies relevant to this study and elaborates on the theoretical basis of the study. The section provides an overview on the climate of Namibia, soil fertility, land degradation in sub-Saharan Africa and small-scale farming in Namibia. Furthermore, the chapter looks into CA practices and adoptability in the world and SSA and the effect of CA on soil fertility.

2.1 Climate of Namibia

Namibia is one of the driest countries in sub-Saharan Africa, with high climatic variability manifested in persistent droughts, unpredictable and variable rainfall patterns, temperature variability, and water scarcity. The weather is generally hot and dry, with sporadic and erratic rainfall (Muhoko et al., 2020). After the Sahara Desert, the country ranks second in terms of aridity. The country's dryness is largely due to the northward flowing Benguela current, which brings cold air to the western shores and is driven by a high-pressure system (Brown, 2009). However, the Inter-tropical convergence Zone (ITCZ) draws moisture from the equator to the country's northern and eastern regions, resulting in the rainy season between October and April (MAWF, 2011). Rainfall in Namibia has historically been extremely variable. The average annual rainfall is only 278 mm, ranging from 650 mm in the northeast to less than 50 mm in the southwest and along the coast (Reid et al., 2007). Rainfall is extremely scarce in the Namib Desert. Rainfall is at its highest in January, February, and March, with mean monthly rainfall averaging 62 mm, 66 mm, and 55 mm, respectively (Muhoko et al., 2020).

According to von Oertzen, (2010), Namibia is an arid, water-stressed country from a hydrological standpoint. High solar radiation, low humidity, and high temperatures result in extremely high evaporation rates that range from 3,800 mm per year in the south to 2,600 mm per year in the north. Mean annual temperatures are high in continental regions, reaching above 22°C in the north, and low in coastal areas due to the Benguela current, and reaching below 16°C in the south. Apart from the coastal zone, there is a distinct seasonal temperature regime, with the highest temperatures occurring just before or during the wet season in wetter areas and during the wet season in drier areas. During the dry season, from June to August, temperatures are at their lowest. Daily maximum temperatures of over 40°C have been recorded regularly, and average temperatures rarely drop below 0°C. Relative humidity in continental regions ranges from 25% to 70% (Midgley et al., 2005).

According to MAWF (2015), the climate of Namibia is expected to become hotter and drier in the near future, with more variability in rainfall. Much of the land currently used for agriculture is marginal and barely capable of supporting the people who rely on it. Any decrease in rainfall is likely to render these areas unfit for agriculture entirely. Several studies have looked into the potential effects of climate change in Namibia, and they have predicted significant negative environmental, economic, and social impacts (Brown, 2009; Midgley et al., 2005; Reid et al., 2007; von Oertzen, 2010). Midgley et al., (2005), have demonstrated that, in the absence of adaptation, the effects of climate change on agriculture could result in economic losses of up to 3.5 percent of GDP per year, exacerbating already high-income inequality. Climate change has the potential to become one of the most significant and costly factor affecting Namibia's national development process (MET, 2010).

According to FAO (2010), climate change will have a significant negative impact on agricultural productivity, resulting in lower yields for the most important crops and higher prices for the world's staples; rice, wheat, maize, and soybeans if it is not addressed. The International Fund for Agricultural Development (IFAD), (2008) also suggests that, as a result of climate change, there will be 20% more malnourished children in 2050. Climate change, combined with rising demand for food, feed, fibre, and fuel, has the potential to irreversibly damage the natural resource base on which agriculture relies, resulting in significant food insecurity (Reid et al., 2007). Climate change may also choke economic development in developing countries that are heavily reliant on agriculture. Climate change projections for agriculture in Sub-Saharan Africa, including where some of the world's poorest people live and farm, are dire (IFAD, 2008). Because of multiple stresses and low adaptive capacity, new studies confirm that Africa is one of the most vulnerable continents to climate variability and change (FAO, 2010).

The solutions call for a shift to more environmentally friendly farming practices that build up carbon in the soil and use fewer pesticides and chemical fertilizers. FAO, (2010) suggested several practices that can be used to reduce agriculture's contribution to climate change. Some of these are crop rotations and better farming system design, improved cropland management, improved nutrient and manure management, improved grazing-land and livestock management, maintaining fertile soils and restoring degraded land, improved water and land management, fertilizer management, land use change, and agroforestry.

2.2 Smallholder farmers in Namibia

When it comes to land-based farming in Namibia, there are two broad categories: subsistence farming and commercial farming. The most common type of farming in the northern regions is subsistence farming. Subsistence farming is the practice of only growing crops and raising livestock to meet one's own needs, with few/no surplus to sell (MAWF, 2015). Most of these farmers are smallholders and small-scale operators who rely on rain for crop production. This type of farming is extremely labour-intensive and requires low-skilled labour. Land is available in Namibia's communal areas mostly in the north (Omusati, Oshana, Ohangwena, Oshikoto, Kavango East, Kavango West, and Zambezi), allowing smallholder farmers to grow crops for their own consumption and raise livestock on a small scale (Nangolo & Alweendo, 2020). Most of the work is done by family members, and with a minimum use of technology in the production of the crops. The majority of what is produced is for personal consumption, and outputs are typically low and cultivation is limited to a small area of land (Shifiona et al., 2016).

Subsistence farmers in northern Namibia cultivate their crops in a traditional/conventional system, the traditional cultivation is cereal-based mono-cropping system with little/no practice of crop rotation, repeated ploughing, removal of crop residue, and subsequent overgrazing of crop fields by domestic animals, leaving the soil bare and vulnerable to erosion (MAWF, 2015). Farmers till the soil each season, this is primary done to loosen the soil, initially control weeds, and provide a good seedbed for seed germination and plant growth. Farmers rarely practice crop rotation with legume crop or use artificial fertilizer due to lack of skills on safe use and availability of artificial fertilizer in the communal areas (Mupangwa et al., 2017). After the harvest, farmers cut crop residue and use them as building materials and the leftover is fed to livestock (Thierfelder et al., 2013). Prior to cultivation farmer clear their fields by cutting every shrub and previous crop residue and burn them. As a result of these practice, soil nutrients have been depleted and organic matter has decreased resulting to poor soil fertility in crop fields (Umar, 2012). In recent years, smallholder farmers in Northeast Namibia have experience poor crop production, making it difficult to meet household consumption and forcing them to rely on the government for draught relief to survive (MAWF, 2015). Additionally, climate change with inconsistent rainfall have worsen the situation whereby heavy rainfall is experience at once, resulting in waterlogging and washing away planted crops followed by a long dry spell that burn planted crops, resulting in poor plant development and poor crop output (MAWF, 2015).

2.3 Production of pearl millet

According to Shindume (2017), pearl millet, (*Pennisetum glaucum*) is an important crop for most farmers in Africa, South Asia, and the Americas. The term "Millet" was derived from the French word "mille," which means "thousand," implying that a handful of millet contains thousands of grains. There is wild millet (*Pennisetum violaceum*) and domesticated pearl millet (*Pennisetum glaucum*) (Figure: 1). Fuller et al., (2021) stated that millet was first domesticated in West Africa's Sahel zone, which is known as one of the world's most diverse crop zones, it has been cultivated since prehistoric times in Africa and the Indian subcontinent. Recent archaeological and botanical research has confirmed the presence of domesticated pearl millet around 4,500 years ago in the Lower Tilemsi Valley of north-eastern.

There are discrepancies in the classification of the millet family, with some references placing it in the *Gramineae* family and others placing it in the *Poaceae* family (Amadou et al., 2013). Some argue that millets belong in the grass subfamily *Panicoideae* with maize, sorghum, and Coix (Job's tears). There are many varieties of millets. The four major types are; Pearl millet (*Pennisetum glaucum*), which accounts for 40% of global production, Foxtail millet (*Setaria italica*), Proso millet (*Panicum miliaceum*), and Finger millet (*Eleusine coracana*). Pearl millet produces largest seeds, which is the most commonly consumed variety. Minor millets include: Barnyard millet (*Echinochloa* spp.), Kodo millet (*Paspalum scrobiculatum*), Little millet (*Panicum sumatrense*), Guinea millet (*Brachiaria deflexa*), Browntop millet (*Urochloa ramosa*), Teff (*Eragrostis tef*) fonio (*Digitaria exilis*) and Job's tears (*Coix lacrima-jobi*) (Amadou et al., 2013).

The growing cycle of pearl millet ranges from 48 to 120 days, and it's characterized by a panicle that comes in a variety of shapes, with the female flowering earlier than the male and being pollinated by the wind (Lemgharbi et al., 2016). Due to the protogyny nature of its allogamous flower, millet is highly outcrossing crop, despite the fact that more than 85 percent of its flowers are hermaphrodite (Dwivedi et al., 2011). Pearl millets have a strong root system and a tall bunch grass that tillers from the base. Although the most productive hybrids and improved open-pollinated varieties are short in stature, it can reach a height of 3m (Shindume, 2017). Cultivated pearl millet has a high degree of phenotypic variability in traits such as flowering time, panicle length, grain and striver characteristics; drought tolerance, pest, and disease tolerance, and high nutritional value (UNDP, 2012).

According to Dwivedi et al., (2011), pearl millet is a sexually propagated diploid plant with 22 chromosomes and a large genome of 2450 Mega base pair. Pearl millet is the world's sixth most important

cereal crop, following rice, wheat, maize, barley, and sorghum, and it is a staple crop for more than 70% of Namibia's population (UNDP, 2012).

In Namibian context pearl millet is known as "Mahangu," and it is widely cultivated under rain-fed but also under irrigation in hot and drought-prone regions due to its drought and high temperature tolerance. Pearl millet production has recently declined in northern Namibia due to abiotic (drought, temperature, salinity, and a lack of nutrients) and biotic (primarily diseases) factors and the land degradation (Bergtold & Sailus, 2020; Shindume, 2017).

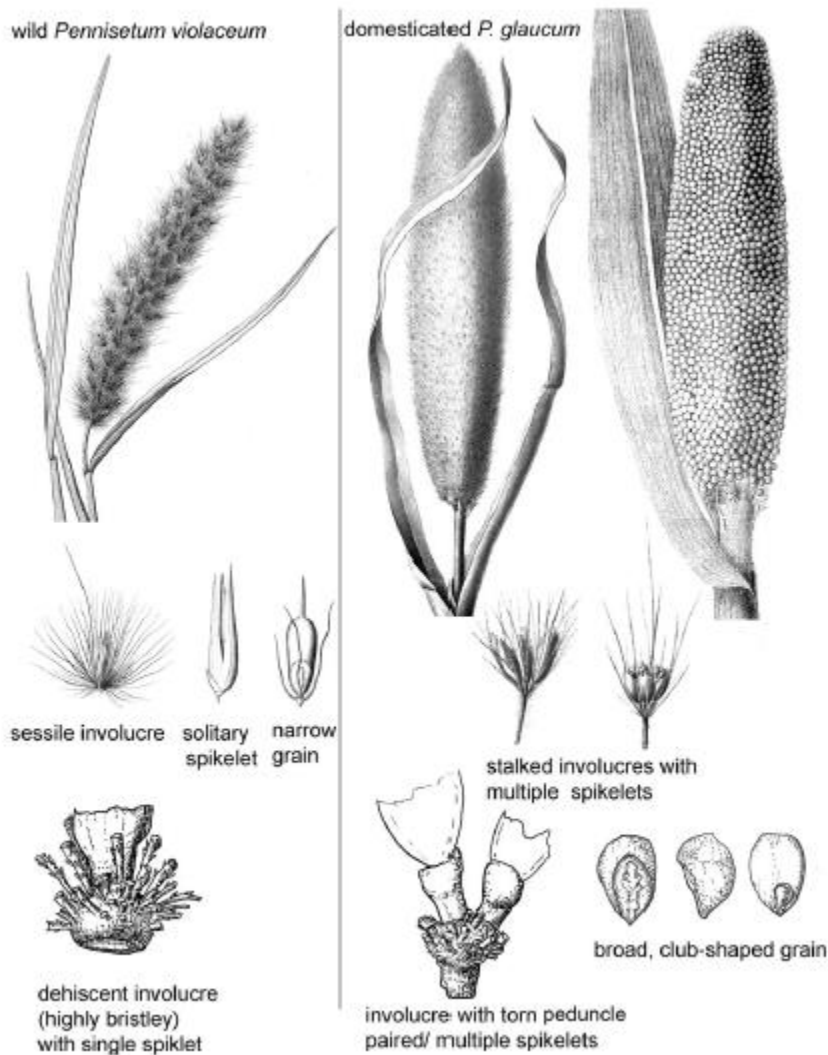


Figure 2: The morphology of wild millet (*Pennisetum violaceum*) and domesticated (*Pennisetum glaucum*) pearl millet.

Source: Fuller et al., 2021

2.4 Importance of legumes/pulses

The Fabaceae or Leguminosae family, is the third largest family of flowering plants, with 800 genera and 20,000 species. Legumes are nutrient-dense staple in many people's diets around the world. They are a good source of protein, vitamins, complex carbohydrates, and fibre (Stagnari et al., 2017). Some legumes are considered as cereal crop weeds, while others are major grain crops; these latter are known as grain legumes or pulses. Pulses are usually described as "the edible seeds of diverse leguminous crops" and mostly referring to dry grain legumes (FAO, 2016b). Some of common legumes are; Cow peas, Ground nuts, Bambara nuts, Pigeon peas, Lentils, Vetches, lupines, and Chickpeas. Despite the importance of leguminous crops in contributing to food and nutrition security as well as sustainable agriculture, they are not well known to most (FAO, 2016b). Legumes can be valuable allies in preserving and improving soil health, recovering degraded soils, and enhancing human well-being. Literate farmers have understood that legumes are crucial for soil health since the dawn of agriculture, and agricultural strategies such as intercropping and crop rotation have been utilised for millennia (FAO, 2016b).

FAO, (2016b) stressed that legumes should not only be planted for their yields, but also because they will improve the soils for future crops. Due to the symbiotic presence of numerous soil bacteria (rhizobia) in the legume roots, legumes promote soil health. Legumes promote biological nitrogen fixation as well as the solubilisation of phosphate ions from bound forms such as calcium and iron phosphates, making these nutrients available to plants. Legumes, in addition to their role in the nitrogen cycle and phosphorous cycles help to enhance soil organic matter, improve soil structure, and preserve soil biodiversity, all of which contribute to improved soil health (Gatsios et al., 2021).

Legumes help to reduce the demand for synthetic fertilisers by fixing atmospheric nitrogen and solubilizing phosphates. This helps to reduce the danger of soil and water pollution, maintain soil biodiversity, and battle and build resistance to climate change. Biological nitrogen fixation is critical for worldwide agricultural productivity and may be regarded as one of the most significant biological processes in the world of agriculture. According to FAO, (2016b), legumes have the potential to supply around 100 million metric tonnes of nitrogen, resulting in an annual fertiliser savings of around USD 10 billion. Lentils alone could fix 35-100 tonnes of nitrogen per hectare. Reducing the requirement for synthetic fertilisers and reduces the amount of greenhouse gases released into the environment indirectly (Gatsios et al., 2021). Legumes, when utilised in intercropping farming systems and/or as cover crops,

enhance soil carbon storage and, as a result, prevent soil erosion. Legumes are also important partners in the global fight against hunger due to their great nutritional value.

Finally, legumes are increasingly being used in multiple cropping systems, such as intercropping or simple crop rotations, to help with integrated soil nutrient management and the transition to conservation and organic agriculture. As a result, this is crucial given the need to increase food production while making better use of input resources and improving climate change resistance.(FAO, 2016b).

2.5 Soil

Gawie (2022) defines soil as the un-cemented aggregate of mineral grains and decayed organic matter with liquid and gas in the pores. The soil composed of five ingredients – minerals, organic matter, living organisms, gas, and water. Soil is the natural medium for plant growth, and usually contains the essential nutrients needed for plant growth. According to Keesstra et al., (2016), the fertility of an agricultural soil can reveal a lot about its productivity potential and its direct impact on crop yield and quality. Soil is one of the most important natural resources because it regulates the hydrological, bio-geochemical, and sediment cycles. Furthermore, soil is essential for agricultural production, ecosystem services, climate change mitigation, and human development. As a result, the United Nations has emphasised the importance of soils in achieving the Sustainable Development Goals (SDGs), as they are intimately linked to 7 of the 17 SDGs (Keesstra et al., 2016).

2.6 Physical properties of soil

2.6.1 Soil texture

The texture of the soil is an important physical soil characteristic that influences the rate of soil water infiltration (FAO, 2016b). The percentage content of sand, silt, and clay in a soil determines its textural class. Soil texture can be determined using two methods; texture by feel (hand texture determination) and by the USDA soil textural class. Classifications are typically classified after the primary constituent particle size or a combination of the most abundant particle sizes (sand, clay, silt) (Figure 3). Sand particles have a diameter of 0.05–2.0 mm, silt particles have a diameter of 0.002–0.05 mm, and the clay fraction has particles with a diameter of less than 0.002 mm. Sand, being the larger size of particles, feels gritty when tested with hands and clay due to its smaller size of particles, feels sticky (FAO, 2016b).

The rate at which water drains through a saturated soil is determined by the texture of the soil; water moves more freely through sandy soils than through clayey soils (Guo et al., 2019). When field capacity is reached, soil texture influences how much water is available to the plant; clay soils hold more water than sandy soils. Furthermore, well-drained soils typically have good soil aeration, which means that the soil contains air that is similar to atmospheric air, which promotes healthy root growth and, as a result, a healthy crop (FAO, 2016b). Soils also differ in their susceptibility to erosion (erodibility) based on texture; a soil with a high percentage of silt and clay particles has a higher erodibility under the same conditions than a sandy soil (Subedi, 2020).

Organic matter (OM) levels are also affected by differences in soil texture; organic matter breaks down faster in sandy soils than in fine-textured soils, given similar environmental conditions, tillage, and fertility management, this is due to a greater amount of oxygen available for decomposition in the light-textured sandy soils (FAO, 2016b). The cation exchange capacity of the soil increases with the percentage of clay and organic matter in the soil, and the pH buffering capacity of a soil (its ability to resist pH change due to lime addition) is also largely determined by clay and organic matter content (Subedi, 2020).

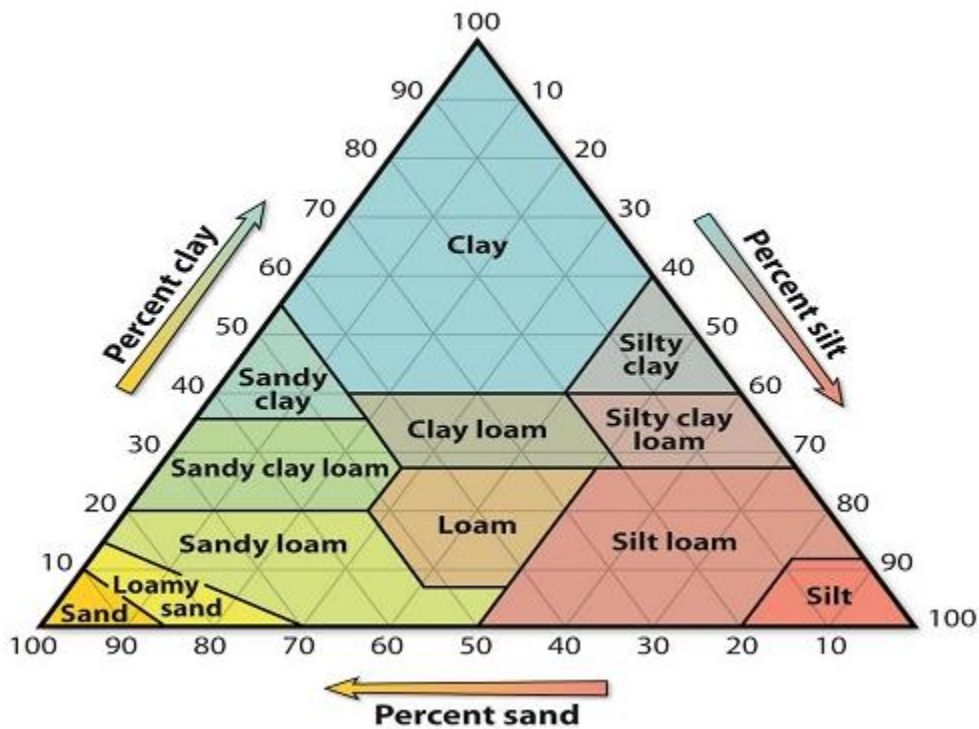


Figure 3: USDA textural triangle for categorizing soil texture names

Source: García-Gaines & Frankenstein, 2015

2.6.2 Soil structure

Soil structure refers to the way individual soil particles (such as sand, silt, and clay) are arranged into aggregates or clumps within the soil (Yudina & Kuzyakov, 2023). These aggregates can vary in size and shape, and their arrangement affects the physical properties of the soil. The ideal soil structure components include 25% air, 25% water, 45% minerals, and 5% organic matter (Mandal, 2019). The structure of soil pore spaces is governed by how individual units are organised, linked together, or clumped to create aggregates. The clumping is caused by organic matter (OM) and biological activities such as earthworms and fungi (Romero-Ruiz et al., 2018).

A well-structured soil has good pore spaces between aggregates. This allows water to infiltrate the soil, reducing surface runoff and enhancing water retention. Adequate drainage is also facilitated, preventing waterlogging which can be detrimental to plant growth. The pore space also allows for the movement of air within the soil. This is important for plant root respiration and the survival of beneficial soil microorganisms (Yudina & Kuzyakov, 2023).

According to Basset et al., (2023), tillage has historically been one of the primary causes of soil structure destruction. The loss of structure limits water infiltration by more than tenfold and contributes to soil compaction. As a result, most of agriculture soil tend to lose the structure due to heavy turning around of the soil during land preparation. Also, the removal of crop residue eventually hinder recovery of soil structure since organic carbon continue to fall, resulting to the instability of soil nutrients.

The structure of the soil is an important component in defining soil fertility and influencing root penetration (Mandal, 2019). Soils with good aggregation and pore spaces are well-structured and provide favourable conditions for water transport, aeration, nutrient availability, microbial activity, and root growth. As a result, plant growth becomes healthier and more productive.

2.6.3 Soil porosity

Another important soil physical characteristic is soil porosity,¹ which refers to the number and size of pores within the soil. Soil porosity influences water and air movement into and within the soil. Also, the pore influences the ability of soil to provide oxygen to organisms decomposing organic matter and plant roots, as well as the ability of water and dissolved nutrients to move and be stored (FAO, 2016b).

According to Topa et al., (2021), tillage reduces macropore spaces and creates a pore space discontinuity between the cultivated surface and subsurface soils. Soil compaction and degradation of soil properties, including porosity, are common side effects of intensive cultivation. In coarse textural soils, macropores

can be found as the spaces between individual sand grains (FAO, 2016b). Because of the dominance of macropores, even though a sand soil has a low total porosity, air, and water movement through it is surprisingly rapid. The pore space in fertile soils with ideal conditions for most agricultural crops is more or less evenly distributed between large (macro) and small (micro) pores (Ofem et al., 2021). The shift from macro-pores to micro-pores that occurs with depth in many soil profiles is associated with a decrease in OM and an increase in clay. Micropores are too small to allow much air to pass through. Water moves slowly through micropores, and much of the water held in these pores is unavailable to plants. Micropores may predominate in fine-textured soils, especially those lacking a stable granular structure, allowing for relatively slow gas and water movement despite the relatively large volume of total pore space (FAO, 2016b).

2.7 Soil chemicals properties

Chemical properties of the soil are the most important among the factors that determine the soil's ability to supply nutrients to plants and microbes (FAO, 2016b). The chemical reactions that take place in the soil have an impact on the processes that lead to soil development and soil fertility (Mebrate et al., 2022). Minerals inherited from soil parent materials release chemical elements over time, causing the soil to undergo various changes and transformations (Subedi, 2020).

The soil contains sixteen essential nutrients for plant growth and living organisms. Of these, Carbon (C), oxygen (O), hydrogen (H), nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) are referred to as "macronutrients" because they are the most important nutrients needed for plant growth. While Iron (Fe), zinc (Zn), manganese (Mn), boron (B), copper (Cu), molybdenum (Mo), and chlorine (Cl) are referred to as "micronutrients" because plants require them in smaller quantities (Neina, 2019). Soil salinity can be caused by an excess of Na, Ca, Mg, K, Cl, S, and carbonates, whereas soil acidity can be caused by an excess of exchangeable sodium (FAO, 2016b).

Light, heat, and water is some of the essential factors required by plants in order to efficiently utilize the available nutrients. Furthermore, diseases and insects control, also play important roles in the efficient use of available fertilizer. Each plant is unique and has an optimum nutrient range as well as a minimum requirement level (Sharma et al., 2022).

2.7.1 Soil pH

When it comes to the chemical properties of soil, soil reaction is expressed in terms of 'pH,' which is a measure of the acidity or alkalinity of the soil (Nweke & Nsoanya, 2013). Descriptive terms commonly

used with certain ranges in soil pH are; (pH < 4.5) = extremely acidic, (pH 4.5-5.0) =very strongly acidic, (pH 5.1-5.5) =strongly acidic, (Ph 5.6-6.0)=moderately acidic, (pH 6.1-6.5) slightly acid, (pH 6.6-7.3)=neutral, (pH 7.4-7.8)= slightly alkaline, (pH 7.9-8.4)= moderately alkaline, (pH 8.5-9.0) strongly alkaline, and (pH > 9.1) =very strongly alkaline (Chirwa et al., 2016). Because of their solubility at different pH levels, changes in pH can make certain ions available or unavailable in the soil. For instance, soils with pH <5.5 tend to have toxic levels of aluminium and manganese, while soils with pH >8.5 tend to disperse due to high levels of sodium. High acidity inhibits soil organisms, and growth of some crops, most agricultural crops thrive in mineral soils with a pH of 6.5 (FAO, 2016b).

2.7.2 Organic matter (OM) and Soil Organic Carbon (SOC)

Soil organic matter is formed by the decomposition of green plant debris, animal residues, and excreta that are deposited on the surface and mixed to varying degrees with the mineral (Sullivan et al., 2019). Soil OM is defined as any living or dead plant or animal material in the soil, and it includes a diverse range of organic species such as humus substances, carbohydrates, proteins, and plant residues (Mebrate et al., 2022). Uncultivated soils usually have more organic matter, both on the surface and in the soil than cultivated soils. According to Musinguzi et al., (2013) organic matter aids in water management and protect the soil surface from direct impact of sunlight and win, hence helping in erosion control. In clay soils, decomposing OM also causes soil aggregation, which aids infiltration and expands pore space. Thus water and oxygen holding capacity is increased, even beyond OM's absorptive capacity (Grönemeyer, 2013). Furthermore, OM increases exchange and buffering capacity because well decomposed OM or humus has a very high CEC, which contributes to the soil's buffering capacity. OM is a sources of nutrients (N, P, S, and most micronutrients) and growth promoting substances, such as hormones or growth-promoting and regulating substances valuable to plants, may be produced by organisms that decompose soil OM (Sullivan et al., 2019). Also OM minimizes leaching loss because organic substances have the ability to hold substances other than cations against leaching (Grönemeyer, 2013). Since OM is difficult to measure most researcher determines OM by looking at the Organic Carbon (OC) in the soil (Musinguzi et al., 2013). The laboratories typically measure soil organic carbon and use a conversion factor to estimate how much organic matter is held within a soil. According to Sullivan et al., (2019), soil organic carbon is a component of soil organic matter, accounting for approximately 58% of the mass of organic matter (Sullivan et al., 2019). As a result, we can estimate the proportion of organic matter in a soil sample by determining the amount of soil organic carbon in a sample and multiplying it by 100/58 (or 1.72):

$$\text{Organic matter (\%)} = \text{SOC (\%)} \times 1.72$$

2.7.3 Cation Exchange Capacity (CEC)

Cation Exchange Capacity (CEC) is a very important soil fertility indicator, and it is included in soil nutrient testing. According to Matthews, (2014) the cation-exchange capacity is the maximum amount of total cations that the soil can hold and exchange with the soil solution at a given pH value. CEC is a measurement of soil fertility, nutrient retention capacity, and groundwater protection from cation contamination. The cations on the CEC of soil particles are therefore easily exchangeable with other cations, and are plant available (FAO, 2016b). Thus, CEC is an important soil parameter because it indicates the type of clay minerals present in the soil, its ability to retain nutrients against leaching, and the fertility and environmental behaviour of the soil. In general, the chemical activity of the soil is determined by its CEC (Kaya et al., 2023). The amount and type of clay in a soil, as well as the amount of OM in the soil, have a significant impact on its CEC. Because clay and colloidal OM are both negatively charged, they can function as anions (Williams et al., 2018). As a result, these two materials have the ability to adsorb and hold positively charged ions, either individually or in combination as a clay-humus complex (cations) (Emamgholizadeh & Mohammadi, 2021). CEC is higher in clay and OM-rich soils than in OM-deficient sandy soils. Because most essential minerals are absorbed by plants as cations, cation exchange is considered to be more important to soil fertility than anion exchange. CEC is used to assess soil fertility, nutrient retention capacity, and groundwater protection from cation contamination (FAO, 2016b).

2.8 Soil nutrients

2.8.1 Total Nitrogen

Nitrogen (N) is an essential plant nutrient that required for growth, N is available to plants in the form of nitrate (NO_3^-) and ammonium (NH_4^+) ions. N is required for the synthesis of amino acids, which are then turned into proteins (FAO, 2016b). Protein is required for the growth of leaves and stems. It also aids in the processing of chlorophyll, which contributes to the green colour of plant (Zhao et al., 2005). Furthermore, because all plant enzymes are made of proteins, N is required for all enzymatic reactions. N improves the consistency and dry matter content of leafy vegetables, as well as the protein content of grain crops (Azimi et al., 2021). N content is lower in continuously and intensively cultivated and highly weathered soils, and high content of OM correlates enhanced nitrogen content. Plants with a nitrogen deficiency have stunted growth, which varies depending on the severity of the deficiency. The growth of

leaves is slowed, especially the growth of younger leaves (Sun et al., 2020). Longitudinal shoot growth and thickness increase are both slowed. Because chloroplast and chlorophyll synthesis are inhibited in N deficient plants, they often turn a pale green to yellowish-green colour. Further leaves begin to wilt and dry out, turning a yellowish brown to a brown colour (Tucker, 2015).

2.8.2 Total Phosphorus

Phosphorus, Symbol: P; available to plants as orthophosphate ions (HPO_4^{2-} , H_2PO_4^-). P aids in seed germination and roots development (Subedi, 2020). Phosphorus is essential for plants to capture, store, and convert solar energy into biomolecules like adenosine triphosphate (ATP), which drive biochemical reactions (such as photosynthesis) from germination to maturity (FAO, 2016c). Phosphorus is found in deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), which contain instructions for how plants should perform routine functions like synthesizing proteins, lipids, and nucleic acid, as well as metabolizing sugars. Phosphorus encourages early root growth, winter hardiness, and seed formation, as well as stimulating tillering and improving water efficiency (Ogunsola & Adetunji, 2016). Furthermore, P plays a major role in energy storage and transfer as ADP (Adenosine diphosphate) and ATP. P also has been shown to reduce the incidence of disease in some plants and to increase the quality of some crops (Sanchez et al., 2021). Phosphorus deficiency inhibits shoot growth. In severe deficiency, the leaves become dark, dull, blue-green, and even pale. Increased anthocyanin synthesis results in a reddish, reddish-violet, or violet colour. The symptoms appear first on the plant's older parts. New leaves appear to be healthy, but they are frequently small. In many plant species, phosphorus deficiency causes an increase in the root-to-shoot ratio (Poirier et al., 2022).

2.8.3 Total Potassium

Potassium, Symbol: K; available to plants as the ion K^+ , K is needed for the development of flowers and fruit. It also helps in disease resistance and control how much water gets into the roots and how much gets out through the leaves (Osmosis) (Subedi, 2020). Poor soil management can result in losing all the essential soil nutrients and leave the soil vulnerable and unable to support plant growth (Umar, 2012). Potassium deficient plants can be identified by their tendency to wilt on hot, sunny days. The plant's overall appearance is wilted or drooping. Plants that are deficient will have a stocky appearance and short internodes. Younger leaves' growth is slowed, and their leaf blades are small (Xu et al., 2020). Leaves can also be dark to bluish green, have a bronze metallic sheen, or be wavy. Older leaves of some species exhibit blotchy chlorosis. Monocots, such as maize, can have inverted V-shaped chlorosis on their leaves (Umar, 2012).

2.8.4 Calcium

Calcium, Symbol: Ca; is available to plants as the ion Ca^{2+} , Ca plays an important role in the formation and plasticity of the cell wall membrane, which affects normal cell division by preserving cell integrity and membrane permeability (FAO, 2016b). Several enzyme systems involved in protein synthesis and carbohydrate transfer are activated by Ca. Ca reacts with organic acids, sulphates, and phosphates, among other anions (Lange et al., 2021). By neutralizing organic acids in plants, it acts as a detoxifying agent. When soils are limed, Ca helps to improve crop yields indirectly by reducing soil acidity (Tasnim et al., 2016). Calcium deficiency symptoms appear first on younger leaves and tissues, growth is inhibited, and plants appear bushy (Sanchez et al., 2021). The youngest leaves are typically small and misshapen, with brown chlorotic spots developing along the margins and eventually merging in the centre of the leaves. Veins are also brown, making dark veins of completely necrotic leaves a common feature of Ca-deficient plants. Leaves can also be crinkled and torn. Root tip growth is inhibited in Ca-deficient plants (Thor, 2019).

2.8.5 Sulfur

Sulfur, Symbol: S; available to plants as the sulfate ion, SO_4^{2-} . It is involved in the biosynthesis of the B vitamins biotin and thiamine, as well as coenzyme A (Sanchez et al., 2021). S aids in seed production, chlorophyll formation, nodule formation in legumes, and stabilizing protein structure. Plants with a Sulphur deficiency is often pale green, yellowish-green, or completely yellow. These traits, which are similar to those seen in nitrogen-deficient plants, are first noticed in the younger. Plants that are deficient have small, often narrow leaves. Also the stems are frail and have slowed longitudinal growth (FAO, 2016b).

2.8.6 Magnesium

Magnesium, Symbol: Mg; available to plants as the ion Mg^{2+} , Mg is a cofactor in a number of enzymatic reactions that promote phosphorylation (Ishfaq et al., 2022). Mg is essential for the stability of ribosome particles as well as the structure of nucleic acids. Mg assists the movement of sugars within a plant (Tasnim et al., 2016). Magnesium deficiency is characterized by bright yellow interveinal chlorotic lesions. In some species, these lesions may have a violet tinge. Older leaves are usually the first to be affected, but younger leaves may also show deficiency symptoms if Mg withdrawal from older leaves is too slow (Jurzwnk et al., 2002).

2.8.7 Iron

Iron, Symbol: Fe; available to plants as Fe^{2+} and Fe^{3+} , Fe is required by the heme enzyme system in plant metabolism (photosynthesis and respiration). Fe is a component of the protein ferredoxin, and it is required for nitrate and sulphate reductions. Also, Fe is required for the synthesis and maintenance of chlorophyll (Ram et al., 2021). According to (Marzorati et al., 2022) Iron deficiency include, younger leaves having interveinal chlorosis. Because Fe, like Mg, is involved in chlorophyll production, the youngest leaves may be white. It's most common in alkaline or over limed soils (Sanchez et al., 2021).

2.8.8 Zinc

Zinc, Symbol: Zn; available to plants as Zn^{2+} , Zn activates enzymes and allows the reading of the plant's genetic code (Sturikova et al., 2018). Zn is necessary for the synthesis of tryptophan, which is required for the formation of indole acetic acid in plants. Zn is an essential component of several metallo-enzymes in plants and thus is required for several different functions in plant metabolism. Zn specifically activates the enzyme carbonic anhydrase (Subedi, 2020).

Zinc deficiency include younger leaves develop interveinal chlorosis, which is similar to Fe deficiency (Barrow & Hartemink, 2023). However, Zn deficiency is more pronounced, resulting in banding at the leaf's base, whereas Fe deficiency causes interveinal chlorosis that runs the length of the leaf (Stanton et al., 2022). The younger leaves in vegetable crops are the first to change colour. In most cases, the new leaves are abnormally small, mottled, and chlorotic (Sturikova et al., 2018). Small, pointed, mottled leaves with irregular interveinal chlorosis appear in citrus. Fruit production is drastically reduced. On the older, lower leaves of legumes, stunted growth with interveinal chlorosis appears. The chlorotic spots produce dead tissue that falls out (FAO, 2016b).

2.8.9 Silicium/Silicon

Si uptake in plants is frequently greater than nitrogen and potassium uptake. Many plant species, particularly grasses, can absorb silicon in quantities comparable to macronutrients. This high silicon concentration in the plant contributes to plant mechanical strength (Yuvaraj & Mahendran, 2020). According to (Huang et al., 2023) silicon, in addition to its structural role, may protect plants from insect attack, disease, and environmental stress by improving the plant's defence response. Despite its high concentration in plants, Si is still vying for essential element status (Raza et al., 2023). Only horsetails have been shown conclusively to require Si as an essential nutrient among terrestrial plants. Si accumulation in rice, for example, is approximately 108% greater than nitrogen accumulation. A rice crop yielding 5000 kg/ha is expected to remove Si from the soil at a rate of 230 to 470 kg/ha (Yuvaraj & Mahendran, 2020).

2.9 Land degradation

According to UNCCD as cited by Umar, (2012), land degradation is “the reduction or loss, in arid, semi-arid, and dry sub-humid areas, of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest, and woodlands as a result of land uses or a process or combination of processes, including processes arising from human activities and habitation patterns”.

Land degradation is a growing problem in the world's drylands, as it generally denotes a temporary or permanent decline in the land's productive capacity. According to Li et al., (2023) land degradation is caused by both natural and human-made factors. Some of the most common natural causes of land degradation are strong winds, fires, changes in the water table, flooding, volcanic activity, and invasion by insects such as locusts (Weinzierl et al., 2016). These may be exacerbated by human activities, which includes; unsustainable agricultural land use, poor soil and water management practices, deforestation, removal of natural vegetation, frequent use of heavy machinery, overgrazing, improper crop rotation, and poor irrigation practices (Sheppard et al., 2020). Land degradation is one of the major challenges faced by smallholder farmers in sub-Saharan Africa, causing farmers to fail produce enough grain to meet household consumption (Thierfelder et al., 2013). Since more than 60% of African societies rely on subsistence farming to meet their daily needs, land degradation puts their socioeconomic and physical well-being at risk (Li et al., 2023). Soils can be physically, chemically, or biologically altered by natural processes. Soil, for instance, forms over millennia as a result of physical and chemical weathering of rocks. Wind erosion shifts dunes and transports dust to other continents in sparsely vegetated deserts. Humans, on the other hand, have accelerated many of these natural processes, causing soil degradation (Higginbottom & Symeonakis, 2014).

According to Briassoulis, (2019) physical degradation can occur when excessive soil tillage breaks down soil aggregates, causing organic matter to decompose quickly, loosening the soil and making it vulnerable to wind and water erosion. Cultivation on steep slopes, vegetation clearing, particularly leaving land bare between cultivation cycles, and poorly managed grazing are the primary causes of soil erosion in SSA.

Chemical soil degradation, unlike physical soil degradation, is not visible to the naked eye. In SSA, nutrient depletion is the most common form of soil degradation. For decades, nutrient outputs have outpaced inputs across SSA, depleting soil nutrient pools (Tully et al., 2015). The traditional mouldboard plough and hand hoe are still used by the majority of smallholder farmers in southern Africa specifically in Namibia for land preparation, and this farming system and type of farming is known as conventional tillage (CT)

(Amakali, 2019). Conventional tillage is the process of preparing soil for planting or seeding by ploughing, cultivating, or turning the soil around. Tillage loosens and aerates the soil, allowing roots to penetrate deeper. Weeds are controlled, and organic matter, fertilizer, and manure are mixed into the soil. According to Thierfelder and Wall, (2010), tillage on the other hand, can contribute to soil moisture loss, increase wind and water erosion, and consume a significant amount of fuel. These traditional land preparation practices have caused soil disturbance and a negative change in soil structure, resulting in soil erosion, compaction, and yield reduction (Thierfelder & Wall, 2010).

With climate change becoming a greater threat, the challenge today is to find sustainable, environmentally friendly ways to increase agricultural productivity in order to meet the demands of an ever-increasing population. In this context, farmers are interested in Conservation Agriculture (CA) as its proposed to potential mitigate the effects of climate change on farm productivity, reduce the loss of important rainfall and conserve top soil, adapt more efficiently to harsh weather conditions, improve the health of their soils, and reduce labour and input costs (Makate et al., 2017).

2.10 Status of soil fertility in sub-Saharan Africa

Only about half of the over 3 billion hectare of arable land in tropical Africa is free of physical and chemical constraints, with 13% having low nutrient content and 17% having a high soil pH (Raimi et al., 2017). In general, 55% of African land is desert, and nomadic grazing was the best way to utilize. Overgrazing, deforestation, and excessive cultivation without effective nutrient management have all contributed to soil nutrient loss in sub-Saharan Africa over the years (Weinzierl et al., 2016). According to Henao and Baanante, (2006) in the last 30 years, an estimated 202 million ha of cultivated land in 37 African countries has lost an average of 660 kg N, 75 kg P, and 450 kg K per ha. NPK losses were estimated to be 800,000t in humid central Africa, 600,000t in North Africa, 1.5 million tons in East Africa, and 8 million tons in sub-Saharan Africa per year. In terms of money, Africa loses an estimated US\$ 4 billion per year due to nutrient mining, as well as US\$ 42 billion in income and 6 billion ha of valuable land due to land degradation and reduced crop productivity (Raimi et al., 2017). Over the last 40 years, the yield gap in SSA has steadily widened, deteriorating to less than 25% of potential attainable yield, while per capita food production has also decreased (Gichangi et al., 2019).

According to Tully *et al.*, (2015) the most common soil types in sub-Saharan Africa are; Arenosols (21.5%), Cambisols (10.8%), Ferralsols (10.4%), and Leptosols (17.5%). Also a quarter of soils in SSA have aluminium toxicity, 25% have high leaching potential (low buffering capacity), and nearly 40% have low nutrient capital reserves (10% weatherable minerals). Middendorf *et al.*, (2017) stressed that SSA soils are largely

unhealthy as a result of extensive nutrient depletion and insufficient organic or inorganic replenishment over time. Crop yields have stagnated as a result, of poor soil fertility and poverty and food insecurity are still widespread problems. Furthermore over 80% of Africa's agricultural lands, according to the World Bank (2013), are considered to be degraded and have biophysical or chemical restrictions that lower food production.

It is estimated that degraded soils affect 485 million Africans and cost the continent nearly \$9.3 billion per year. As a result smallholder farmers cannot benefit from yield gains offered by improved plant genetics and other associated agronomic practises unless soil health issues are addressed. Due to soil degradation, yield increases from improved crop varieties are estimated to be only 28% in Africa, compared to 88% in Asia (Middendorf et al., 2017).

2.11 Status of soil fertility in Namibia

Namibia is characterized by diverse soil types due to its varied geography and climate. The country's soils vary widely in fertility, texture, structure, and nutrient content across different regions. Much of Namibia falls within arid and semi-arid climate zones, which has an impact on soil formation and fertility (GIZ, 2020). The low and erratic rainfall in these regions contributes to limited vegetation cover, low organic matter input, and reduced nutrient availability in the soil. Sandy soils are common in Namibia, particularly in desert and coastal areas (Lisao, 2015). These soils have low water-holding capacity and low nutrient content. They are prone to leaching, which can wash away essential nutrients. Many parts of Namibia, especially arid and semi-arid regions, have alkaline soils with high pH levels. Alkaline soils restrict the availability of certain nutrients to plants and impact their growth (Dirkx et al., 2008). The arid and semi-arid conditions in Namibia contribute to limited vegetation growth, resulting in low organic matter content in the soil (Imbamba, 2003). Organic matter is crucial for soil structure, water retention, and nutrient cycling. Intensive and continuous agricultural practices without proper nutrient management have been reported to contribute significantly on nutrient depletion in the soil (Grönemeyer, 2013). Which was evidence unveiling in the crop production in Namibia, which is reduced crop yields and overall productivity in recent years (MAWF, 2015). Soil erosion and degradation are significant challenges in Namibia, driven by factors such as wind, water, and unsustainable land use practices. Most of the soil in Namibia are eroded and are often less fertile and more susceptible to further degradation (Zingore et al., 2010). According to Lisao, (2015) fertility levels vary widely across different regions of Namibia. Some

2.12 Conservation agriculture (CA)

2.12.1 Definition of CA

According to FAO, (2016), conservation agriculture is a resource-conserving agricultural crop production concept that aims to achieve acceptable profits while maintaining high and consistent production levels while also conserving the environment. The concept of CA is to improve natural biological processes both above and below ground (FAO, 2016c). Mechanical soil tillage are minimized and external inputs such as agrochemicals and mineral or organic nutrients are applied at the optimum level, in a way and quantity that does not interfere with or disrupt biological processes (Nyamangara et al., 2013).

2.12.2 Global spread of CA

The term "conservation agriculture" was coined in the 1990s, but the concept of minimizing soil disturbance dates back to the United States of America's Dust Bowl in the 1930s (Johnson et al., 2019). In the 1940s the concepts for reducing tillage and keeping soil covered arose, and seeding machinery which enabled direct seeding without soil tillage were established (Awada et al., 2014). Currently CA adoption is highest in the southern parts of South America and the north-western parts of North America, with adoption rates exceeding 50% in both regions. In Latin America countries such as; Argentina, Paraguay, Uruguay, and Brazil are approaching 100% adoption of no-till farming (Kassam et al., 2014). CA has been promoted in Europe by the European Conservation Agriculture Federation (ECAAF) since 1999, and adoption is visible in Spain, Finland, France, and the United Kingdom, with some farmers in Ireland, Portugal, Germany, Switzerland, and Italy at the proof of concept stage (Kassam et al., 2014). In Spain, Portugal, and Italy CA adoption in perennial crops such as fruit orchards, vineyards, and olive plantations has outpaced that in annual crops (Friedrich et al., 2017).

In sub-Saharan Africa, conservation agriculture has received a lot of research and promotion support from various organizations over the last few decades (Mango et al., 2017). Conservation agriculture is widely promoted as one of the few win–win technologies available to farmers, in the sense that it has the potential to increase farmer yields while also conserving the environment over time (Jayaraman et al., 2021a). At least 14 African countries (Kenya, Uganda, Tanzania, Sudan, Swaziland, Lesotho, Malawi, Madagascar, Mozambique, South Africa, Zambia, Zimbabwe, Ghana, and Burkina Faso) are now at the fast pace to adopt conservation agriculture practices. In African context some

of CA practices such as; direct seeding and hand hoe basin builds on indigenous knowledge (Troccoli et al., 2015). Conservation Agriculture can assist farmers in maintaining and increasing yields and earnings while also reversing land degradation, safeguarding the environment, and reacting to the growing problems of climate change (Chaudhary et al., 2019). Minimum soil disturbance with residue cover conserves water, progressively enhances soil organic matter, and controls weeds while lowering the expenses of machinery, fuel, and time spent tilling. Furthermore leaving the soil undisturbed enhances water infiltration, retains soil moisture, and aids in the prevention of topsoil erosion (Verma, 2021).

2.12.3 The key elements of CA – The three pillars

i. Permanent soil cover

One of the fundamental principles of conservation agriculture is to maintain permanent soil cover even when regular crops are absent from the field (Ahmed et al., 2017). Crop residues that remain on the soil surface form a layer of mulch. This layer not only protects the soil from the physical effects of rain and wind, but it also maintains soil moisture and temperature in the surface layers (Friedrich et al., 2009). As a result, this zone becomes a home for a variety of organisms, ranging from larger insects to soil-borne fungi and bacteria. These organisms macerate the mulch, incorporate and mix it with the soil, and decompose it, converting it to humus and contributing to the physical stability of the soil structure and porosity (Ligowe et al., 2017). At the same time, the organic matter in the soil acts as a buffer for water and nutrients (Carbonell-Bojollo et al., 2019). Mulch harbours soil fauna, such as earthworms that provide a soil structuring effect, resulting in very stable soil aggregates as well as continuous macropores leading from the soil surface down to the subsoil and allowing rapid water infiltration during heavy rainfall events (FAO, 2016b). Keeping the soil covered with mulch or planting green cover crops protects the soil and also improves the growing environment for plants (Friedrich et al., 2009). Organic soil cover can be classified into three categories: 30-60%, > 60-90%, and > 90%; CA requires soil cover of more than 30%, which is measured shortly after direct planting (Friedrich et al., 2009). Under CA cover crops are planted for the purpose of covering the soil. Cover crops are plants that can be planted when regular crops are removed from the field. They are planted to protect the soil rather than to be harvested (Amakali, 2019).

ii. ***Minimum soil disturbance***

Farmers have believed for over 2000 years that they must plough the land in order to get a good crop, associating soil tillage with increased fertility, which can occur in the short run due to mineralization and the breakdown of organic matter as a result of soil tillage (Friedrich et al., 2009). However the more frequently the land is ploughed, the faster it loses vital organic matter and the biotic activity it supports (Jat et al., 2018). Soil become capped and less porous as organic matter content decreases, losing its ability to absorb and retain water (Araya et al., 2012; Carbonell-Bojollo et al., 2019; Friedrich et al., 2009; Khan et al., 2017). According to Alam et al., (2014), tillage practices affects the physical and biological features of the soil, resulting in changes in plant development and productivity. They further stated that soil tillage influence soil characteristics and contributes up to 20% of crop production variables and has an impact on the sustainable use of soil resources due to its influence on soil qualities. Effects of tillage can be reversed by no-or minimum soil disturbance (Friedrich et al., 2009).

iii. ***Crop rotation***

Crop rotation is the practice of growing different crops in different sequences on the same piece of land (FAO, 2013a). By including smothering crop species such as cowpeas or green manure cover crops in the rotation, pests and diseases in the cropping system are reduced, and weeds are controlled (Carbonell-Bojollo et al., 2019). Also leguminous crop has the ability to fix nitrogen in the soil, thus by including legume crops in rotation improve soil quality, and enhances different root systems which increase biological activity, and improve nutrient distribution in the soil profile (Naab et al., 2017). Furthermore crop diversification can help reduce the risk posed by extreme weather events like droughts and floods, as bad seasons or parts of seasons can affect some crops more than others (Friedrich et al., 2009). Crop rotations can also help to balance residue production by alternating crops that produce few and/or short-lived residues with crops that produce a large number of long-lasting residues. Also diversification of crops makes a farmer's livelihood more resilient by improving soil properties and increasing the potential for higher yields (Carbonell-Bojollo et al., 2019).

2.12.4 Impact of CA on soil quality

Conservation agriculture and its components have been linked to a variety of advantages, including increased soil water storage, improved soil quality, reduced erosion, and in a long run increased yield and net farm income (Page et al., 2020). These advantages have led to the recognition of CA as an important tool for ensuring future food production and buffering agricultural productivity against extreme climate events such as drought and heat waves, which are expected to become more common as a result of climate change (Jat et al., 2018; Page et al., 2020).

When compared to conventional tillage (CT) systems, Conservation Agriculture (CA) has been reported to have the potential to change soil physical, chemical, and biological soil quality parameters (Araya et al., 2012; Carbonell-Bojollo et al., 2019; Thierfelder et al., 2012). Through permanent soil cover, CA has the ability to reduce SOC loss from the soil profile by slowing the turnover rate of macro aggregates, improving the physical protection of particulate organic matter, and lowering microbial attack (Shrestha et al., 2020). Covering the soil with crop residue is good way to encourage an agricultural production system with more microbial life in the soil. also have an impact on the functional diversity of soil microbes, which is important for improved soil quality, crop production, and a variety of ecosystem services (Palm et al., 2014).

Because leguminous crops have the ability to fix nitrogen in the soil, integrating legume crops in rotation improves soil quality and strengthens diverse root systems, increasing biological activity and improving nutrient distribution in the soil profile (Jayaraman et al., 2021a). In comparison to conventional tillage which practice deep tilling, no soil cover and no/few crop rotation, the conservation tillage systems have the potential advantage to improve soil organic matter content, plant available water capacity, soil aggregation, and soil water transmission capacity, as well as infiltration characteristics and saturated hydraulic conductivity (Shrestha et al., 2020). Palm *et al.*, (2014) pointed out that conservation tillage has a higher gravimetric water content of the soil at different depths than conventional tilling. Also CA can help to mitigate the negative effects of unsystematically applying chemical fertilizers, pesticides, and herbicides, which have degraded soil health (Jayaraman et al., 2021b). CA is increasingly being referred to as Climate Smart Agriculture, as it helps with both adaptation and mitigation of climate change (FAO, 2013a). Furthermore conservation agriculture is gaining traction as a viable alternative to both conventional and organic agriculture in many parts of the world (Chaudhary et al., 2019; Thierfelder & Wall, 2010).

Conservation agriculture, according to Shrestha, Chaudhary and Subedi, (2020) is a productive system with improved interactions between the four factors of productivity: physical, better characteristics of porosity for root growth, water movement, and root-respiration gases; chemically raised cation exchange capacity of soils gives better capture, with greater control/release of nutrients; biologically (Shrestha et al., 2020). Jayaraman *et al.*, (2021) further pointed out that CA is a method of managing agroecosystems for increased and sustained productivity, profits, and food security while preserving and enhancing the resource base and the environment. In the long run, CA aims for sustainable intensification, which is defined as a process or system that increases agricultural yields without having a negative impact on the environment or requiring the conversion of additional non-agricultural land (Shrestha et al., 2020).

Reduced tillage operations under CA help to keep the remainder of the harvested crops in the soil, improving soil penetration and preventing moisture loss due to evaporation, also CA helps to prevent and control soil erosion by reducing the physical chemical disruptions caused by soil, which improves soil fertility, reduces labour, and lowers input costs (Limousin & Tessier, 2007; Pierre et al., 2018). CA reduces soil particle disruption by reducing tillage operations to a bare minimum, improving the physical, chemical, and biological properties of the soil as well as crop production, in direct opposition to traditional farming methods (Thierfelder & Wall, 2010).

The use of crop residues and the cultivation of cover crops help to maintain a permanent organic soil cover. Legumes intercropped with perennial crops or diversified crop rotation help boost soil biological properties, cycle, and crop productivity in annual crops (Amakali, 2019; Shrestha et al., 2020). The introduction of conservation agriculture, has the potential to improve soil penetration rate, soil moisture retention, runoff loss minimization, and evaporation loss in a short-to-long period of time depending of the soil type (Chaudhary et al., 2019; Friedrich et al., 2009). CA studies have demonstrated that conservation agriculture can improve soil water holding capacity, soil fertility, water use efficiency, and nutrient use efficiency which results in increased crop yields (Araya et al., 2012; Chaudhary et al., 2019; FAO, 2016c; Friedrich et al., 2009; Mupangwa et al., 2017; Shrestha et al., 2020; Thierfelder & Wall, 2010).

2.12.5 Impact of CA on crop yield

It is frequently stated that the CA system can assist agriculture in adapting to increased climate variability and the occurrence of extreme events (Page et al., 2020). Various researchers have

reported that CA can result in erosion protection, reduced soil temperatures, and improved infiltration rates (Rusinamhodzi et al., 2011). Furthermore CA have been proposed to assist in dealing with more intense rainstorms, as well as increased daily temperature ranges and drought frequency through soil cover (Rusinamhodzi et al., 2011). Also in dry years, CA have been reported to provide advantages through mulch/soil cover which results in conserving the moisture in the soil (Jat et al., 2018; Knapp & van der Heijden, 2018; Page et al., 2020). Some studies have found that CA practices, particularly the incorporation of cover crops, are associated with increased crop yield stability (Page et al., 2020). The increased yields commonly observed in dry climates are commonly attributed to CA-induced improvements in soil water storage (Thornton & Radford, 2011). Because of the reduced land preparation requirements in CA systems, the possibility of early planting is also increased, which may result in more efficient use of rainfall and a lower risk of crop failure due to terminal heat stress (Jayaraman et al., 2021b; Thierfelder et al., 2013). Lower soil temperatures under CA systems due to residue retention can also help improve plant growth and yield in hot regions (Page et al., 2020). Improvements in soil fertility and pest/disease reductions as a result of incorporating legumes and diverse species into cropping rotations have also been reported to contribute to yield increases in some cases (Williams et al., 2018).

Due to various benefits observed under CA over the past years, CA practices has been widely adopted and practiced globally about 180M ha of cropland, 12.5% of total global cropland area in 2015/16, and a 69 percent increase globally since 2008/09 (Jayaraman et al., 2021b). Because it provides numerous benefits to agricultural production through soil and water conservation and soil health improvement. CA is currently promoted as a sustainable farming practice capable of not only maintaining or increasing crop productivity, but also of improving carbon storage, environmental quality, and ecosystem services (ES) (Jayaraman et al., 2021b).

However other studies have found no impact of CA in the yield stability when compared to conventional agricultural (Daigh et al., 2018; Knapp & van der Heijden, 2018; Rusinamhodzi et al., 2011). Nyagumbo *et al.*, (2016) pointed out that where yield decrease is observed, it is frequently associated with increased waterlogging as a result of increased water infiltration and decreased evaporation in CA systems, with higher rainfall areas and poorly drained soils being the most severely affected (Nyagumbo et al., 2016). Reduced soil temperatures can also cause plant maturity to be delayed, especially in cooler, higher latitude regions, and have a negative impact on yield. As a result, CA is often unlikely to increase yield in cold, wet environments with poorly drained soils

(Page et al., 2020; Rusinamhodzi et al., 2011). Other causes of yield loss have been linked to: inadequate weed, pest, and/or disease control in the absence of tillage (Page et al., 2020).

2.12.6 Challenges to adoption of CA

Despite the proven benefits of CA, its use has been mainly limited to developing countries (Jayaraman et al., 2021b). CA Uptake in developing countries is frequently very low due to various socioeconomic and logistical barriers to implementation, some of these barriers are; lack of skills and knowledge, culture and traditions, insufficient access to finance, appropriate machinery, poor extension services, and poor crop yield in early years due to weed, residue and soil fertility management problems (Amakali, 2019). Other issues that impede CA adoption in both developed and developing regions include weed shift, herbicide resistance, nutrient stratification, residue-borne pests and diseases (Jayaraman et al., 2021b).

According to Friedrich, Kassam and Shaxson, (2009) one of the challenges to adopt CA principles is the mindset of the plough. The plough has become a symbol of agriculture, and many people, including farmers, extension agents, researchers, university professors, and politicians, find it difficult to believe that farming can be done without tilling the soil. Thus CA principles like direct planting, or minimum tilling with rippers are not easily accepted by farmers as cultivation methods (Pittelkow et al., 2015). Also, in subsistence farming crop residues are in high demand. The majority of small-scale farmers in SSA have mixed crop/livestock systems and rely on crop residues for animal feed and, building materials (Amakali, 2019). As CA systems does not incorporate livestock in its systems it leaves farmers with few choices on how to feed their livestock. And due to the setup of the communal farming where all resources are shared it is difficult to keep livestock from entering crop fields specifically during dry season (FAO, 2013a).

Weed control supposed to be the primary function of tillage, so when tillage stops, weed control becomes a major factor (Friedrich et al., 2009). Herbicides, particularly the broad-spectrum glyphosate have been used successfully in many cases to control weeds present at seeding time. However, for farmers who do not have access to herbicides or the equipment to apply them, or who prefer to farm organically, manual weed control can be difficult and time-consuming in the first years of CA practices if no specific technical advices are provided (Amakali, 2019).

According to Johnson et al., (2019), CA's success is dependent on adequate residue coverage. In very infertile and degraded soils, sufficient fertility amendments must be applied to overcome shortages

of specific soil nutrients that may be limiting soil life and plant growth. This increases production of not only the economic portion of the crop, but also of the residues/cover crops.

In Africa, small-scale equipment for seeding crops without tillage is not readily available. Thus the willingness of farmers to shift from conventional tillage to conservation agriculture is jeopardized (Mupangwa et al., 2017).

2.13 Soil testing

The United State Department of Agriculture (USDA), (2018) stressed that soil fertility management program should include soil testing. Soil testing provides information on the fertility status, the soil results can be used to make fertilizer or lime application recommendations, track changes in soil fertility over time, and even identify and target low fertility soils within larger fields (Nafiu et al., 2012). Furthermore soil testing can help improve on-farm nutrient efficiency, resulting in a higher return on investment for fertilizer and lime applications and a lower risk of nutrient movement (Ferguson et al., 2007).

2.13.1 Soil sampling

Collecting representative samples in the field is an important step in obtaining accurate soil tests. According to USDA, (2018), uniform fields should typically be sampled in a simple random pattern across the field, with at least 10-20 equal size soil cores collected in a zig zag pattern. Areas like abandoned such as farmsteads, feedlots, manure piles, fences, roads, eroded knolls, low areas, and salty or wet spots should be avoided or sampled separately (Ferguson et al., 2007). Furthermore fields with significant differences in the landscape or other factors should be sampled and tested separately (Ackerson, 2018). Factors like slope, degree of erosion, drainage, crop and/or manure history, and other factors that influence soil nutrient levels may influence the result of the soil test. Also where detailed information about within-field nutrient variability is required for instance precision application techniques and zone development, more intensive sampling should be used (USDA, 2018).

2.13.2 Sampling process

For accurate fertility recommendations, careful soil sampling and sample handling are essential. Poor soil sampling will result in misleading results. Ackerson, (2018) urged that in order to make good analysis, interpretations, and recommendations that accurately reflect the nutrient status of the entire fields, proper procedures need to be followed when taking soil sample and soil analysis. Accurate sampling and results can lead to better fertilizer use, lower costs, and less environmental degradation (USDA, 2018). A

uniform field area should be represented by a composite soil sample. Each area should have a similar history of crops and fertility. The colour, slope, texture, and drainage of the soil should all be similar (Ferguson et al., 2007).

2.13.3 Sampling depth

Tests in the laboratory are calibrated to specific depths (USDA, 2018). Since a core taken deeper or shallower will produce erroneous results, it is critical to collect samples from appropriate depths with a specific purpose (Ackerson, 2018; Ferguson et al., 2007; USDA, 2018). According to Chirwa et al., (2016) a sample depth of 0-30cm intervals is usually the sampling depth for most soils. Since the top 15cm of soil have the most root activity, determining soil fertility at this depth is critical. Traditional tests of organic matter, phosphorus, potassium, pH, and salt levels are typically performed on topsoil. If nitrogen fertilizer recommendations are desired for deep-rooted crops like wheat and barley, deeper samples are required (Ackerson, 2018).

2.14 Summary of related research

This section examines the related research conducted on effect of conservation agriculture on soil fertility elsewhere, the purpose of this section is to ensure a good understanding of the background of conservation agriculture on soil fertility signifying a directional guide to this study.

Ligowe *et al.*, (2017) conducted a study to assess the medium-term effects of a 5-year CA experiment's potential for improving soil quality. The findings revealed that chemical nutrient accumulation in CA is gradual, with significant differences between treatments becoming apparent after the fourth year of practice. In the fifth year, CA treatments had pH and soil organic matter (SOM) levels that were 14 and 21% higher, respectively, than standard practice.

Page, Dang and Dalal, (2020) looked at the Conservation Agriculture's ability to Conserve Soil Organic Carbon and Its Impact on Physical, Chemical, and Biological Properties and Yield. The study concluded that CA systems, when well-designed and adapted to local conditions, can improve the SOC content of many soils when compared to conventional agricultural systems, leading to significant improvements in soil physical, chemical, and biological properties, as well as productive capacity.

Nebo *et al.*, (2020) conducted a study on Short-Term Effects of Conservation Agriculture on Soil Strength and Saturated Hydraulic Conductivity in South African Semiarid Areas, the results showed no significant difference between no-till (NT) and conventional tillage (CT), maize-fallow-soybean (MFS) and residue management after three years .

Jat *et al.*, (2018) investigated the impact of climate smart agriculture where zero tillage, crop residue retention and crop diversification were among techniques used. And the results showed significant results in soil pH, organic carbon and in crop yield in four years.

Thornton and Radford, (2011) observed CA for over 20 years “The effects of 27 years of reduced tillage practices on soil properties and crop performance in Australia's semi-arid subtropics”. During the subsequent 5 years reduced tillage treatments outyielded the former traditional tillage in all 5 crops grown. And the long-term NT produced an average yield of 3.3 t/ha, whereas the traditional tillage, produced only 2.1 t/ha for 20 years. The results showed a 57% yield increase in the long-term no-till.

Williams *et al.*, (2018) assessed short-term impacts of regionally-adapted CA systems on soil properties and explored linkages with maize and soybean yield stability. The results showed an increase in organic matter, increased soil cation exchange capacity, which improved soybean yield stability. Implying that regionally-adapted CA may play an important role in developing high-yielding, climate-resilient agricultural systems.

Thierfelder and Wall, (2010) assessed “rotation in conservation agriculture systems of Zambia: effects on soil quality and water relation”. The results demonstrated a significant difference whereby, a sensitive indicator of soil quality, was significantly lower on conventionally ploughed plots compared to CA plots in all cropping seasons. In CA maize treatments seeded after cotton, higher water infiltration rate resulted in higher soil moisture content. CA plots also had significantly higher levels of earthworm populations, total carbon, and aggregate stability. Moreover soil quality improvements resulted in increased rainfall use efficiency and maize grain yield on CA plots, particularly those with a two- or three-year rotation (Thierfelder & Wall, 2010).

Chapter 3: Research Methodology

This chapter describes the methodologies utilised in data collection and analyses that are pertinent to the research. The methodology cover topics such as the study's location, data collection, sampling and sample procedure, indices, and the limitation of the study.

3.1 Study location

The experiment was conducted in two regions; Kavango West (KW) and Kavango East (KE) region, the two regions on average are located at 18.2710° S latitude, 18.4276° E longitude, at an average elevation about ±1000m above sea level. The two Kavango regions (Figure 5) are bordered by Angola in the north and Kavango west is bordered by the Ohangwena region on the northwest and Oshikoto region on the southwest and Kavango east is boarded by Zambezi region on the northeast and Botswana on the southeast. Kalahari sands are predominant in the study area, specifically low fertility *Ferralic arenosols*, and *Chromic luvisols* are the dominant soil type (Muhoko et al., 2020). Generally, *Ferralic Arenosols* are sandy soils with low natural CEC due to their sandy texture and low clay content and the *Chromic luvisols* soil's CEC is influenced by factors such as clay and organic matter content. The two regions are semi-arid areas with uniform landscape. The average annual rainfall ranges from 450-600 mm, the rainy season extends from November to April. Temperature is generally mild to hot, winter is from May to August and days are clear and sunny with an average minimum temperature ranging from 5°C to 10°C while the maximum is well above 20°C. The heat for summers is from September with mean minimum temperature above 25°C and the daily maximum temperatures can reach 40°C in summer (Muhoko et al., 2020). The two regions were selected due to their highly involvement in agricultural activities at subsistence level and understanding the impact of Conservation Agriculture (CA) on soil fertility in these regions is crucial for improving crop production at subsistence level. Also, both regions have been facing challenges related to poor soil fertility, leading to reduced crop yields and food insecurity. The prevalence of sandy soils in these areas poses particular soil fertility management challenges, making them ideal locations to study the effectiveness of CA in addressing soil health concerns. Furthermore, the two region are vulnerable to the impacts of climate change, including erratic rainfall patterns and prolonged droughts. CA, as a sustainable agricultural practice, holds the potential to improve soil resilience and mitigate the adverse effects of climate change on agriculture.

In 2016, the Ministry of Agriculture Water and Forestry (MAWF) now Ministry of Agriculture and Land Reform (MAWLR) , in partnership with the Deutsche Gesellschaft für Internationale Zusammenarbeit

(GIZ), launched a conservation agriculture project aimed at tackling the challenges of low crop yields and soil fertility (MAWF, 2015). This initiative focused on educating farmers about conservation agriculture principles, including minimum tillage, soil cover, and crop rotation. The selected crops for cultivation were millet, groundnut, and cowpeas, with the latter two serving as legume crops used in crop rotation to improve biological nitrogen fixation and improve soil fertility.

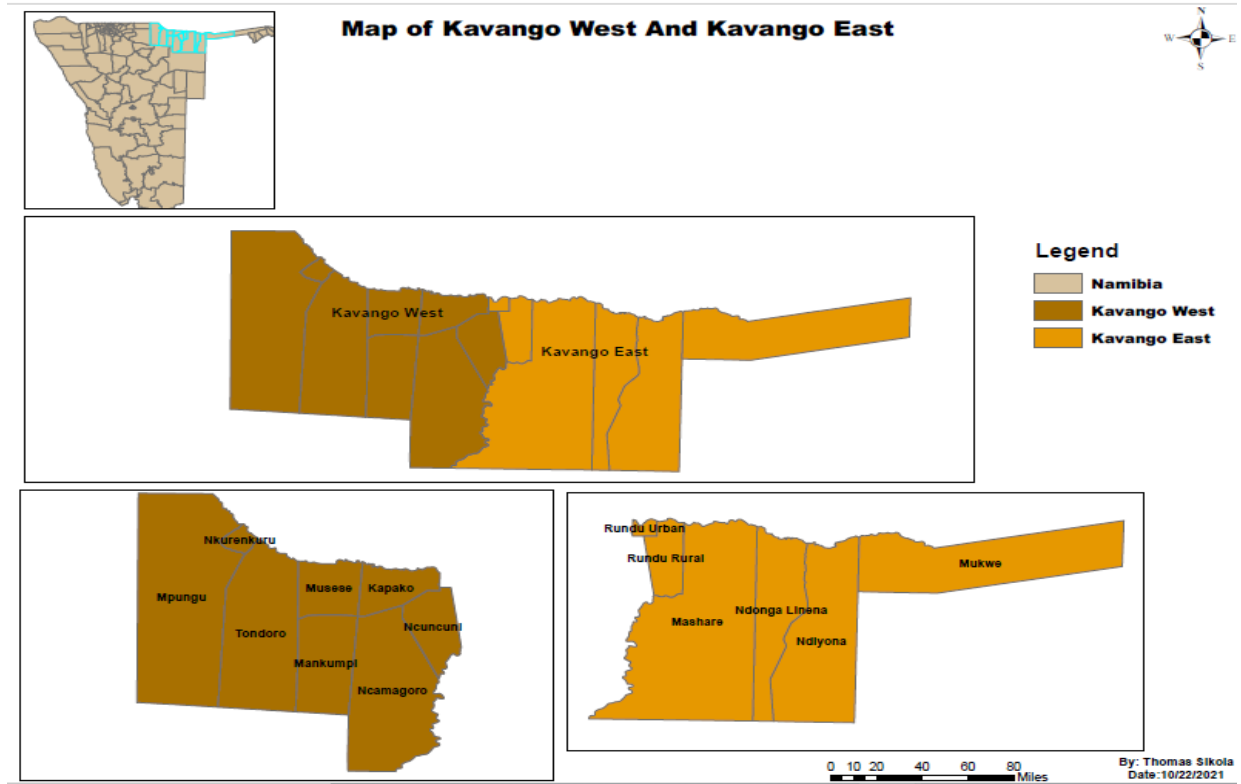


Figure 5: Map of Kavango west and Kavango east

3.2 Data collection

The study used secondary and primary data from 2016 to 2022 for analyses. Since 2016 Ministry of Agriculture, Water and Land Reform in collaboration with GIZ trained smallholder farmers in conservation agriculture practices in Kavango east and kavango west. Farmers that participated in the CA initiative reserved 0.5-1ha of land in their field. The reserved plots were prepared using various rippers, either with the Animal drawn Magoye ripper, Animal drawn Baufi ripper, or Tractor Baufi ripper, all of which adhere to CA principles. Variety of pearl millet (Okashana 2) and Cowpea (Bira/Shindimba or Nakare) were used. Millet was planted 75cm between rows and 25 cm (adult feet) between plants while cowpeas was planted

37.5cm between rows and 30cm between plants. Crop residues were retained to the soil as mulch and crop rotation between legumes and cereals was practiced after every season. In the first years chemical fertilizer was applied, basal dressing of NPK (2.3.2) was applied at a rate of 150kg/ha and top dressing of Urea N (46%) was also applied at a rate of 150kg/ha on millet only. Each farmer received a rain gauge, and farmers were trained on how to measure rainfall data and the farmers recorded rainfall at their specific village every year. Prior to CA implementation soil samples were collected from farmer's field to determine soil fertility content and soil samples were collected at least after every season to monitor changes in soil fertility. For the 2022 soil data, the researcher set a criterion for selecting farms that were suitable for the study. The criteria required that the farmers (i) have been involved in CA for the previous five years and (ii) had soil data collected for the previous five years, with laboratory analysis results available at the soil lab. A total of 17 farms met the requirement and soil samples were collected from these farms. The 2022 data served as primary data for the study whereas the study's secondary data came from data that we collected between 2016 and 2021 by the project and the ministry.

The study used secondary rainfall data that was collected between 2017 and 2020 by the farmers at Singuruve and Mile 20 village in Kavango West region and at Shikoro village in Kavango East region, the rainfall data were combined to get an average rainfall (Figure 7) for the year, representing the two regions.

3.3 Soil sampling

Initial soil samples were collected in 2016 at 5-30cm depth in farmers' fields prior to CA implementation and soil samples were collected at least after every season to determine soil fertility. In 2022, soil samples were collected again at the same depth (5-30cm) for mineral content analyses. A systematic random sampling was employed to collect at least 10 subsamples (soil cores) using a shape spade (Figure 6) in a zig zag (w) pattern. Soil cores were put in a bucket and mixed thoroughly to form a composite sample. At least ½ Kg of composite sample were put into a clearly labelled plastic bags and taken to soil lab for soil analysis.

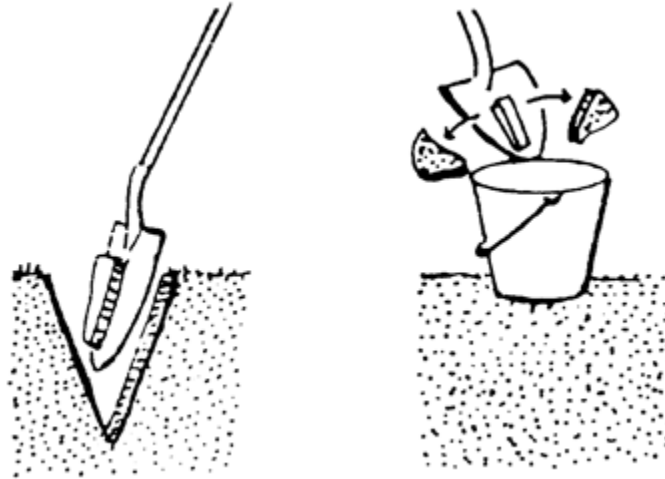


Figure 6 shows how to take soil sample with a spade

Source: Assam Agricultural University (2021)

3.4 Laboratory soil analysis

The collected soil samples were air dried, cleaned of roots and debris, and sieved through a 2 mm sieve. The soil samples were analysed using Bruker Alpha I Spectrometer. The Spectrometer screens the soil for various soil characteristics and the results are given out as follows: pH (KCl) (pH Value), Organic Carbon (g/kg), Total Nitrogen (g/kg), Potassium (exch.) (mmol+/kg), Phosphorus (g/kg), Calcium (exch.) (mmol+/kg), Magnesium (exch.) (mmol+/kg), Zinc (M3) (mg/kg), Cation Exchange Capacity (mmol+/kg), Total Aluminium (g/kg), Total Silicium (g/kg), Total Iron (g/kg) and percentage of soil texture. Since it is difficult to measure soil organic matter directly, laboratories typically measure soil organic carbon and use a conversion factor to estimate how much organic matter is held within a soil (Sullivan et al., 2019). According to Sullivan et al., (2019) soil organic carbon is a component of soil organic matter, accounting for approximately 58% of the mass of organic matter. Therefore, soil organic matter can be estimated from organic carbon content by determining the amount of soil organic carbon in a sample and multiply it by 100/58 (or 1.72). The soil organic matter was therefore determined using this formula (Sullivan et al., 2019):

$$SOM (\%) = TOC (\%) \times 1.72$$

Where

TOC= is the total organic carbon in percent

1.72 = is the conversion factor (100/58 or the 58% content of organic carbon in organic matter).

3.5 Soil quality indexes

3.5.1 Soil indexes based on GIZ/SoilCare soil laboratory

The GIZ/SoilCare laboratory analyses the soil and provides soil fertility results as well as the required range of the chemical properties in the soil (Table 1).

Table 1: Soil quality indexes based on GIZ/SoilCare laboratory

Parameter	Units	Low	Optimal range	High
pH (KCl)	pH Value	<4.9	6-7	>7.1
Organic Carbon	g/Kg	<17	17-50	>50
Total Nitrogen	g/Kg	<1	1-2	>2
Potassium (exch)	mmol+/Kg	<1.5	1.5-3	>3
Phosphorus	g/Kg	<0.2	0.2-0.6	>0.6
Calcium (exch)	mmol+/Kg	<15	15- 25	>25
Magnesium (exch.)	mmol+/Kg	<4.5	4.5-10	>10
Zinc	mg/Kg	<2.5	2.5-4	>4
Total Iron	g/Kg	<31	31-81	>81
Silicium	g/Kg	<240	240-340	>340
Aluminium	g/Kg	<70	70-112	>112
Cation Exchange Capacity	mmol+/Kg	<75	75-200	>200

3.5.2 pH (Acidification)

The soil acidification was calculated using the formula adopted from Interactive Soil Quality Assessment Information System (iSQAPER)(Barao and Basch, 2017), where the acidity change is calculated by comparing the current soil pH, with the initial/first year where the soil sample was first collected. If the current measured pH is higher than the initial year, then no acidification is taking place and if the measured pH is lower by up to 10%, then moderate acidification is occurring and if the difference is greater than 10% then the situation is more serious.

$$\frac{pH_{2016} - pH_{actual}}{pH_{2016}} \times 100$$

Where;

pH_{actual} is the pH on the current year (2022)

pH_{2016} is the pH in the initial year (2016)

3.5.3 Soil organic matter decline

The soil organic matter decline was also calculated using the formula adopted from iSQAPER. The soil organic matter decline indices is classified “low” when the actual SOC is higher than the initial year, “moderate” when the stock is decreasing less than 1% each year and "high" if the rate decrease is higher than 1% (Barao & Basch, 2017).

$$\frac{C_{2016} - C_{actual}}{C_{2016}} \times 100$$

Where;

C_{2016} is the organic carbon stock in 2016

C_{actual} is the organic carbon stock in the current year (2022)

3.5.4 Soil texture classification

The determination and classification of soil texture are crucial in understanding and managing various aspects of soil properties and behaviour. To achieve this, the widely recognized United States Department of Agriculture (USDA) texture classification method is employed. This system categorizes soil textures based on the relative proportions of sand, silt, and clay present in a soil sample.

Table 2: USDA Soil texture classification

Texture	Definitions
Sands	More than 85 percent sand, the percentage of silt plus 1.5 times the percentage of clay is less than 15.
Loamy sands	Between 70 and 91 percent sand and the percentage of silt plus 1.5 times the percentage of clay is 15 or more; and the percentage of silt plus twice the percentage of clay is less than 30.
Sandy loams	7 to 20 percent clay, more than 52 percent sand, and the percentage of silt plus twice the percentage of clay is 30 or more; or less than 7 percent clay, less than 50 percent silt, and more than 43 percent sand.
Loam	7 to 27 percent clay, 28 to 50 percent silt, and 52 percent or less sand.
Clay loam	27 to 40 percent clay and more than 20 to 46 percent sand.
Silty clay loam	27 to 40 percent clay and 20 percent or less sand.
Sandy clay	35 percent or more clay and 45 percent or more sand.
Silty clay	40 percent or more clay and 40 percent or more silt.
Clay	40 percent or more clay, 45 percent or less sand, and less than 40 percent silt.

Source (García-Gaines & Frankenstein, 2015, p. 6)

3.6 Limitation of the study

The study initially aimed to collect over 50 soil samples. However, due to various reasons such as unavailability of soil test results from the laboratory and some farmers dropping out of conservation agriculture project, only 17 samples (farms) were analysed. The 17 samples analysed were selected based on specific criteria, including consistency with CA practice over 6 years and the availability of soil samples collected at least after every season. Thus, some farmers who were consistent with CA but did not have samples taken in previous years were excluded from the analysis. Similarly, farmers who dropped out of CA before 2022 were also excluded.

3.7 Statistical analysis

All data were entered into IBM SPSS statistics version 28, where all statistical analyses were performed. The combined data of the two regions were first subjected to a normality test using a Shapiro-Wilk test and most of the data were found to be deviating from normality see appendix 1. Since the data was not normally distributed a nonparametric Kruskal Wallis test was employed to compare means and run descriptive statistics of the soil fertility parameters. The Kruskal-Wallis test was selected for its robustness in handling non-normally distributed data and its greater stability with outliers as compared to One-Way ANOVA (Nwobi & Akanno, 2021). A further multiple comparison post hoc Dunn's test was performed to obtain more detail on the data, and a nonparametric Spearman rank correlation was run to investigate the relationship among soil fertility parameters. All test used a 95% statistical confidence level.

Chapter 4: Results

4.1 Rainfall during the Study

The rainfall data was recorded at Singuruve village at farm Ndara D, and Mile 20 village at farm Kampanza P in Kavango West and at Shikoro village at farm Kapere N in Kavango East. The data were combined to represent the rainfall data in the study area. However, there was no data recorded at Shikoro in 2020, this might be caused by the Covid 19 pandemic.

The total amount of rainfall and its distribution throughout the seasons changed from year to year (Figure 7). The highest average rainfall was recorded during 2017 season (579.84mm), while the lowest was recorded during the 2019 season (359.50 mm) (Figure 7). The 2019 season was the driest season on record, with rainfall being unevenly distributed and 38% lower than 2017 season. The 2017 season stood out with a good rainfall record, with rain beginning in November with 53mm and continuing with a record above 100mm for December (111.69mm), January (194.47mm), and February(149.41mm). The highest rainfall was recorded in January, 2017 season (194.47mm) and 2019 season recorded the lowest rainfall in both November (4.00mm), December (64.67mm) and January(74.33) (Figure 7).

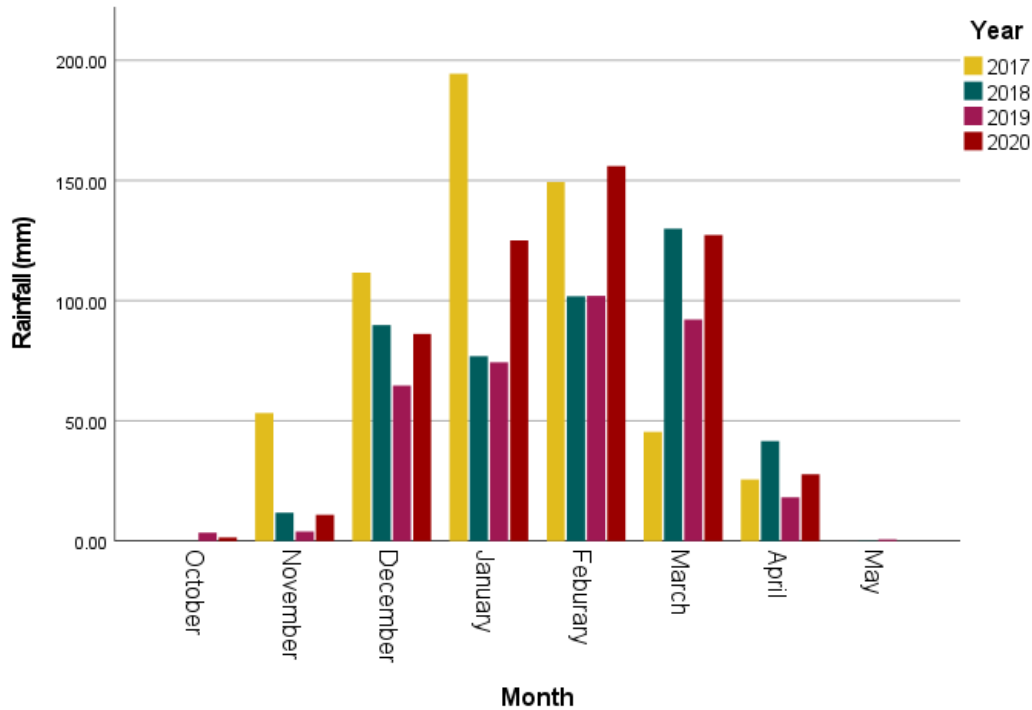


Figure 7: Rainfall during the growing season 2017-2020

Figure 8 represents the rainfall data recorded from 3 different villages Singuruve, Mile 20 and Shikoro. On the record Singuruve had a total annual rainfall of 545.55 mm in 2017. The highest monthly rainfall was recorded in January (150.80 mm), followed by November (108.78 mm) and the least was recorded in April (13.00 mm), and there was no rainfall recorded in October and May. Mile 20 received a total of 620.20 mm of rainfall in 2017. The highest monthly rainfall was in January (216.48 mm), followed by February (174.85 mm) and the least was in November (25.05 mm) while Shikoro had a total annual rainfall of 573.78 mm in 2017. The highest monthly rainfall was in January (216.125 mm), followed by February (182.50 mm) and there was no rainfall in November and May (Figure 8).

In 2018 Singuruve received a total of 466.68 mm of rainfall. The highest monthly rainfall was in February (141.08 mm), followed by March (119.10 mm) and the least was recorded in November (2.25 mm). Mile 20 had a total annual rainfall of 429.08 mm in 2018. The highest monthly rainfall was in February (133.48 mm), followed by January (110.85 mm) the least was in May (0.5 mm). While Shikoro received a total of 460.50 mm of rainfall in 2018. The highest monthly rainfall was in February (151.04 mm), followed by March (137.28 mm).

In 2019, Singuruve had a total annual rainfall of 269.50 mm only. The highest monthly rainfall was in March (92 mm), followed by December (86.50 mm). Mile 20 received a total of 356 mm of rainfall in 2019. The highest monthly rainfall was in March (120 mm), followed by December (75 mm). Shikoro had a total annual rainfall of 453 mm in 2019. The highest monthly rainfall was in March (140 mm), followed by December (128 mm). The 2019 season was the driest season on record in all the villages.

Singuruve received a total of 546.65 mm of rainfall in 2020. The highest monthly rainfall was in February (152.13 mm), followed by January (123.28 mm) the least was in November (17.38 mm). Mile 20 had a total annual rainfall of 523.10 mm in 2020. The highest monthly rainfall was in February (160 mm), followed by January (126.89 mm) and the least was in October (3.00 mm).

Mile 20 generally received higher rainfall than the other two villages in all years except for 2019 when Singuruve received more rainfall. Shikoro consistently received the least amount of rainfall among the three villages. Across all years and villages, January and February appear to be the months with the highest rainfall, while May tends to be the driest month (Figure 8). There was no rainfall data received from shikoro in 2020 and also there was no rainfall data recorded in 2021 and 2022. All the villages recorded the lowest rainfall in 2019 making it the driest year on record.

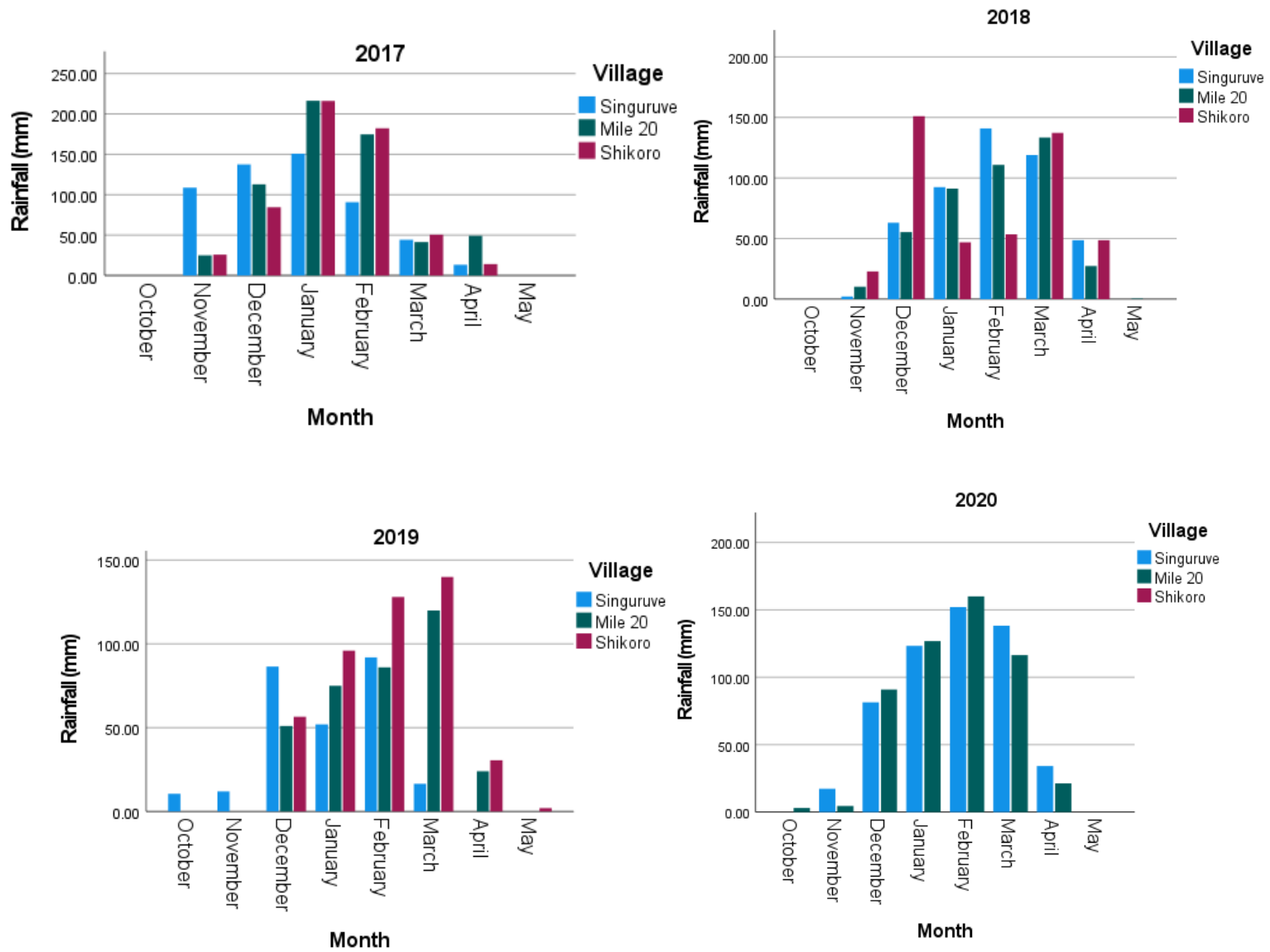


Figure 8: Rainfall recorded at Singuruve, Mile 20 and Shikoro village, from 2017-2020

4.2 Soil physical properties

4.2.1 Soil texture

The soil texture of each field in the study area are presented in Table 3. The results showed that most (59%) of the soil in KW and KE under CA were Loamy sand, 35% were Sand and 6% were Sandy loam. The results indicates that most of the soil in both KW and KE were loamy sandy and sandy soils.

Table 3: Soil physical properties in Kavango west

Field Name	Region	Sand			Textural class
		%	Silt %	Clay %	
Ndara D	KW	85	11	4	Loamy Sand
Veiko N	KW	75	18	8	Sandy Loam
Katewa D	KW	86	14	0	Sand
Kameya M	KW	97	0	3	Sand
Kambinda L	KW	89	8	3	Sand
Kampanza P	KW	85	11	3	Loamy Sand
Karwapa L	KW	91	8	0	Sand
Muronga E	KW	86	10	4	Loamy Sand
Kampanza N	KW	84	14	2	Loamy Sand
Karwapa Maria	KW	85	11	4	Loamy Sand
Kampanza C	KW	84	11	4	Loamy Sand
Sitarara K	KE	90	8	2	Sand
Mununga T	KE	84	13	3	Loamy Sand
Poroto A	KE	82	13	4	Loamy Sand
Kapere N	KE	86	11	4	Loamy Sand
Hamushira C	KE	90	7	4	Sand
Haingura M	KE	82	14	4	Loamy Sand
Mean		86	11	4	Loamy Sand

KW = Kavango West

KE = Kavango East

Soil Chemical properties

The data was collected from 2016 to 2022 in 17 farms to analyse the influence of Conservation Agriculture on soil fertility in the Kavango West and Kavango East regions. The data were combined to represent the two regions. The study analysis focused on analysing various soil chemical properties, including: pH, organic carbon, organic matter, nitrogen, potassium, phosphorus, calcium, magnesium, zinc, iron, silicon, aluminium, and cation exchange capacity. These properties are critical indicators of soil fertility and play a crucial role in determining the suitability of soils for sustainable crop production. The descriptive statistics for the soil chemical properties under CA in KW and KE from 2016 to 2022 are reported on Table 10 and Table 11. The distribution of the data is represented on the box plot graph. The soil parameters were also benchmarked with the soil laboratory standards and other critical limits set by several authority.

4.2.2 Soil pH (KCI)

The soil pH under CA in KW and KE in 2016, 2018, 2019 and 2022 ranged from 5.0 to 7.6, 4.3 to 7.2, 4.5 to 7.1, and 4.7 to 8.8 respectively, with a mean value of 6.5, 6.1, 5.6, and 5.8 respectively (Table 10). The results shows that most of the soil under CA were slightly acidic in, 2019, and 2022 with a mean value of, 5.65 ± 0.67 and 5.77 ± 1.00 respectively. While most soil pH in the first years of CA (2016 and 2018) were in the required pH range (6-7.2) for plant growth (Table 10). According to Kruskal wallis test there was statistically significant difference ($H(3) = 14.855$ $p < .002$) in soil pH under CA in six different years. However the average pH under CA in the 6th year (5.76 ± 1.00) was lower than that of the first year (6.55 ± 0.70), indicating that the soil pH under CA was getting slightly acidic instead of moving to neutral or desired pH range (Figure 9). Farm Veiko N had the highest pH during the study years with a mean value of 7.35 ± 1.08 whereas Farm kampanza P recorded the lowest pH mean 4.9 ± 0.82 (Table 11).

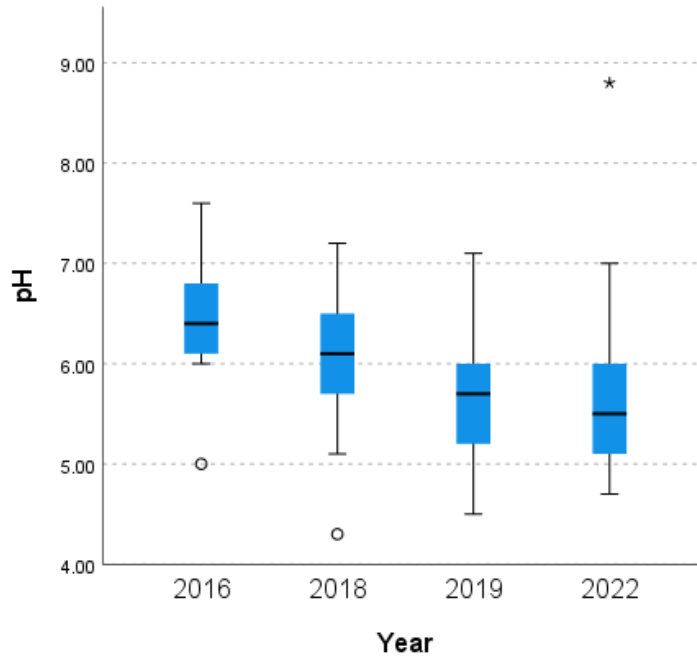


Figure 9: Distribution of the soil pH under CA 2016-2022

To understand the results better a further Post Hoc Dunn's test using Bonferroni adjusted alpha level of 0.5 was used to determine in which exact years did the statistically significant difference occurred (Table 4). The pairwise comparison table is generated, which displays the difference test from year-to-year. A significant difference in soil pH was observed between 2016-2019 ($p < .001$), 2016-2022 ($p < .001$) and other years did not show a significant difference (Table 4).

Table 4: Pairwise Comparisons of pH 2016-2022

Years	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	10.441	6.772	1.542	.123	.739
2016-2019	22.382	6.772	3.305	<.001	.006
2016-2022	21.882	6.772	3.231	.001	.007
2018-2019	11.941	6.772	1.763	.078	.467
2018-2022	11.441	6.772	1.689	.091	.547
2019-2022	-.500	6.772	-.074	.941	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

Significance values have been adjusted by the Bonferroni correction for multiple tests.

4.2.3 Soil Organic Carbon and Soil Organic Matter

The average SOC under CA in KW and KE fluctuated in every year, the highest SOC was recorded in 2018 with a mean value of $5.28 \pm 1.71 \text{ g Kg}^{-1}$ (about 0.9% SOM) while the least was recorded in 2022 with a mean value of $4.00 \pm 1.86 \text{ g Kg}^{-1}$ (about 0.69% SOM), resulting into a mean decrease of around 1 g Kg^{-1} of SOC (Table 10). The mean value ($4.00 \pm 1.86 \text{ g Kg}^{-1}$) of SOC in the 6th year is far below the GIZ/SoilCare laboratory critical limits of 17 g Kg^{-1} - 50 g Kg^{-1} (Table 1). Also lower than SOC average indices 20 g Kg^{-1} (about 3.44% SOM) given by several authorities (Chirwa et al., 2016; Eshetu et al., 2004; Musinguzi et al., 2013). Given this findings it is clear that all the soils under CA in KW and KE had very low organic matter content and CA did not have any significant improvement on soil organic carbon as Kruskal Wallis test did not find a statistically significant difference ($H(3) = 7.512$ $p = .057$) in soil organic carbon from 2016 to 2022 (Figure 10).

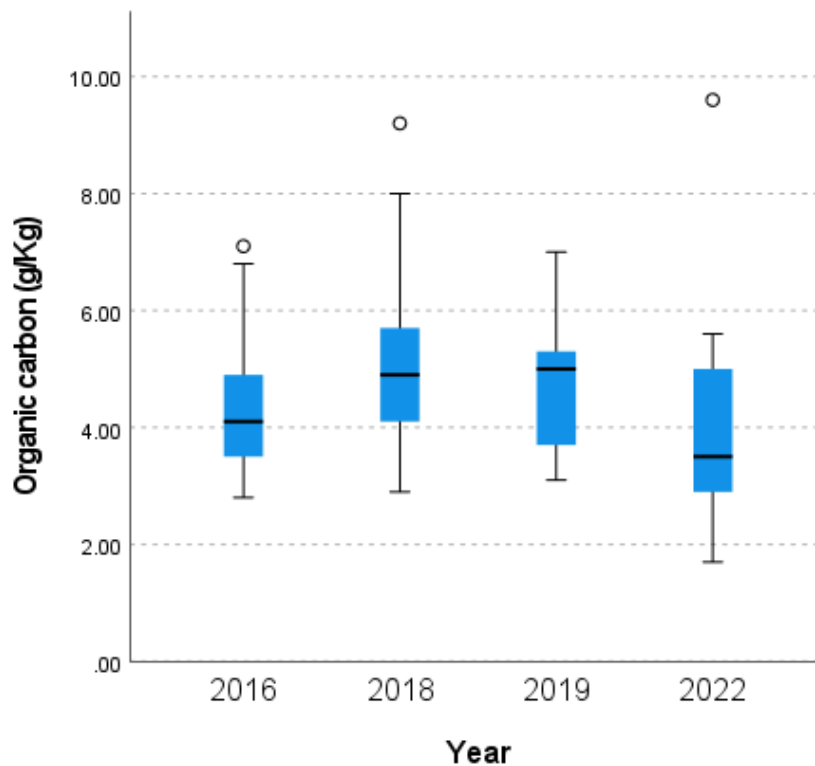


Figure 10: Distribution of the SOC under CA 2016-2022

4.2.4 Total Nitrogen

After six years of CA practise N was still below the lowest critical limit of 1 g Kg^{-1} , with a mean value of $0.27 \pm 0.18 \text{ g Kg}^{-1}$ (Table 10). Total Nitrogen was significantly decreasing ($H(3) = 17.025 \text{ } p < .001$) from a mean of $0.40 \pm 0.22 \text{ g kg}^{-1}$ in 2016 to $0.27 \pm 0.18 \text{ g kg}^{-1}$ in 2022. The statistically significantly differences within years was observed between 2018 and 2022 (Figure 11) and (Table 5). Farm Veiko N recorded the highest N with a mean of $0.80 \pm 0.40 \text{ g kg}^{-1}$ while farm Karwapa M recorded the least N over the years with a mean of $0.23 \pm 0.09 \text{ g kg}^{-1}$ and Farm Kameya M recorded the highest N 0.8 g Kg^{-1} in the 6th years (Table 11).

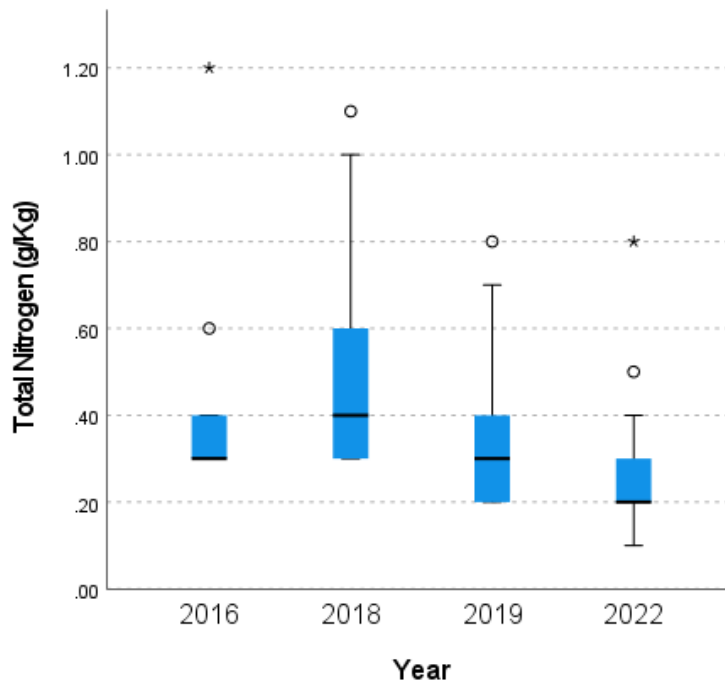


Figure 11: Distribution of the Total Nitrogen under CA 2016-2022

Table 5: Pairwise Comparisons of Total Nitrogen 2016-2022

Years	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	-9.088	6.582	-1.381	.167	1.000
2016-2019	7.647	6.582	1.162	.245	1.000
2016-2022	16.971	6.582	2.578	.010	.060
2018-2019	16.735	6.582	2.543	.011	.066
2018-2022	26.059	6.582	3.959	<.001	.000
2019-2022	9.324	6.582	1.417	.157	.940

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

4.2.5 Potassium (exch.)

There was no statistically significant difference ($H(3) = 1.611, p = .657$) observed in potassium exchangeable within six years (Table 10). However, the highest average K were observed in 2022 (2.00 mmol Kg⁻¹) showing slightly improvement of potassium exchangeable in CA fields, and the lowest K⁺ was recorded in 2019 (1.28 mmol kg⁻¹). In 2022 the average K⁺ (2.00 mmol kg⁻¹) was within the required range (1.5 to 3 mmol Kg⁻¹). The distribution of K⁺ within the years can be observed on the box plot (Figure 12). Farm Kameya M recorded the highest K⁺ with a mean value of 4.20±2.29 mmol Kg⁻¹ over the years (Table 12).

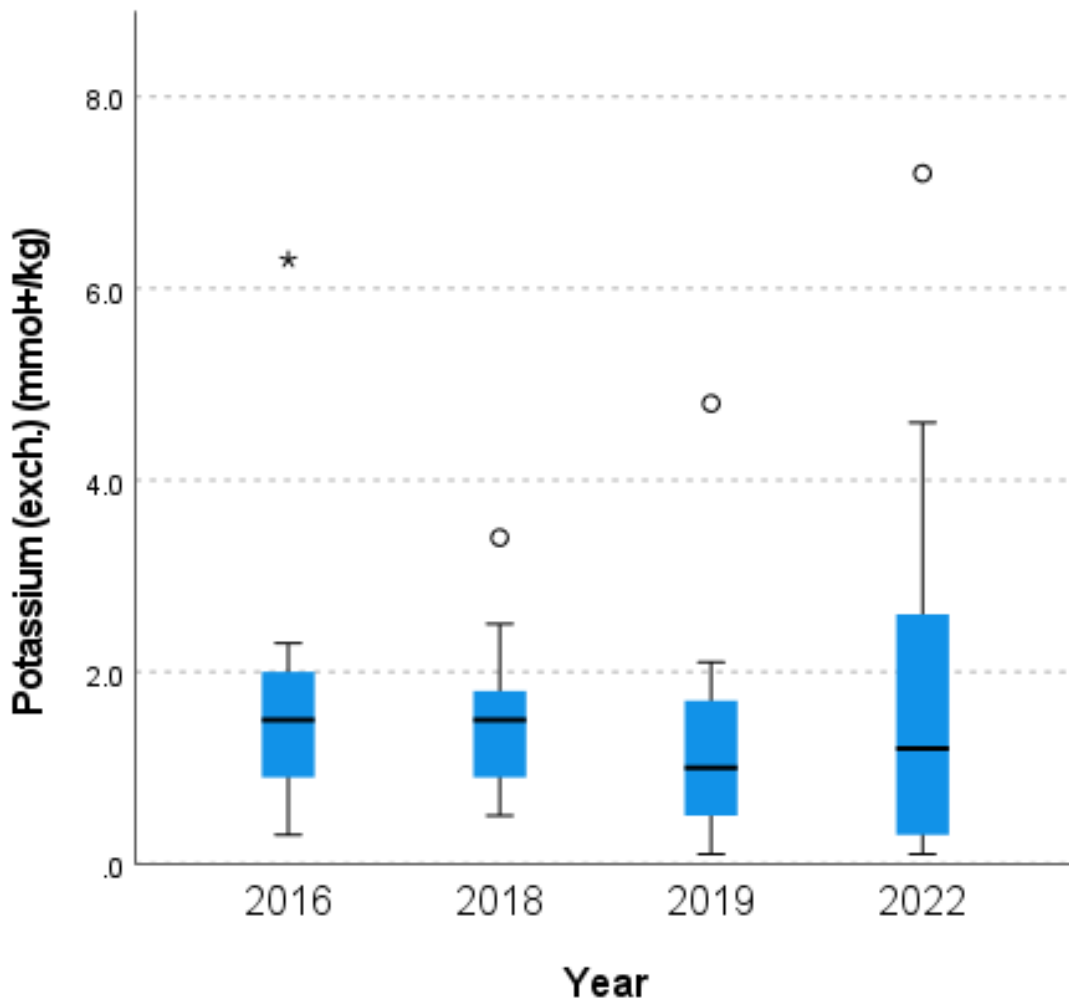


Figure 12: Distribution of the Potassium (exch.) under CA 2016-2022

4.2.6 Total phosphorus

The critical limit for P was 0.20 to 0.60 g/kg⁻¹ (Table 1), and according to this, there was very low P contents in all farms and years, ranging from 0.01 g Kg⁻¹ to 0.2 g Kg⁻¹, with a mean value of 0.05±0.05 g/kg⁻¹ in 2022 (Table 10), and in some fields it was undetectable. For instance, no P was detected in farm Kampanza P from the first year to the sixth year (Table 11). Most of the P distribution was below 0.1 g Kg⁻¹ (Figure 13) and there was no statistically significant difference ($H(3) = 3.027, p = .388$) observed in P under CA for a period of six years.

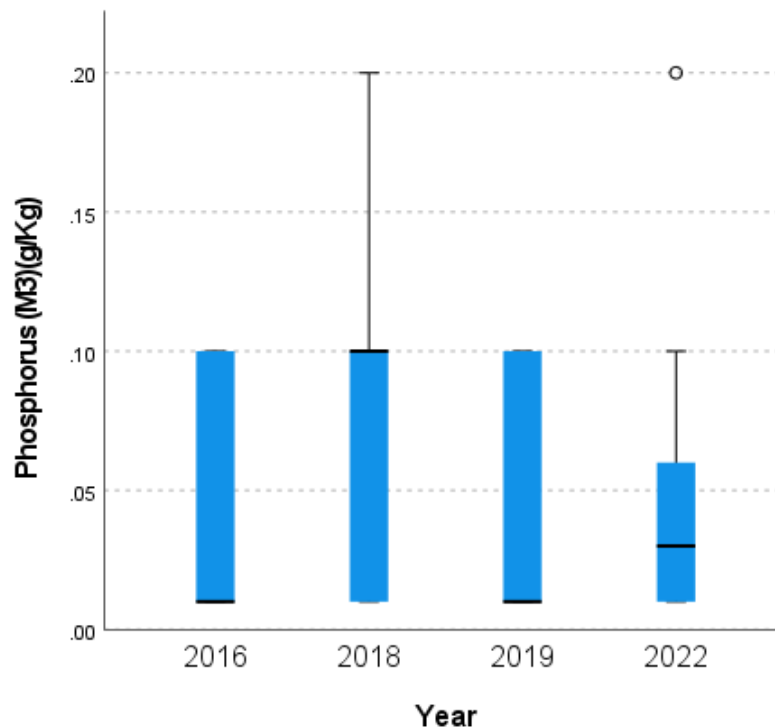


Figure 13: Distribution of the Phosphorus under CA 2016-2022

4.2.7 Calcium (exch.)

The Ca²⁺ ranged from 10.90 to 207.70, 14.40 to 74.20, 4.50 to 102.20, and 9.70 to 179.60 in 2016, 2018, 2019, and 2022 respectively (Table 10). The mean for exchangeable Ca²⁺ was observed to be 36.56±41.57 mmol kg⁻¹ in 2022 (Table 10) and the critical limits for Ca²⁺ was 15 mmol kg⁻¹ to 25 mmol kg⁻¹ (Table 1). There was no statistically significant difference ($H(3) = 6.620, p = .085$) in Ca²⁺ for a period of six year under CA, the Ca²⁺ content remained relatively high during the study period (Figure 14). Farm Kameya M recorded the highest Ca²⁺ with a mean value of 102.78±54.51 mmol kg⁻¹ and farm Katewa D recorded the lowest 12.38±4.13 mmol kg⁻¹ (Table 11).

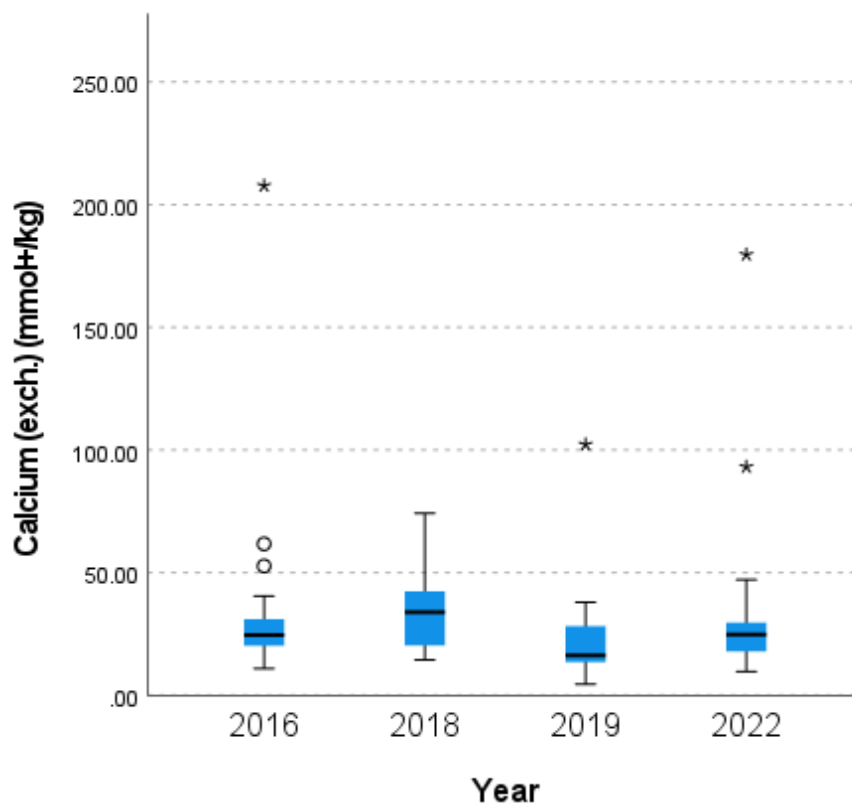


Figure 14: Distribution of Calcium (exch.) under CA 2016-2022

4.2.8 Magnesium (exch.)

The exchangeable Mg^{2+} in 2016 was high with a mean of $12.56 \pm 8.56 \text{ mmol kg}^{-1}$ above the critical limit (4.5 to 10 mmol kg^{-1}) (Table 1) and it reduced to 8.86 ± 5.31 , 5.63 ± 4.04 and $6.08 \pm 8.60 \text{ mmol kg}^{-1}$ in 2018, 2019 and 2022 respectively (Table 10). Overall Mg^{2+} was within acceptable threshold 4.5 to 10 mmol kg^{-1} , with a mean value of $8.28 \pm 7.31 \text{ mmol kg}^{-1}$. However, there was variation in the Mg^{2+} contents within farms ranging from as little as 0.50 to 41 mmol kg^{-1} (Table 11). There was statistically significant difference ($H(3) = 17.672, p < .001$) in Mg^{2+} over the years (Table 6). The results show that Mg^{2+} contents reduced from high content to adequate level under CA practice. Figure 15 represents the distribution of Mg^{2+} over the years. Farm Kameya M recorded the highest Mg^{2+} $22.60 \pm 11.43 \text{ mmol kg}^{-1}$ and farm Katewa D recorded the lowest $2.50 \pm 1.74 \text{ mmol kg}^{-1}$ (Table 11).

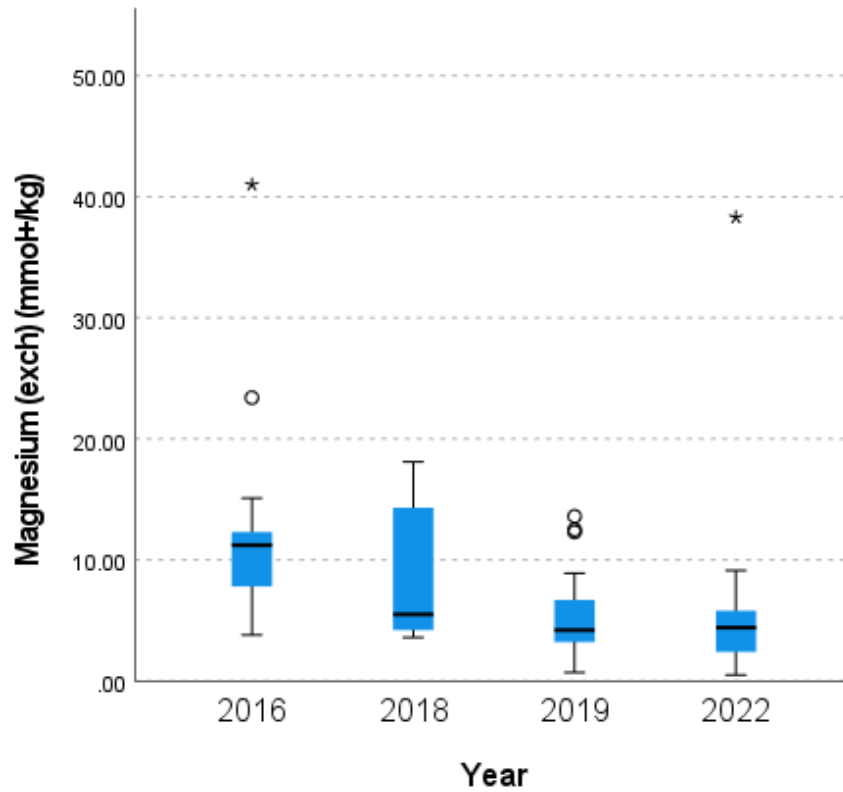


Figure 15: Distribution of Magnesium (exch.) under CA 2016-2022

Table 6: Pairwise Comparisons of magnesium 2016-2022

Year	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	10.029	6.781	1.479	0.139	0.835
2016-2019	22.176	6.781	3.271	0.001	0.006
2016-2022	25.324	6.781	3.735	0.000	0.001
2018-2019	12.147	6.781	1.791	0.073	0.439
2018-2022	15.294	6.781	2.256	0.024	0.145
2019-2022	3.147	6.781	0.464	0.643	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

4.2.9 Zinc (exch.)

Zinc is one of the elements that was undetectable in some farms, it ranged from 0.0 to 4.6 mg Kg⁻¹ (Table 10). The lowest Zinc was observed in the 6th years of CA where it was not detected in most of the farms (Figure 16). According to GIZ/SoilCare lab the threshold limits was 2.5 mg Kg⁻¹ to 4.0 mg Kg⁻¹. The exchangeable Zn significantly reduced from the highest mean of 1.1 mg Kg⁻¹ in 2018 to 0.07 mg Kg⁻¹ in 2022 all of which were lower than the threshold. There was statistically significant difference ($H(3) = 34.753, p < .001$) in Zn (Table 10). Zn had statistically significant difference in most of the years (Table 7). However, the Zn was decreasing instead of increasing as an effect of CA.

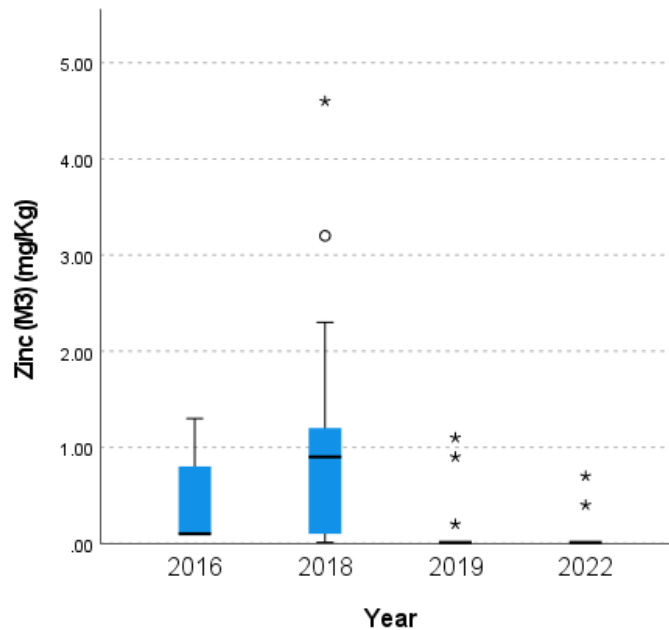


Figure 16: Distribution of Zinc under CA 2016-2022

Table 7: Pairwise Comparisons of Zinc 2016-2022

Years	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	-4.176	6.433	-.649	.516	1.000
2016-2019	23.206	6.433	3.608	<.001	.002
2016-2022	25.794	6.433	4.010	<.001	.000
2018-2019	27.382	6.433	4.257	<.001	.000
2018-2022	29.971	6.433	4.659	<.001	.000
2019-2022	2.588	6.433	.402	.687	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

4.2.10 Iron

Iron is the elements that had most missing/undetected values (see appendix 3 and 4) and most of the undetectable were in 2022 when the lab changed the units for measuring Fe from g/Kg^{-1} to mmol Kg^{-1} the lab just gave < 0 in the case were Fe was less than zero, and most of the farm had < 0 , therefore the data for 2022 was disqualified only data from 2016 to 2019 was analysed. And there was no statistically significant difference ($H(2) = 2.279, p = .320$) in Fe in 2016 to 2019. Fe was very low in all the years with a mean value of $3.66 \pm 1.02 \text{ g/Kg}^{-1}$ in 2019 while the critical limits was 31.0 to 81.0 g/Kg^{-1} and most of the distribution of Fe in CA fields were just below 5 g/Kg^{-1} (Figure 17).

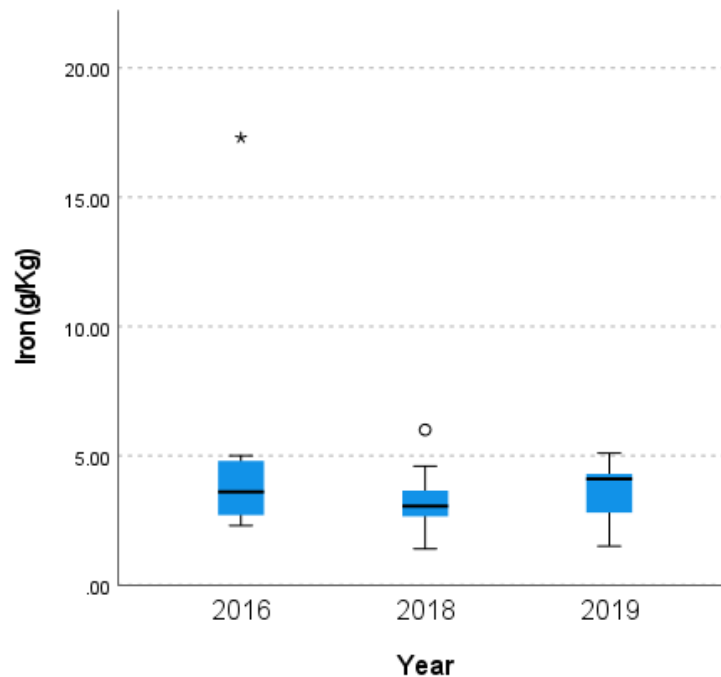


Figure 17: Distribution of Iron under CA 2016-2022

4.2.11 Silicium

Silicon was relatively high in all the years with the mean values of $447.97 \pm 19.32 \text{ g Kg}^{-1}$, $445.54 \pm 9.04 \text{ g Kg}^{-1}$, $441.93 \pm 8.03 \text{ g Kg}^{-1}$, $440.94 \pm 13.79 \text{ g Kg}^{-1}$, and $444.10 \pm 13.32 \text{ g Kg}^{-1}$ in 2016, 2018, 2019 and 2022 respectively (Table 10). Si was above the threshold (240 to 340 g Kg^{-1}) in all the years. However, Si significantly decreased from a mean of 447.97 g Kg^{-1} in 2016 to 440.94 g Kg^{-1} in 2022 and there was statistically significant difference ($H(3) = 10.150, p < .017$) in Si under CA from 2016 to 2022. The pairwise (Table 8) and the box plot (Figure 18) indicated that statistically significant difference occurred between 2016 and 2019 and 2016 and 2022.

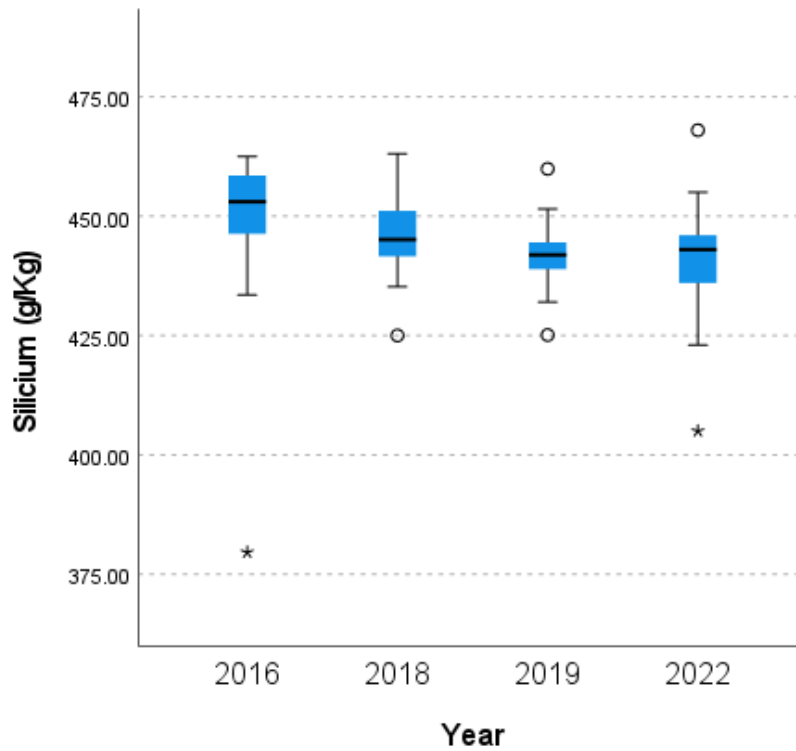


Figure 18: Distribution of Silicium under CA 2016-2022

Table 8: Pairwise Comparisons of Silicium 2016-2022

Years	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	10.794	6.782	1.592	.111	.669
2016-2019	19.618	6.782	2.893	.004	.023
2016-2022	17.471	6.782	2.576	.010	.060
2018-2019	8.824	6.782	1.301	.193	1.000
2018-2022	6.676	6.782	.984	.325	1.000
2019-2022	-2.147	6.782	-.317	.752	1.000

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

4.2.12 Total Aluminium

The results showed that the total Al content in the CA fields were consistently low throughout the years, with a mean value of $7.74 \pm 2.23 \text{ g Kg}^{-1}$ in 2022 (Table 10). This value is considerably lower than the critical limit for Al, which ranges from 70 to 112 g Kg^{-1} (Table 1). The highest Al content was 44.20 g Kg^{-1} , while the lowest was 2.2 g Kg^{-1} (Table 10). Farm Sitatara K recorded the highest Al content with a mean value of $18.50 \pm 17.17 \text{ g Kg}^{-1}$ and Muronga E recorded the lowest $5.90 \pm 1.72 \text{ g Kg}^{-1}$ of which were all below the recommended Al in the soil (Table 11). There was no statistically significant difference ($H(3) = 5.240, p = .155$) in Al over the years and Figure 19 shows the distribution of Al over the years.

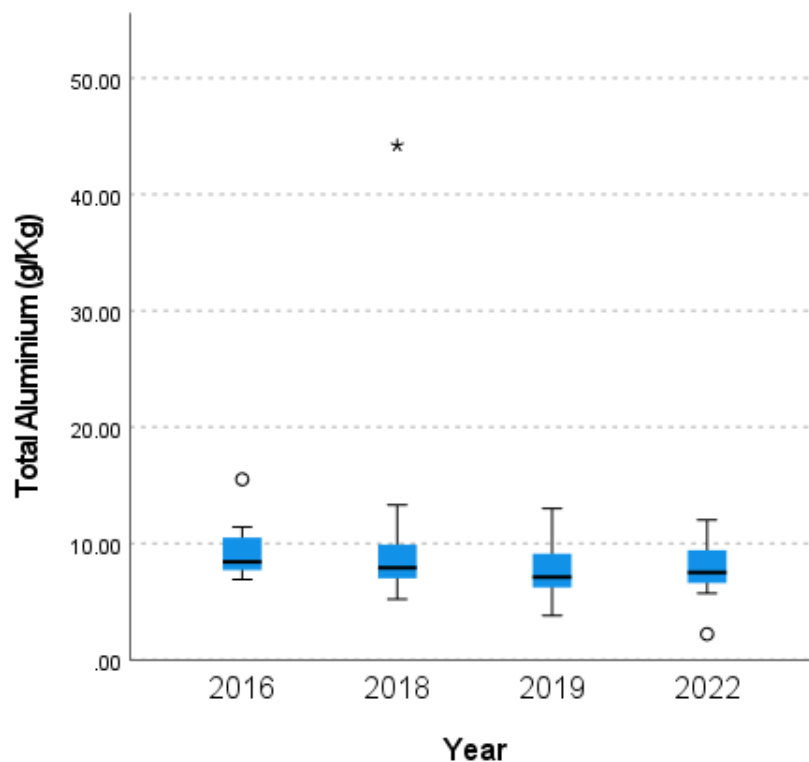


Figure 19: Distribution of Aluminium under CA 2016-2022

4.2.13 Cation exchange capacity

The soil Cation Exchange Capacity (CEC) in CA fields ranged from 23.7 to $314.3 \text{ mmol Kg}^{-1}$ with a mean of $44.69 \pm 30.93 \text{ mmol Kg}^{-1}$ in 2022 (Table 10). The CEC can be classified as low because the average value was low and could not fall in the required range of 75 to 200 mmol Kg^{-1} (Table 1). The CEC was significantly reducing from a mean of $60.08 \text{ mmol Kg}^{-1}$ in 2016 to $44.69 \text{ mmol Kg}^{-1}$ in 2022 (Table 10). Due to decreasing

of CEC, Kruskal-Wallis test found a statistically significant difference ($H(3) = 21.838, p < .001$) in CEC (Table 10 and Table 9). Figure 20 presents the distribution of CEC over the years.

Table 9: Pairwise Comparisons of CEC 2016-2022

Years	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig. ^a
2016-2018	-23.353	6.782	-3.443	<.001	.003
2016-2019	-4.176	6.782	-.616	.538	1.000
2019-2018	19.176	6.782	2.828	.005	.028
2022-2016	6.824	6.782	1.006	.314	1.000
2022-2018	30.176	6.782	4.450	<.001	.000
2022-2019	11.000	6.782	1.622	.105	.629

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

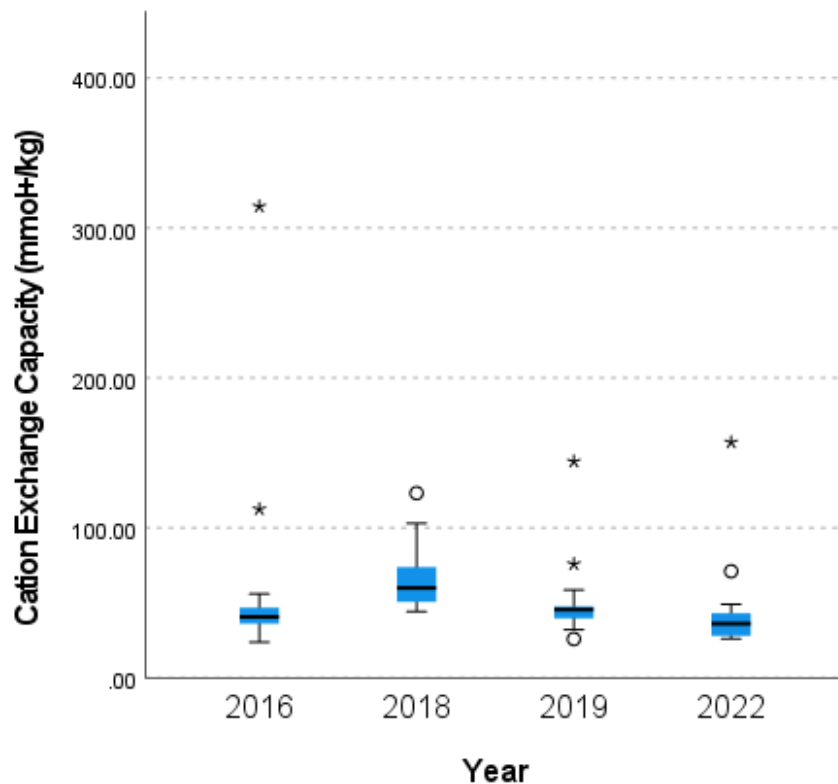


Figure 20: Distribution of CEC under CA 2016-2022

Table 10: Descriptive statistics for soil chemicals properties in Kavango West and Kavango East 2016-2022

Parameter	Years																Sig
	2016				2018				2019				2022				
	Mean	STDV	Min	Max	Mean	STDV	Min	Max	Mean	STDV	Min	Max	Mean	STDV	min	max	
pH(KCl)	6.55	0.70	5.00	7.60	6.07	0.74	4.30	7.20	5.64	0.67	4.50	7.10	5.77	1.01	4.70	8.80	0.002
OC	4.35	1.29	2.80	7.10	5.29	1.71	2.90	9.20	4.71	1.12	3.10	7.00	4.01	1.86	1.70	9.60	0.057
OM	7.49	2.22	4.83	12.24	9.12	2.94	5.00	15.86	8.12	1.93	5.34	12.07	6.91	3.21	2.93	16.55	0.057
N	0.40	0.22	0.30	1.20	0.51	0.26	0.30	1.10	0.34	0.17	0.20	0.80	0.27	0.18	0.10	0.80	0.001
K	1.64	1.35	0.30	6.30	1.49	0.77	0.50	3.40	1.29	1.13	0.10	4.80	2.00	1.97	0.10	7.20	0.657
P	0.04	0.04	0.01	0.10	0.07	0.07	0.01	0.20	0.01	0.00	0.01	0.01	0.05	0.05	0.01	0.20	0.388
Ca	38.37	45.60	10.9	207.70	35.78	18.06	14.40	74.20	24.29	22.25	4.50	102.2	36.56	41.57	9.70	179.60	0.085
Mg	12.57	8.57	3.80	410	8.86	5.32	3.60	18.10	5.63	4.04	0.70	13.60	6.08	8.60	0.50	38.30	0.001
Zn	0.45	0.48	0.10	1.30	1.10	1.25	0.01	4.60	0.14	0.33	0.01	1.10	0.07	0.18	0.01	0.70	0.001
Fe	4.42	3.46	2.30	17.30	3.23	1.08	1.40	6.00	3.66	1.02	1.50	5.10					0.320
Si	447.97	19.32	379.6	462.50	445.54	9.06	425.00	463.10	441.93	8.03	425.10	459.90	440.94	13.79	405.00	468.00	0.017
Al	9.11	2.17	6.90	15.50	10.51	9.01	5.20	44.20	7.55	2.19	3.80	130	7.74	2.30	2.20	12.00	0.155
CEC	60.09	68.36	23.70	314.30	66.68	21.42	44.20	123.10	50.59	26.41	25.80	144.20	44.69	30.93	26.00	157.00	0.001

Table 11: Descriptive statistics for soil chemical properties between farmers

Parameter	Farm								
	Ndara D	Veiko N	Katewa D	Kameya M	Kambinda L	Kampanza P	Karwapa L	Muronga E	Kampanza N
pH(KCl)	6.10±0.68	7.35±1.08	5.080±0.10	7.23±0.26	5.93±0.65	4.90±0.82	5.58±0.49	6.03±0.85	5.85±0.39
OC	4.95±0.26	6.05±0.54	4.15±0.83	7.62±1.60	5.68±2.95	4.60±0.91	4.70±2.33	4.33±1.41	3.35±0.53
OM	8.53±0.46	10.43±0.94	7.15±1.43	13.15±2.75	9.78±5.09	7.93±1.56	8.10±4.01	7.46±2.43	5.78±0.91
N	0.40±0.00	0.80±0.41	0.28±0.10	0.70±0.08	0.55±0.35	0.38±0.05	0.33±0.17	0.28±0.10	0.43±0.39
K	0.90±0.70	3.55±2.30	0.35±0.19	4.20±2.30	0.90±0.62	0.85±0.25	1.08±0.67	0.70±0.45	1.80±1.11
P	0.08±0.09	0.07±0.04	0.03±0.05	0.07±0.09	0.06±0.09	0.01±0.00	0.01±0.00	0.02±0.03	0.04±0.04
Ca	22.15±5.94	97.02±77.52	12.38±4.12	102.48±54.50	24.82±33.03	21.03±5.10	21.65±6.95	25.60±15.23	28.85±6.83
Mg	7.83±7.15	18.20±15.72	2.50±1.74	22.60±11.43	5.90±7.16	4.65±1.40	5.30±4.01	4.28±2.83	8.33±5.06
Zn	0.38±0.62	0.73±1.06	0.06±0.05	1.01±1.51	1.18±2.28	0.28±0.42	0.03±0.05	0.33±0.58	0.40±0.67
Fe	2.77±0.38	8.23±7.87	3.40±0.00	4.77±0.49	3.43±1.02	2.50±0.17	2.57±0.25	1.97±0.42	3.23±1.59
Si	444.85±13.14	434.60±37.79	450.45±8.83	427.25±14.89	442.90±12.72	446.65±12.71	450.65±9.54	446.88±4.66	449.47±18.95
Al	9.35±3.94	10.60±3.45	7.88±1.57	9.20±2.70	9.78±3.31	6.90±0.67	6.70±1.58	5.90±1.72	6.68±0.69
CEC	41.50±12.21	141.02±116.37	37.80±8.22	125.40±31.20	53.15±46.83	37.03±11.66	45.65±16.66	44.65±13.78	56.53±16.15

Parameter	Karwapa M	Kampanza C	Sitarara	Mununga T	Poroto A	Kapere N	Hanushira C	Haingura M	Av. \bar{x}
	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	Mean ±2STDV	
pH(KCl)	5.63±0.79	5.95±0.13	5.80±0.28	5.83±0.71	6.40±0.96	6.45±1.01	5.85±0.58	6.15±0.56	6.00
OC	3.75±1.24	4.83±0.70	4.93±0.10	3.38±1.10	3.55±0.70	3.78±0.53	4.48±1.96	3.90±0.75	4.59
OM	6.47±2.15	8.32±1.21	8.50±0.17	5.82±1.89	6.12±1.22	6.51±0.91	7.71±3.37	6.72±1.30	7.91
N	0.23±0.10	0.33±0.10	0.33±0.05	0.28±0.10	0.25±0.06	0.30±0.08	0.38±0.15	0.28±0.10	0.38
K	0.65±0.47	1.90±0.23	0.83±0.57	2.00±0.58	2.13±1.14	2.60±1.17	0.90±0.36	1.95±0.31	1.60
P	0.01±0.00	0.02±0.01	0.08±0.05	0.06±0.05	0.06±0.05	0.06±0.05	0.02±0.01	0.01±0.00	0.05
Ca	15.13±3.43	34.83±16.34	24.73±6.05	26.15±3.73	29.40±9.29	40.88±10.80	21.00±11.13	25.56±11.87	33.75
Mg	7.80±6.22	8.30±5.71	7.40±2.94	7.30±2.91	7.33±4.89	8.50±2.20	5.88±3.69	8.73±3.34	8.28
Zn	0.06±0.05	0.21±0.33	0.78±0.54	0.75±0.55	0.28±0.34	0.46±0.61	0.33±0.58	0.26±0.43	0.44
Fe	3.30±0.26	4.97±0.96	4.20±0.46	3.70±0.85	4.17±1.27	4.40±0.70	2.93±0.11	3.63±0.81	3.78
Si	447.15±6.83	449.55±7.20	436.43±10.16	447.38±5.40	440.40±3.03	444.05±3.35	441.62±11.54	449.38±2.39	444.20
Al	7.88±1.46	8.58±1.62	18.50±17.17	8.25±0.83	8.73±1.72	8.90±2.10	6.10±2.70	8.45±1.38	8.73

CEC	43.73±6.12	50.65±14.29	41.23±4.05	46.55±2.73	45.40±5.43	49.98±10.10	40.05±14.72	43.40±20.92	55.51
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Av. \bar{x} = Average mean

4.3 Correlation analysis of soil chemical properties

A Spearman rank correlation matrix was performed, and the results are presented in Table 12. The analysis revealed a significant and positive relationship between pH and several soil elements. pH showed a positive correlation with N, ($r = 0.440$, $p = .001$), K ($r = 0.547$, $p = .001$), Ca ($r = 0.671$, $p = .001$), Mg ($r = 0.642$, $p = .001$), CEC ($r = 0.461$, $p = .001$), Zinc ($r = 0.452$, $p = .001$), Fe ($r = 0.416$, $p = .003$) and Al ($r = 0.472$, $p = .001$). There was positive but weak correlation between pH and P ($r = 0.340$, $p = .005$) and pH and OC ($r = 0.208$, $p = .089$). In contrast to the positive relationships observed with most soil elements, silicon (Si) exhibited a negative and non-significant correlation with pH, ($r = -0.032$, $p = .798$) implying that Si was not positively influenced by pH.

There was a positive and significant relationship between OC and N, ($r = 0.655$, $p = .000$), and CEC ($r = 0.438$, $p = .001$), and there was a positive but weak correlation between OC and Ca ($r = 0.235$, $p = .054$), and Mg ($r = 0.234$, $p = .055$).

The CEC had a positive and significant relationship with; OC, N, K, Ca, Mg, ($r = 0.438$, $p = .001$, $r = 0.575$, $p = .001$, $r = 0.467$, $p = .001$, $r = 0.668$, $p = .001$, $r = 0.521$, $p = .001$). The significant positive relationships between CEC and OC, N, K, Ca, and Mg suggest that higher CEC values are associated with improved nutrient retention and availability in the soil. There was a positive but weak correlation between N and K ($r = 0.188$, $p = .125$), and P ($r = 0.179$, $p = .144$). The three major nutrients NPK did not show a strong positive correlation, indicating that the availability of one of the nutrients does not significantly impact the availability of others. However, there was a positive and significant correlation between N, and Ca and Mg ($r = 0.495$, $p = .001$; $r = 0.449$, $p = .001$). Table 23, 24 and 25 indicates the linear relationships among different elements.

Table 12: Spearman's correlation of soil chemical properties.

	Correlations											
	pH	OC	OM	N	K	P	Ca	Mg	CEC	Zn	Fe	Si
OC	0.208											
OM	0.208	1.000**										
N	.440**	.655**	.655**									
K	.547**	0.058	0.058	0.188								
P	.340**	0.073	0.073	0.179	.312**							
Ca	.671**	0.235	0.235	.495**	.710**	.383**						
Mg	.642**	0.234	0.234	.449**	.605**	.272*	.657**					
CEC	.461**	.438**	.438**	.575**	.467**	.282*	.668**	.521**				
Zn	.452**	0.098	0.098	.467**	0.230	0.205	.394**	.534**	.390**			
Fe	.416**	-0.036	-0.036	0.002	.566**	.422**	.493**	.467**	0.237	0.059		
Si	-0.032	-0.159	-0.159	-0.237	-0.106	-.326**	-0.184	0.019	-0.138	0.099	-.281*	
Al	.472**	0.123	0.123	.251*	.257*	.545**	.309*	.367**	0.091	.311**	.623**	-0.216

*. Correlation is significant at the 0.05 level (2-tailed).

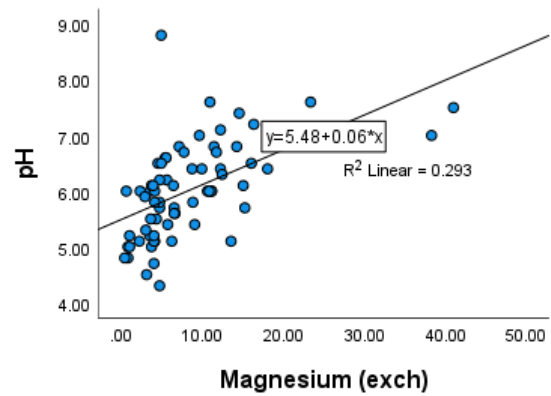
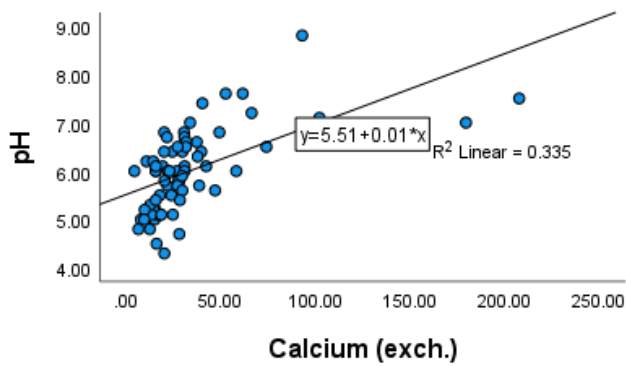
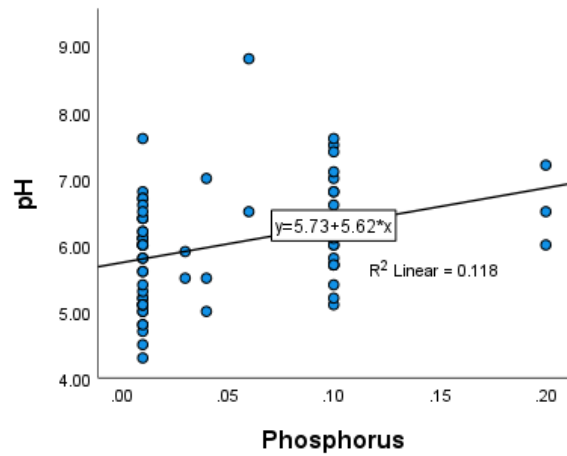
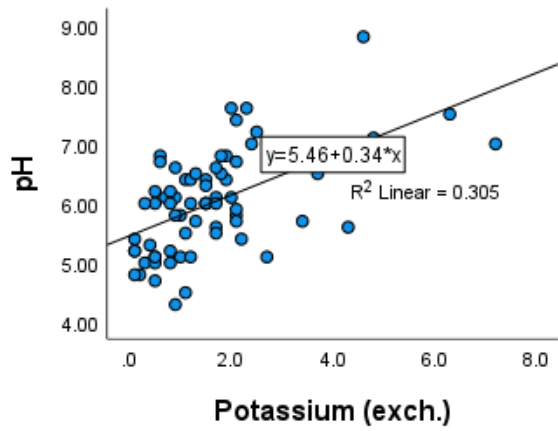
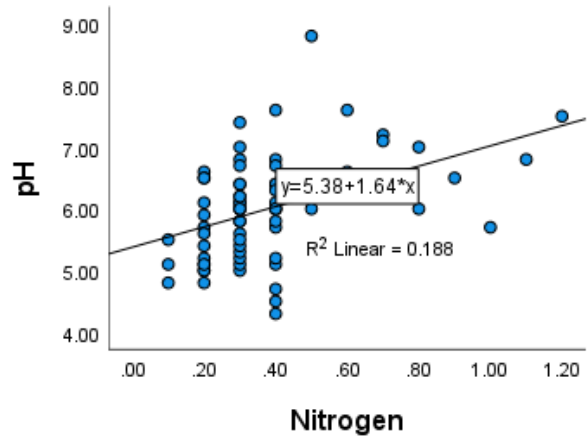
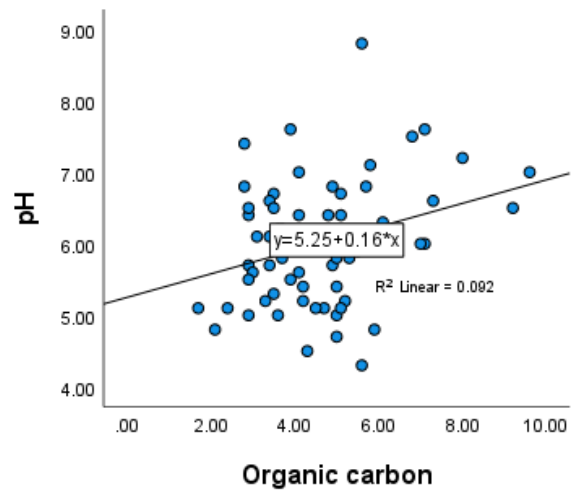


Figure 21: The relationship between pH and OC, nitrogen, potassium, phosphorus, calcium and magnesium

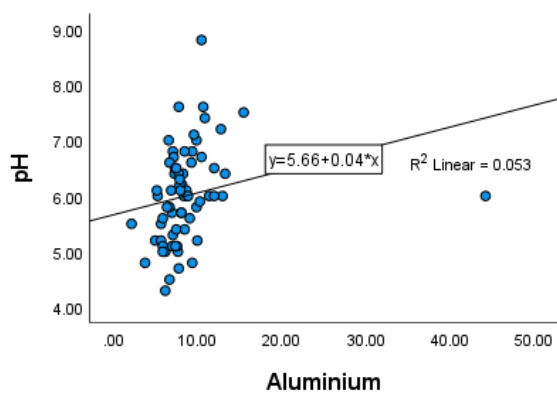
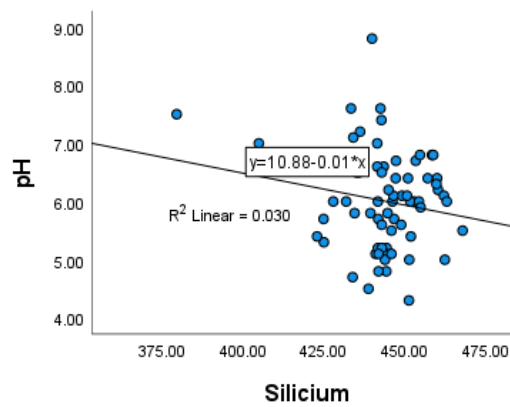
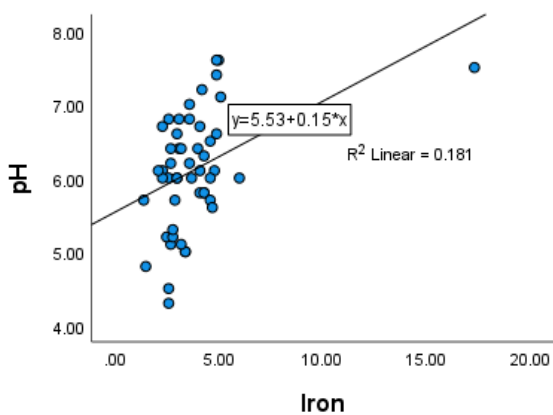
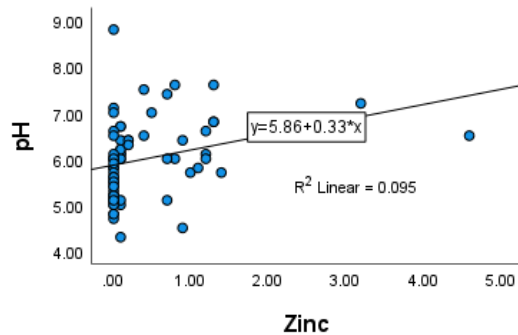
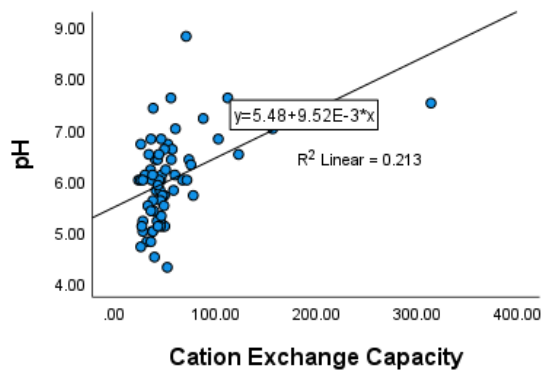


Figure 22: The relationship between pH and CEC, zinc, iron, silicium and aluminium

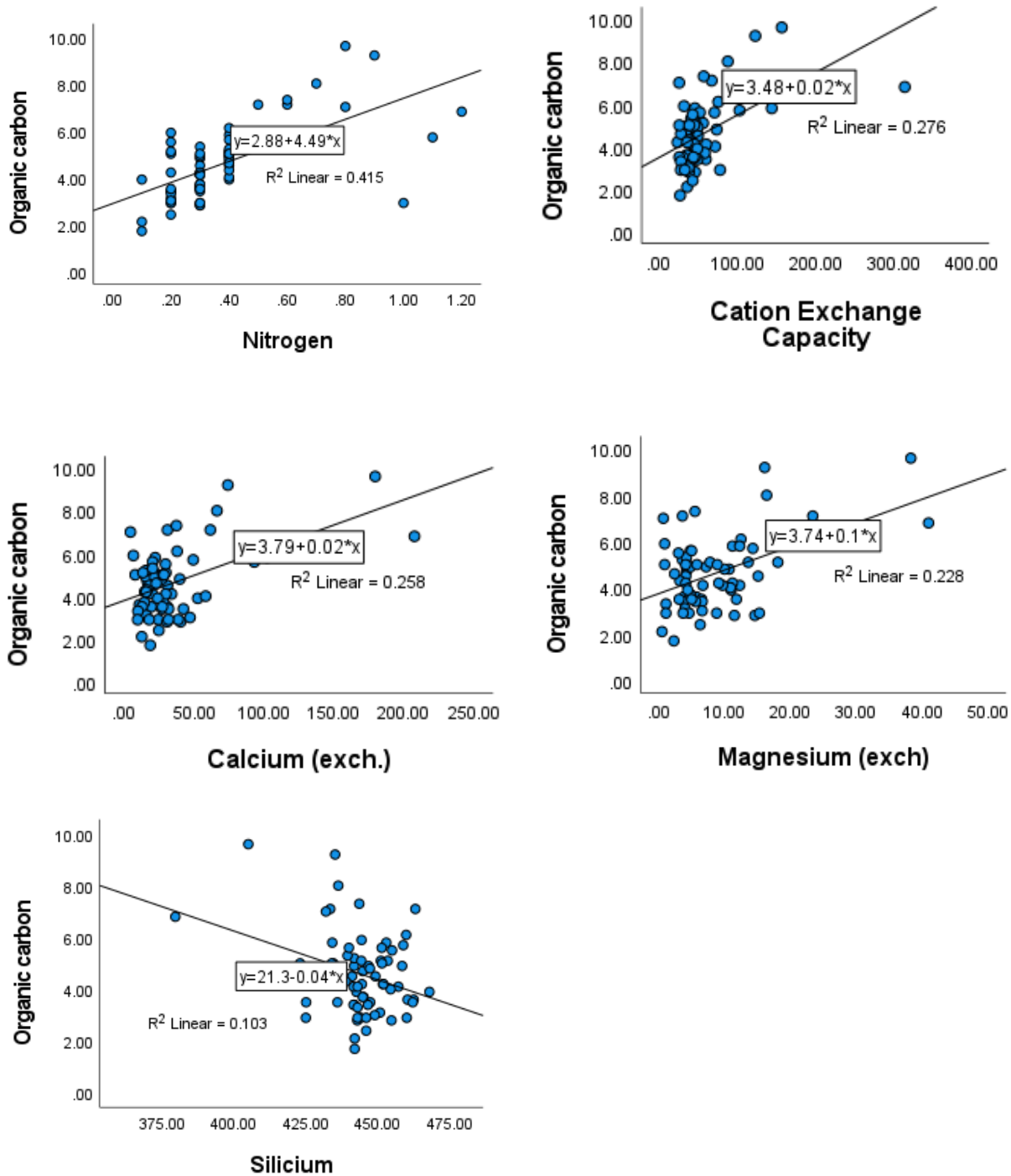


Figure 23: The relationship between OC and nitrogen, CEC, calcium, magnesium and silicium

4.4 Soil acidification

The soil acidification was calculated using the Interactive Soil Quality Assessment Information System (iSQAPER) formula (see section 3.5.2) and the results were reported on Table 13. The results indicated that most soil under CA were getting acidic after 6 years of CA practice. Farms such as, Kameya M, Muronga E, Kampanza C, and Hamushira C experienced low acidification with percentage differences ranging from -4% to 10%. While farms including Ndara D, Kambinda L, Kampanza P, Karwapa L, Kampanza N, Karwapa Maria, Mununga T, Poroto A, Kapere N, and Haingura M displayed high acidification levels with percentage differences ranging from 12% to 26%. Moderate acidification was observed in Sitarara K with a percentage difference of 8% and farm kapere N recorded the highest acidification level of 26%. Farm Veiko N, and Katewa D were the only farm that did not experience any acidification with -17% and -4%. The results of the acidification calculation are in correspondence with the descriptive statistics (Table 10) which also observed the decreasing of soil pH in the 6th years in most farms. According to Ejersa, (2021) some factors that could contribute to acidity of the soil under CA fields is organic matter decomposition; when the OM decomposes it releases H⁺, which causes acidity. Also, the carbon dioxide produced by decaying organic matter combine with water in the soil and form carbonic acid. This is the same acid that forms naturally when CO₂ in the atmosphere combines with rain to generate acid rain. These could be the reason why soil pH under CA might have been decreasing.

Table 13: Calculation of soil acidification among farms

Farm	2016	2022	Difference	%	Level of acidification
Ndara D	6.8	6.0	-0.8	12%	high
Veiko N	7.5	8.8	1.3	-17%	low
Katewa D	5	5.2	0.2	-4%	low
Kameya M	7.6	7.0	-0.6	8%	low
Kambinda L	6.2	5.0	-1.2	19%	high
Kampanza P	6.1	4.7	-1.4	23%	high
Karwapa L	6	5.1	-0.9	15%	high
Muronga E	6.7	6.5	-0.2	3%	low
Kampanza N	6.4	5.5	-0.9	14%	high
Karwapa M	6.4	4.8	-1.6	25%	high
Kampanza C	6.1	5.9	-0.2	3%	low
Sitarara K	6	5.4	-0.6	10%	moderate
Mununga T	6.8	5.1	-1.7	25%	high
Poroto A	7.4	6.5	-0.9	12%	high
Kapere N	7.6	5.6	-2.0	26%	high

Hamushira C	6	5.5	-0.5	8%	low
Haingura M	6.7	5.4	-1.3	19%	high

4.5 Soil organic matter decline

The decline of soil organic matter was also determined using iSQAPER formula and the results are reported on Table 14. The results indicates that there has been a decline in soil organic matter content in most of the farms. Most of the farms including, Karwapa L, Muronga E, Karwapa M, Kapere N, Hamushira C Kambinda L and Veiko N showed high percentages of SOM decline ranging from 18% to 71%. These farms have experienced a significant reduction in soil organic matter, indicating potential soil degradation and decreased fertility. While farms like Ndara D, Katewa D, and Mununga T, exhibited a decline of less than 18% percentages of SOM decline, according to the indices this percentages is still high.

However, farms like Kameya M, Kampanza P, Kampanza N, Kampanza C, Poroto A, Haingura M showed an increase in soil organic matter (Table 14). This indicates an increase in soil organic matter content over the study period, suggesting that this farm managed to maintain or improve the SOM levels.

The farm with the highest soil organic matter (SOM) decline was Karwapa L, with a decline of 71%. This indicates a significant reduction in soil organic matter content from 2016 to 2022. The results indicates that most farmers had problem with maintaining soil cover with crop residue which could lead to improve SOM. There was lack of crop residue to cover the soil throughout the year, which could lead to slow decomposition rate of crop residues in the soil. Also, the quality and quantity of crop residues may not have been optimal for SOM improvement, highlighting the need for tailored residue management strategies.

Table 14: Calculation of Soil SOM decline

Farm	2016	2022	Difference	%	Classification
Ndara D	4.9	4.6	-0.3	6%	high
Veiko N	6.8	5.6	-1.2	18%	high
Katewa D	3.6	3.3	-0.3	8%	high
Kameya M	7.1	9.6	2.5	-35%	low
Kambinda L	3.6	2.9	-0.7	19%	high
Kampanza P	3.5	5	1.5	-43%	low
Karwapa L	5.8	1.7	-4.1	71%	high
Muronga E	5.1	2.9	-2.2	43%	high
Kampanza N	2.9	3.9	1.0	-34%	low
Karwapa M	4.1	2.1	-2.0	49%	high
Kampanza C	4.5	5.5	1.0	-22%	low
Sitarara K	4.8	5	0.2	-4%	low
Mununga T	2.8	2.4	-0.4	14%	high
Poroto A	2.8	3.5	0.7	-25%	low
Kapere N	3.9	3	-0.9	23%	high
Hamushira C	4.2	2.9	-1.3	31%	high
Haingura M	3.5	4.2	0.7	-20%	low

Chapter 5: Discussion

The objective of the study was to evaluate the medium term (6 years) impact of CA on soil fertility that was based on minimum tillage, crop rotation (cowpea and millet) and retention of crop stalks, on smallholder farmer's field in Kavango East and Kavango West, Northeast Namibia. The study investigated the build-up of soil chemical elements namely: pH, organic carbon, nitrogen, phosphorus, potassium, calcium, magnesium, iron, zinc, silicon, aluminium and Cation Exchange Capacity.

5.1 Soil physical properties

5.1.1 Soil texture

Soil texture is a key property of soil that has a significant impact on crop yields, land utilisation, and overall land management (Kompała-Bąba et al., 2019). It has a direct impact on a soil's ability to retain nutrients and properly control drainage. It is crucial to note that soil texture is very stable and is regarded as a permanent property of the soil. Because these soil characteristics are largely immutable, there are few possibilities for modifying them (Moral & Rebollo, 2017). According to Jaja, (2016), the best suitable soil texture for crop production is loam soil containing 7 to 27 percent clay, 28 to 50 percent silt, and 52 percent or less sand . While the soil in KW and KE under CA had an average of 3 percent clay, 11 percent silt and 86 percent sand by 2022. The soil in KW and KE currently has a less suitable composition, with low clay and high sand content. This suboptimal texture affects various soil characteristics, including infiltration, structure, porosity, water-holding capacity, and chemistry, making it less conducive to nutrient and water retention, which is vital for plant growth. To improve soil in KW and KE, interventions like adding organic matter, cover crops, and nutrient amendments can be implemented to enhance its suitability for crop production.

5.2 Soil chemical properties

5.2.1 Soil pH

Soil pH is one of the most essential soil properties that influences nutrient availability. According to Nweke and Nsoanya (2013), a pH range of about 6-7 encourages the most readily available plant nutrients, and the pH below 6 and above 7 can inhibit the availability of most minerals. At low pH, aluminium in the soil becomes soluble and replaces cations such as calcium and magnesium in the soil. It also reacts with water to release more H⁺ which leads to further acidification. Most soil nutrients are not available at low pH level. For instance phosphorous is never readily soluble in low acidic soil but is most available in soil

with a pH range centred around 6.5 (Chirwa et al., 2016). Extremely and strongly acidic soils induces high concentrations of soluble aluminium (Al^{3+}) ion and manganese, which both can be toxic to plant growth. The study results indicated that most off the soil under the study area were slightly acidic. And it showed that CA did not lead to improve soil pH for good crop production in a period of six years in KE and KW in Namibia. This results is in contrast with Ligowe et al., (2017) who reported a significance improvement of soil pH as result of CA. However according to Ejersa, (2021) some of the factors that could contribute to acidity of the soil under CA fields is organic matter decomposition; when the OM decomposes it releases H^+ , which causes acidity. Also, the carbon dioxide produced by decaying organic matter combine with water in the soil and form carbonic acid. Thus, the decrease of soil pH in the study area can be attributed to, addition of crop residue and other organic matter on the soil as soil cover after the soil have remain bare for some years.

5.2.2 Organic carbon

One of the fundamental concepts of CA is to leave crop residues on the field to protect the soil and add organic matter (Mugandani & Mwadzingeni, 2021). However, if farmers do not manage soil cover properly, it may not contribute to increase of SOM efficiently. Also, if decomposition does not take place and crop residue is not integrated into the soil there will be no improvement in SOM. The SOC levels in the study area were found to be far below the critical range of 17 g Kg^{-1} to 50 g Kg^{-1} as specified in Table 1. also lower than SOC average indices 20 g Kg^{-1} (about 3.44% SOM) given by several authorities (Chirwa et al., 2016; Eshetu et al., 2004; Musinguzi et al., 2013). This finding shows that the soils under CA in the study area, had very low organic matter content. It is also evident that CA did not lead to any significant improvement in soil organic carbon levels, as there was no statistically significant difference observed in SOC from 2016 to 2022 in CA fields. According to Musinguzi et al. (2013), sustainable crop production requires soils to have a minimum SOM content of 3.44%. This threshold is crucial for achieving sustainability as higher SOM levels stabilize soil structure, reduce bulk density, and promote increased nutrient cycling. Musinguzi et al. (2013) further highlighted that soils containing 2.06% SOM or less are susceptible to degradation. Based on these findings, it is evident that most of the soils in the study area were susceptible to soil degradation due to their low organic matter content. This vulnerability to degradation can have significant consequences for crop production, as degraded soils often exhibit poor structure, reduced water-holding capacity, and limited nutrient availability (Umar, 2012). The low SOC/SOM can be attributed to insufficient cover materials in the study area. It was observed that most farmers struggled to maintain permanent soil cover as the crop residues left on the ground were later

grazed by livestock as most CA fields were not fenced and there was lack of materials to cover the soil throughout the year.

5.2.3 Total Nitrogen

Nitrogen is a key macronutrient that is necessary for plant growth and is a component of amino acids, which are the building blocks of plant proteins and enzymes (Sembiring & Sabrina, 2021). Nitrogen is also important for the chlorophyll molecule, which allows the plant to capture sunlight energy through photosynthesis, resulting in increased plant growth and grain output (Hu et al., 2016). Nitrogen is essential within the plant to guarantee that energy is supplied when and where the plant requires it to maximise output. This essential element can even be found in the roots, where proteins and enzymes regulate water and nutrient intake (Azimi et al., 2021). According to (Chirwa et al., 2016), 1% of total nitrogen is marginally suitable for crop growth, these indices is nearly the same with GIZ/SoilCare laboratory range of 1 g Kg⁻¹ to 2 g Kg⁻¹. After six years of CA practise N was still below the threshold. As a results, the soil under CA were rated as containing very low N. there was a statistically significant difference in N over the years, however the significance was a result of the decreasing N in the last years of CA. According to Page et al., (2020) total nitrogen may decrease in the first years of CA implementation due to the number of plant available and lack of SOM accumulation. Thus, application of N may be required to maintain yield and farmers need to ensure sufficient crop residue for soil cover and organic matter improvement. The low N under CA can also be attributed to the low pH and low SOM observed in the study area, as soil pH and SOM highly influence the availability of N in the soil (Zhou et al., 2019).

5.2.4 Potassium

Potassium (K) is the most abundant inorganic cation and is essential for plant growth (Xu et al., 2020). K is an activator of numerous essential enzymes, including those involved in protein synthesis, sugar transport, N and C metabolism, and photosynthesis. It is critical in the development of yield and the improvement of quality (Kusumiyati et al., 2022; Martynenko et al., 2022). There was no statistically significant difference observed in potassium exchangeable within six years. However, the highest average K was observed in 2022 showing slightly improvement of potassium exchangeable in CA fields. In 2022 the average K⁺ (2.00 mmol kg⁻¹) was within the required range. Some of the factors known to influence potassium in the soil are: soil type, temperature, wetting and drying cycles, pH, aeration and moisture (Xu et al., 2020). Thus, the low K can be attributed to low pH observed in the study area as K was find to positively correlate with soil pH.

5.2.5 Phosphorus

Phosphorus is a frequently limiting nutrient in crop production. Though some soils had sufficient present P, the amount of P that is readily available in the soil is low due to slow mineralization of this nutrient (Ogunsola & Adetunji, 2016). There was very low P content in all farms under CA over the years, and in some fields it was undetectable. For example, no P was detected in farm Kampanza P from the first to the last sixth year. Most of the P distribution was below the threshold and there was no statistically significant difference in P under CA for a period of six years. Phosphorus is absorbed by crops as phosphates and is essential for seed germination and roots development, which influences nodulation in legume plants, flowering, which influences yield, respiration, and fruit maturation. However, when soils become too acidic, phosphorus reacts with iron and aluminium and these ions makes P unavailable to plants. Also, when soils become too alkaline, phosphorus reacts with calcium and becomes inaccessible (Ogunsola & Adetunji, 2016). According to (Nweke & Nsoanya, 2013), a pH range of around 6.5 promotes the most readily available phosphorus, whereas a pH above 7 inhibits phosphorus availability to plants absorption. Thus, the low P observed in the study area can be attributed to the low pH that was detected in the CA fields.

5.2.6 Calcium

The mean for exchangeable Ca^{2+} was observed to be high than the critical limits. And there was no statistically significant difference in Ca^{2+} for a period of six year under CA, the Ca^{2+} content remained relatively high during the study period. Thor (2019) reported that Ca deficiency due to poor soil availability is uncommon. Because Ca is not a nutrient that can be easily leached, it is relatively considered insoluble. This can be related as when most nutrients are leached Ca remains, which eventually results to high content of Ca in highly reached soil. However, the availability of Ca to plants can be influenced by other factors like pH, Mg and CEC. The relative proportion of calcium (Ca) to magnesium (Mg) (Ca:Mg ratio) is an important soil characteristic (Lange et al., 2021). When the Ca:Mg ratio is high, it means there is relatively more calcium than magnesium in the soil. Soils with a higher Ca:Mg ratio tend to have improved soil structure and better water infiltration. However, excessive calcium in relation to magnesium may reduce the availability of magnesium to plants, leading to potential magnesium deficiency symptoms like interveinal chlorosis (yellowing between veins) in leaves (Schulte & Kelling, 2009). Conversely, when the Ca:Mg ratio is low, there is relatively more magnesium compared to calcium. This situation may lead to increased soil acidity, affecting nutrient availability and potentially leading to micronutrient imbalances (Brearley, 2018).

5.2.7 Magnesium

Mg is a key component of chlorophyll (Chl) pigments in the light-capturing complex of chloroplasts and thus plays a role in photosynthetic CO² assimilation. Approximately 15-35% of the Mg absorbed by plants is fixed in Chl pigments, with the remainder (65-85%) deposited in vacuoles or used for protein synthesis and other related biological processes (Ishfaq et al., 2022). The exchangeable Mg²⁺ in 2016 was above the critical limit and it decreased to the required range in 2022. Overall Mg²⁺ was within acceptable threshold. However, there was huge variation in the Mg²⁺ contents within farms ranging from as little as 0.50 to 41 mmol/kg. A statistically significant difference was observed in Mg²⁺ within six years of practising CA, implying that Mg contents reduced from high content to adequate level under CA practice. Just like Ca the availability of Mg can be influenced by other factors like pH, Ca, and CEC. The ideal Ca:Mg ratio can vary depending on the soil type and the specific requirements of different plants. In general, a balanced Ca:Mg ratio falls within the range of 3:1 to 7:1. However, certain plants may prefer slightly different ratios (Lange et al., 2021).

5.2.8 Zinc

Zinc is one of the elements that was undetectable in some farms, it ranged from 0.0- 4.6 mg Kg⁻¹. The lowest Zinc was observed in the 6th years of CA where it was not detected in most of the farms. The exchangeable Zn significantly reduced from the highest mean of 1.1 mg Kg⁻¹ in 2018 to 0.07 mg Kg⁻¹ in 2022 all of which were lower than the threshold. There was statistically significant difference in the availability of Zn in CA fields. However, the Zn was decreasing instead of increasing as result of CA. According to Subedi, (2020), some of the major factors that affect zinc availability is the soil pH and organic matter. Zinc is mostly available in pH ranges ranging from slightly acidic to neutral (pH 6-7) and zinc availability drops dramatically at extreme pH values, such as strongly acidic or highly alkaline soils. Acidic soils with pH levels below 6 may cause zinc shortage, whilst alkaline soils with pH levels above 7 may make zinc less accessible to plants (Desta et al., 2021; Grant, 2018). Organic matter in the soil is also important for zinc availability. Through mineralization, organic matter works as a source of zinc and releases it into the soil solution. Zinc availability is often higher in soils with higher organic matter content than in soils with low organic matter content (Subedi, 2020; Thingujam et al., 2019). Thus, the low level of Zn can be attributed to the low pH and organic matter that was observed in the study area.

5.2.9 Iron

Iron is the elements that had most missing/undetected values and most of the undetectable were in 2022 when the lab changed the units for measuring Fe from g/Kg^{-1} to mmol Kg^{-1} the lab just give < 0 in the case were Fe was less than zero, and most of the farm had < 0 , therefore the data for 2022 was disqualified only data from 2016 to 2019 was analysed. And there was no statistically significant difference in Fe in 2016 to 2019. Fe was very low in all the years and most of the distribution of Fe in CA fields were below the threshold. Fe is a critical component of electron chains as well as a cofactor in many important enzymes. According to Schmidt et al., (2020) only a few bacteria can substitute iron for other metals, making it a necessary element for almost all life. Just like Zn and Mg, Fe is also required for photosynthesis and chlorophyll synthesis in plants. Inadequate iron uptake results in stunted growth, interveinal chlorosis, and decreased fitness and limits crop yield and nutritional quality (Schmidt et al., 2020). Just like Zn the availability of Fe is heavily influenced by soil pH. Iron is best available to plants in soils that are slightly acidic to neutral, with a pH range of 6-7 (Jensen, 2010). Iron availability diminishes dramatically in alkaline soils with pH more than 7, resulting in iron shortage in plants. While, very acidic soils with pH levels below 6 might cause increased iron availability, which can be hazardous to plants (Barrow & Hartemink, 2023). SOM also affects Fe availability the high the organic matter the high Fe and the low SOM the low the Fe (Neina, 2019). As a result, the low Fe observed in the study could be attributed to the low pH and low organic matter observed in the study.

5.2.10 Silicon

Silicon was relatively high than the threshold in all the years in the study period. However, Si significantly decreased from a mean of 447.97 g Kg^{-1} in 2016 to 440.94 g Kg^{-1} in 2022 and there was statistically significant difference in Si under CA from 2016 to 2022. Many plant species, particularly grasses, can absorb silicon in quantities comparable to macronutrients. This high silicon concentration in the plant contributes to plant mechanical strength (Schaller et al., 2021; Yu et al., 2022). Silicon, in addition to its structural role, may protect plants from insect attack, disease, and environmental stress by improving the plant's defence response (Raza et al., 2023). However, Si is still vying for essential element status. According to Yuvaraj & Mahendran, (2020), only horsetails have been shown conclusively to require Si as an essential nutrient among terrestrial plants. Si accumulation in rice, for example, is approximately 108% greater than nitrogen accumulation. A rice crop yielding 5000 kg/ha is expected to remove Si from the soil at a rate of 230 to 470 kg/ha . Si did not show to be affected by pH as it showed a negative correlation with pH and other soil elements.

5.2.11 Total Aluminium

The results showed that the total Al content in the CA fields were consistently low throughout the years, and there was no statistically significant difference observed in Al. Aluminium can have both positive and negative effects on crop production, depending on several factors such as the type of plant, the amount and form of aluminium present in the soil, and the soil pH (Liu et al., 2022; Panda et al., 2009). In general, aluminium toxicity is a common problem for plants grown in acidic soils (pH below 5.5) as soluble aluminium ions become more available and can inhibit root growth, reduce nutrient uptake, and impair plant development (Panda et al., 2009). This can lead to stunted growth and lower crop yields (Mugandani & Mwadzingeni, 2021; Yan et al., 2022). However low aluminium content observed in the study area may suggest that aluminium toxicity is not a significant concern for crop production in the study area. However, it is essential to consider other factors that might influence plant growth and soil fertility, such as nutrient availability, pH levels, and the presence of other toxic elements or compounds (Yan et al., 2022).

5.2.12 Cation Exchange Capacity

When soil nutrients are dissolved, they exist as either positively or negatively charged ions. Cations are positively charged ions, while anions are negatively charged ions (Kaya et al., 2023). Cation exchange capacity (CEC) is a measure of the total negative charges in the soil that adsorb plant nutritional cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) (Jia et al., 2021). Therefore, the CEC is a soil attribute that describes a soil's ability to provide nutrient cations to the soil solution for plant absorption. The soil Cation Exchange Capacity (CEC) in CA fields in KE and KW was lower than the threshold. The CEC was significantly reducing from a mean of $60.08 \text{ mmol Kg}^{-1}$ in 2016 to $44.69 \text{ mmol Kg}^{-1}$ in 2022. Low CEC is a limiting factor in crop production because it reduces the soil's buffering capacity. When this occurs soluble nutrients tend to leak out of the root zone (Emamgholizadeh & Mohammadi, 2021). The low CEC can be attributed to the high sand content and low organic matter content of the soils in the study area. The higher the CEC, the more clay or organic matter the soil contains. This means that high CEC (clay) soils can hold more water than low CEC (sandy) soils. Low CEC soils are more likely to develop potassium and magnesium and other cation deficiencies, whereas high CEC soils are less susceptible to these cation leaching losses (Ketterings et al., 2007). The lower the CEC, the faster the pH of the soil will decrease over time. As a result, sandy soils require lime application more frequently than clay soils (Matthews, 2014).

5.3 Correlation

The correlation analysis aimed to explore the relationships between various soil chemical elements in order to gain a better understanding of their interactions. A Spearman rank correlation matrix was performed, and the results are presented in Table 12. The findings shed light on the associations between the soil chemical properties. The analysis revealed a significant and positive relationship between pH and several soil elements. pH showed a positive correlation with N, K, Ca, Mg, CEC, Zn, Fe, and Al. These results indicate that pH influences the availability of these elements, it therefore shows that pH is a potential determinant of their availability. There was also a positive correlation between pH and P and a positive but weak association between pH and OC. Similarly Chirwa *et al.*, (2016) analysed soil status in Zambia and they found out that pH positively correlated with Ca, Mg, K and P, implying that pH influences the availability of Ca, Mg, K and P. In contrast to the positive relationships observed with most soil elements, silicon (Si) exhibited a negative and non-significant correlation with pH, implying that Si was not positively influenced by pH. The correlation of organic carbon (OC) and other soil fertility variables sheds light on the interactions between OC and different components. There was a positive and significant relationship between OC and N, and CEC and there was a positive but weak correlation between OC and Ca, and Mg. These results indicate that OC influences the availability of N and influence the contents of CEC in the soil. Fe and Si had a negative correlation with OC (Table 12). The CEC had a positive and significant relationship with, OC, N, K, Ca, and Mg. The significant positive relationships between CEC and OC, N, K, Ca, and Mg suggest that higher CEC values are associated with improved nutrient retention and availability in the soil. Soils with higher CEC have a greater capacity to hold and exchange cations, allowing a better nutrient cycling and plant nutrient uptake. N was observed to be positively correlate with pH, OC, and CEC, implying that the availability of total N depended on pH, CEC, and OC. Similarly Chirwa *et al.*, (2016) reported that total N was positively and significantly correlated with OC and CEC. This mean that High OC/SOM and CEC increases total N. It therefore follows that the low OC/SOM and CEC observed in the CA fields contributed to the low level of N, Ca, Mg, and other soil chemical properties. There was a positive but weak correlation between N and K, and P. The three major nutrients NPK did not show a strong positive correlation, indicating that the availability of one of the nutrients does not significantly impact the availability of others. However, there was a positive and significant correlation between N, and Ca and Mg. This indicates that as nitrogen levels increase in the soil, calcium and magnesium availability also tends to increase, it further indicates that any factors that might influence the availability of nitrogen it might also affect the availability of Ca and Mg. As evident in the study that both N, Ca, and Mg correlative

positively with pH and CEC it can be concluded that these elements might have been influenced by pH and CEC.

5.4 Discussion summary

In summary, after six years of practicing CA in Kavango East and Kavango West, the research findings indicated that there was no significant impact of CA on soil fertility. Most of the elements evaluated were below the soil fertility threshold and did not show significant improvement. The imbalance between soil fertility influencers like pH, soil organic matter and CEC played a role in the soil's fertility. Most nutrients, including nitrogen, potassium and phosphorus, were below the threshold limits, though there was statistical significance difference in N, the availability of the soil elements was reducing in the six years as compared to the first years of CA. The low NPK in the soil could be attributed to the low pH, SOC and CEC that was observed in the CA fields.

Some further possible reasons for the limited impact of CA on soil fertility observed in the study area can be attributed to the adoption timeframe, implementation challenges, soil characteristics, climatic factors and COVID 19 pandemic. Six years may not have been sufficient to observe significant changes in soil fertility. CA is a long-term practice that requires time for the benefits to manifest fully (Chaudhary et al., 2019). Soil fertility improvements, such as increased organic matter content, nutrient cycling, and microbial activity, often occur gradually over an extended period. Therefore, the six-year duration of the study might not have been long enough to capture the full potential of CA on soil fertility. The findings of the study is in agreement with Nebo *et al.*, (2020) who did not observed significant impact of CA on soil fertility after 4 years. In contrast (Jat et al., 2018; Ligowe et al., 2017; Thierfelder & Wall, 2010) reported some significant impact of CA on soil fertility from 4 years.

The implementation of CA practices plays a critical role in determining its impact on soil fertility. Several challenges that might hindered the effectiveness of CA implementation is, inadequate residue retention, improper crop rotation, and nutrient management (Naab et al., 2017). Proper residue management is vital in CA to enhance soil fertility. Crop residues help maintain soil moisture, prevent erosion, and provide organic matter (Chaudhary et al., 2019; Jayaraman et al., 2021a; Nyagumbo et al., 2016). If farmers do not retain a sufficient amount of crop residues on the soil surface, the expected benefits to soil fertility may not be realized. As it was observed in the study area, most the CA field were not fenced and after harvesting period, livestock enter the fields and graze on the crop residue that was meant to cover the

soil, leaving the soil bare and exposed to sunlight and erosion. Crop rotation is an essential component of CA that helps break pest and disease cycles, improves nutrient availability, and enhances soil structure. However, if farmers do not implement proper crop rotation strategies, the potential benefits to soil fertility may be limited. Inadequate crop rotation can lead to nutrient imbalances and the depletion of specific nutrients, negatively impacting soil fertility (Osujieke et al., 2019).

Soil characteristics, including texture, nutrient content, pH levels, and inherent low fertility, can significantly influence the impact of CA on soil fertility. In the case of Kavango East and Kavango West regions in Namibia, the dominant sandy soil might have presented inherent challenges for soil fertility improvement through CA practices. According to Page et al., (2020) if the soils in the regions have inherently low nutrient content as it was observed in the study, it can be more challenging to achieve significant improvements in soil fertility through CA alone. In such cases, additional soil amendment strategies or targeted nutrient supplementation may be necessary to overcome nutrient deficiencies and enhance soil fertility. Also soil texture and structure influence water infiltration, drainage, and nutrient availability. If the soils in the regions have inherently poor texture or compaction issues, it can limit the effectiveness of CA practices in improving soil fertility (FAO, 2013a). Addressing soil structure and compaction issues through appropriate soil management techniques might be necessary to optimize the benefits of CA.

Climate and environmental conditions might have also impacted the effectiveness of CA in improving soil fertility. Namibia's arid and semi-arid climate, coupled with limited water availability, may have posed challenges for nutrient availability, nutrient cycling, and organic matter decomposition in the soil. Water scarcity affects nutrient availability and microbial activity in the soil, which are crucial for enhancing soil fertility. In arid regions, the limited availability of water for irrigation or rainfall can constrain the potential benefits of CA practices, especially when sporadic rainfall is received (Friedrich et al., 2017). Furthermore, high temperatures and temperature fluctuations can influence microbial activity, nutrient cycling, and organic matter decomposition.

Finally, the COVID-19 pandemic might have also presented inherent limitation in the full implementation of CA especially in 2019 and 2020. The lockdown which limited social interaction made it difficult to get enough labour to implement CA practises, implicating the effective implementation of CA. COVID-19

restrictions limited farmers' access to extension services and agricultural training, making it difficult for them to receive guidance on implementing CA practices effectively.

Chapter 6: Conclusion and recommendations

6.1 Conclusion

Conservation Agriculture (CA) has been promoted as a sustainable farming practice with the potential to improve soil fertility and agricultural productivity. Similarly, the implementation of CA in Kavango East and West was expected to improve soil fertility through practices such as reduced tillage, residue retention, and crop rotation.

However, after six years of practicing CA in Kavango East and Kavango West, the research findings indicated that there was no significant impact of CA on soil fertility. Soil fertility factors, including nitrogen, potassium, phosphorus, zinc, iron, and the CEC remained low and did not show significant improvements. These results are contrary to the expected outcomes of CA, which emphasize the potential for improving soil fertility over time. One possible reason for this limited impact might be the lack of crop residue to cover the soil throughout the year, which leads to slow decomposition rate of crop residues in soil. It was observed during the study that farmers had difficulties in maintaining soil cover as most of the farms had no fence to keep animal from entering the fields. Thus, during dry season when animals are let loose, they entered into CA fields and feed on the crop residue left for soil cover. Also, during ploughing season farmers struggled to get materials to cover the soil, the principle of permanent soil cover was therefore not implemented effectively. Furthermore, the quality and quantity of crop residues may not have been optimal for soil fertility improvement, highlighting the need for tailored residue management strategies. Since Kavango East and West are characterized by low natural soil fertility it requires enough organic matter and time to correct the soil fertility problem.

Inadequate training and extension services may also hinder the proper adoption and effective implementation of CA techniques, resulting in suboptimal outcomes. To improve the impact of Conservation Agriculture on soil fertility in Namibia, a multi-faceted approach is required. Aspects like; long-term monitoring and evaluation, farmer education, customized crop rotation plans, optimal residue management, integrated nutrient management, soil conservation measures, water management, and collaboration are essential components for success. Continued research, training and monitoring will be key to refining and optimizing CA practices in the unique context of Kavango East and West, ultimately leading to long-term soil fertility improvement and agricultural sustainability.

6.2 Recommendations

Although this study did not find any evidence that CA improves soil fertility, its well-known from other studies (Jat et al., 2018; Ligowe et al., 2017; Page et al., 2020; Thierfelder & Wall, 2010; Thornton & Radford, 2011; Williams et al., 2018) that CA can improve soil fertility and improve crop production. These collective findings underscore the notion that although this study did not find the effect of CA on soil fertility improvement, it does not negate the substantial body of evidence supporting the positive effects of CA on soil health and crop production. It's essential to consider that agricultural systems are complex and influenced by a myriad of factors, including soil type, climate, crop choice, and management practices. Therefore, for promoting sustainable farming practices in Namibia, the following recommendation are provide based on the existing notion of CA:

Long-term Monitoring and Evaluation

To better understand the impact of CA on soil fertility, it is essential to establish long-term monitoring and evaluation programs. This will help track changes in soil nutrient levels, organic matter content, and overall soil health over an extended period. By continuously monitoring and analysing the data, researchers and farmers can gain valuable insights into the effectiveness of CA practices and make informed adjustments to maximize soil fertility improvements.

Farmer Education and Training

Effective farmer education and training programmes play a pivotal role in promoting successful CA adoption. Providing farmers in Namibia with comprehensive training on CA principles, techniques, and best practices will enable them to implement the approach more effectively. Farmers should receive guidance on proper residue management, crop rotation strategies, nutrient management, and water conservation techniques. By enhancing farmers' knowledge and skills, may results in farmers making informed decisions and optimize the benefits of CA for soil fertility improvement.

Optimal Residue Management.

Proper residue management is a key aspect of CA for improving soil fertility. Farmers should be encouraged to retain an adequate amount of crop residues on the soil surface to enhance organic matter content, moisture retention, and nutrient cycling. Strategies such as mulching, cover cropping, and no-till practices can help optimize residue management. Farmers should receive training on residue retention techniques and understand the benefits of residue cover for soil fertility enhancement.

Integrated Nutrient Management:

Effective nutrient management is critical for enhancing soil fertility in CA systems. Implementing integrated nutrient management practices can help overcome nutrient deficiencies and imbalances. Farmers should be educated on the use of organic sources of nutrients, such as compost, green manure, and crop residues, to replenish soil nutrient levels. Additionally, targeted use of mineral fertilizers, based on soil testing and crop nutrient requirements, can ensure optimal nutrient availability for crops, and promote soil fertility improvement.

Water Management

Given the arid and semi-arid conditions in Namibia, effective water management is crucial for successful CA implementation. Farmers should be educated on water conservation techniques, proper mulching, and rainwater harvesting. These practices can help optimize water use, improve moisture retention in the soil, and support crop growth and nutrient availability. Various water management strategies should be integrated into CA practices to enhance soil fertility and crop productivity. Practices like direct planting should be combined with proper mulching to insure moisture retention.

Collaboration and Knowledge Sharing

Promoting collaboration and knowledge sharing among farmers, researchers, agricultural extension services, and policymakers is essential. Establishing farmer field schools, demonstration plots, and farmer-to-farmer exchange programs can facilitate the exchange of experiences, best practices, and lessons learned. This collaborative approach will enable continuous learning and adaptation, leading to the refinement and improvement of CA practices in Namibia.

Finally, by implementing these recommendations, CA may lead to enhance soil fertility, increase agricultural productivity, and promote sustainable farming practices in Namibia. Continued research, monitoring, and adaptation will be key to refining and optimizing CA practices in the country, ultimately leading to long-term soil fertility improvement and agricultural sustainability.

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Appendices

Appendix 1 Shapiro-wilk normality test results

	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
pH	0.107	50	.200*	0.981	50	0.600
Organic carbon (g/Kg)	0.113	50	0.150	0.934	50	0.008
Organic Matter (%)	0.113	50	0.150	0.934	50	0.008
Total Nitrogen (g/Kg)	0.331	50	0.000	0.730	50	0.000
Potassium (exch.) (mmol+/kg)	0.170	50	0.001	0.803	50	0.000
Phosphorus (M3)(g/Kg)	0.437	50	0.000	0.601	50	0.000
Calcium (exch.) (mmol+/kg)	0.228	50	0.000	0.618	50	0.000
Magnesium (exch) (mmol+/kg)	0.129	50	0.038	0.814	50	0.000
Cation Exchange Capacity (mmol+/kg)	0.270	50	0.000	0.556	50	0.000
Zinc (M3) (mg/Kg)	0.263	50	0.000	0.663	50	0.000
Iron (g/Kg)	0.235	50	0.000	0.547	50	0.000
Silicium (g/Kg)	0.160	50	0.003	0.806	50	0.000
Total Aluminium (g/Kg)	0.242	50	0.000	0.486	50	0.000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Appendix 2 Nonparametric Kruskal Wallis test results

	Test Statistics ^{a,b}												
	pH	OC	OM	N	K	P	Ca	Mg	CEC	Zn	Fe	Si	Al
Kruskal-Wallis H	14.855	7.512	7.512	17.025	1.611	3.027	6.620	17.672	21.838	34.753	2.279	10.150	5.240
df	3	3	3	3	3	3	3	3	3	3	2	3	3
Asymp. Sig.	0.002	0.057	0.057	0.001	0.657	0.388	0.085	0.001	0.000	0.000	0.320	0.017	0.155

a. Kruskal Wallis Test

b. Grouping Variable: Year

Appendix 3 Soil pH acidification

Soil pH (KCl)	Classification
pH actual > pH 2016	Low
$\text{pH}_{2016} - \text{pH}_{\text{actual}} / \text{pH}_{2016} \times 100 < 10\%$	Moderate
$\text{pH}_{2016} - \text{pH}_{\text{actual}} / \text{pH}_{2016} \times 100 > 10\%$	High

Appendix 4 Soil organic matter decline

SOM decline	Classification
$C_{\text{actual}} > C_{2016}$	Low
$C_{2016} - C_{\text{actual}} / C_{2016} \times 100 < 1\%$	Moderate
$C_{2016} - C_{\text{actual}} / C_{2016} \times 100 > 1\%$	High

Appendix 5 Raw data showing values of soil chemical properties from 2016 to 2022

Year	Farmer Name	pH	OC	OM	N	K	P	Ca	Mg	CEC	Zn	Fe	Si	Al
2016	Ndara D	6.8	4.9	8.45	0.4	0.6	0	20	7.2	36	1.3	2.6	459	7.1
2016	Veiko N	7.5	6.8	11.7	1.2	6.3	0.1	208	41	314	0.4	17	380	16
2016	Katewa D	5	3.6	6.21	0.3	0.3	0	15	3.8	37	0.1	3.4	463	7.7
2016	Kameya M	7.6	7.1	12.2	0.6	2.3	0	62	23.4	112	0.8	5	434	7.8
2016	Kambinda L	6.2	3.6	6.21	0.3	0.5	0	11	5.7	36	0.1	2.7	460	8.2
2016	Kampanza P	6.1	3.5	6.03	0.3	0.9	0	19	6.5	30	0.1	2.3	462	6.9
2016	Karwapa L	6	5.8	10	0.4	1.5	0	22	11.2	46	0.1	2.6	453	8.8
2016	Muronga E	6.7	5.1	8.79	0.4	0.6	0	22	7.8	53	0.1	2.3	454	7.2
2016	Kampanza N	6.4	2.9	5	0.3	1.1	0	25	8.8	41	0.2	4	460	7.3
2016	Karwapa M	6.4	4.1	7.07	0.3	1.2	0	20	12.3	43	0.1	3.1	457	8.3
2016	Kampanza C	6.1	4.5	7.76	0.4	1.7	0	31	15.1	47	0.1	4.8	449	8.7
2016	Sitarara K	6	4.8	8.28	0.3	1.5	0.1	27	10.7	37	0.8	4.6	446	11
2016	Mununga T	6.8	2.8	4.83	0.3	1.9	0.1	31	11.5	46	1.3	3.6	455	9.4
2016	Poroto A	7.4	2.8	4.83	0.3	2.1	0.1	40	14.6	38	0.7	4.9	443	11
2016	Kapere N	7.6	3.9	6.72	0.4	2	0.1	53	11	56	1.3	4.9	443	11
2016	Hamushira C	6	4.2	7.24	0.3	1.2	0	16	11.2	24	0.1	3	452	8.4
2016	Haingura M	6.7	3.5	6.03	0.3	2.1	0	31	11.8	26	0.1	4.1	447	11
2018	Ndara D	6.4	5.1	8.79	0.4	1.9	0.1	30	18.1	56	0.2	3.2	451	13
2018	Veiko N	6.8	5.7	9.83	1.1	1.8	0.1	49	14.3	103	2.3	3.1	459	8.5
2018	Katewa D	5.1	4.7	8.1	0.4	0.5	0	17	4.2	48	0.1	0.1	445	7.6
2018	Kameya M	7.2	8	13.8	0.7	2.5	0.2	66	16.4	88	3.2	4.2	436	13
2018	Kambinda L	6.5	9.2	15.9	0.9	1.8	0.2	74	16.1	123	4.6	4.6	435	12
2018	Kampanza P	4.3	5.6	9.65	0.4	0.9	0	20	4.8	52	0.1	2.6	451	6.2
2018	Karwapa L	6	7.1	12.2	0.5	1.5	0	31	3.6	67	0.01	2.3	463	5.3
2018	Muronga E	6.1	3.4	5.86	0.3	0.7	0	42	3.8	60	1.2	2.1	447	5.2
2018	Kampanza N	5.7	2.9	5	1	3.4	0.1	39	15.3	78	1.4	1.4	425	7
2018	Karwapa M	6.2	3.7	6.38	0.3	0.8	0	14	4.8	51	0.1	3.6	445	7.9
2018	Kampanza C	6	4	6.9	0.4	1.7	0	58	10.9	72	0.7	6	455	8.9
2018	Sitarara K	6	4.9	8.45	0.3	0.8	0.1	16	4.2	44	1.2	3.7	442	44
2018	Mununga T	5.7	4.9	8.45	0.4	1.3	0.1	22	4.8	50	1	2.9	447	8.1
2018	Poroto A	5.1	4.5	7.76	0.3	1	0.1	18	4.1	50	0.01	2.7	441	7.2
2018	Kapere N	7	4.1	7.07	0.3	2.4	0.1	34	9.7	60	0.5	3.6	442	9.9
2018	Hamushira C	6.6	7.3	12.6	0.6	0.9	0	37	5.5	57	1.2	3	444	6.7
2018	Haingura M	6.4	4.8	8.28	0.4	1.5	0	40	10	74	0.9	2.7	447	7.8
2019	Ndara D	5.2	5.2	8.96	0.4	0.8	0	16	3.6	46	0.01	2.5	442	5
2019	Veiko N	6.3	6.1	10.5	0.4	1.5	0.1	38	12.5	76	0.2	4.3	460	7.9
2019	Katewa D	5	5	8.62	0.2	0.5	0	7.9	0.9	38	0.01	3.4	452	6.2
2019	Kameya M	7.1	5.8	10	0.7	4.8	0.1	102	12.3	144	0.01	5.1	434	9.6

2019	Kambinda L	6	7	12.1	0.8	0.5	0	4.5	0.7	26	0.01	3	432	13
2019	Kampanza P	4.5	4.3	7.41	0.4	1.1	0	16	3.2	40	0.9	2.6	439	6.7
2019	Karwapa L	5.2	4.2	7.24	0.3	0.1	0	15	4.1	42	0.01	2.8	445	5.7
2019	Muronga E	4.8	5.9	10.2	0.2	0.2	0	6.6	0.9	32	0.01	1.5	444	3.8
2019	Kampanza N	5.8	3.7	6.38	0.3	1	0	28	4.8	59	0.01	4.3	445	6.7
2019	Karwapa M	5.1	5.1	8.79	0.2	0.5	0	14	13.6	46	0.01	3.2	444	5.9
2019	Kampanza C	5.8	5.3	9.14	0.3	2.1	0	20	4.2	41	0.01	4.1	440	6.4
2019	Sitarara K	5.8	5	8.62	0.4	0.9	0.1	28	8.9	45	1.1	4.3	435	9.9
2019	Mununga T	5.7	3.4	5.86	0.2	2.1	0.1	27	6.6	48	0.01	4.6	442	8.1
2019	Poroto A	6.6	3.4	5.86	0.2	1.7	0.1	32	5.6	50	0.01	4.9	442	9.3
2019	Kapere N	5.6	4.1	7.07	0.3	1.7	0	30	6.7	46	0.01	4.7	443	9.1
2019	Hamushira C	5.3	3.5	6.03	0.3	0.4	0	13	3.1	46	0.01	2.8	425	7.1
2019	Haingura M	6.1	3.1	5.34	0.2	2	0.1	16	4	38	0.01	4.1	451	8
2022	Ndara D	6	4.6	7.93	0.4	0.3	0.2	23	2.4	28	0.01	<0	428	12
2022	Veiko N	8.8	5.6	9.65	0.5	4.6	0.1	93	5	71	0.01	<0	440	11
2022	Katewa D	5.2	3.3	5.69	0.2	0.1	0.1	9.9	1.1	28	0.01	<0	443	10
2022	Kameya M	7	9.6	16.6	0.8	7.2	0	180	38.3	157	0.01	<0	405	6.6
2022	Kambinda L	5	2.9	5	0.2	0.8	0	9.7	1.1	28	0.01	<0	444	5.9
2022	Kampanza P	4.7	5	8.62	0.4	0.5	0	28	4.1	26	0.01	<0	434	7.8
2022	Karwapa L	5.1	1.7	2.93	0.1	1.2	0	19	2.3	27	0.01	<0	442	7
2022	Muronga E	6.5	2.9	5	0.2	1.3	0.1	32	4.6	34	0.01	<0	443	7.4
2022	Kampanza N	5.5	3.9	6.72	0.1	1.7	0	24	4.4	49	0.01	<0	468	5.7
2022	Karwapa M	4.8	2.1	3.62	0.1	0.1	0	13	0.5	36	0.01	<0	442	9.4
2022	Kampanza C	5.9	5.5	9.48	0.2	2.1	0	30	3	43	0.01	<0	455	10
2022	Sitarara K	5.4	5	8.62	0.3	0.1	0.1	29	5.8	39	0.01	<0	423	8.5
2022	Mununga T	5.1	2.4	4.14	0.2	2.7	0	25	6.3	43	0.7	<0	446	7.4
2022	Poroto A	6.5	3.5	6.03	0.2	3.7	0	27	5	44	0.4	<0	436	7.5
2022	Kapere N	5.6	3	5.17	0.2	4.3	0	47	6.6	38	0.01	<0	449	5.9
2022	Hamushira C	5.5	2.9	5	0.3	1.1	0	18	3.7	33	0.01	<0	446	2.2
2022	Haingura M	5.4	4.2	7.24	0.2	2.2	0	16	9.12	36	0.01	<0	452	7.5

Appendix 6 Sample of soil test result from the laboratory

Fertilization and Management Advice

Thomas Sikoka (SOIL CARBON)

Namibia

0818217055

-17.862712, 23.846746



John Meindert street
House number : 88
Namibia
Khomas/Windhoek East

General Information

Sample Number : ATTON00591A22

Date : 2022-09-08

Field Size : 1 ha

Soil Texture : Loamy Sand

Field Name : Karwapa Maria

Crop Name : millet

Target Yield : 1000 kg

Suitable Crop Types

Potatoes



Beans



Grains

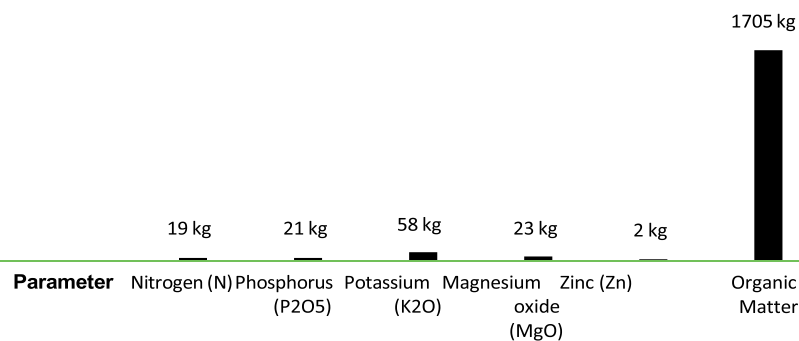


Vegetables






Your soil is suitable for growing potatoes, grains and beans. Growing vegetables will be more difficult.

Actual Nutrient Need (in kg)



Fertilizer recommendations

Activities	Instructions	Best Option	First Alternative	Second Alternative
1  Before Planting	If Available	1704 kg Compost or Animal Manure		
2  At Planting	Place the fertiliser at the bottom of the planting holes, put 10 cm of soil on top, add the seed and cover the seed with soil.	630 kg Gwano Pellets and 25 kg Limestone Ammonium Nitrate (LAN) and 70	630 kg Gwano Pellets and 25 kg CAN and 70 kg MOP	630 kg Gwano Pellets and 25 kg ASN and 70 kg MOP
3  6 weeks after	You can topdress when your crops are 6 weeks old and healthy (no pests, sufficient rain).			

General Information

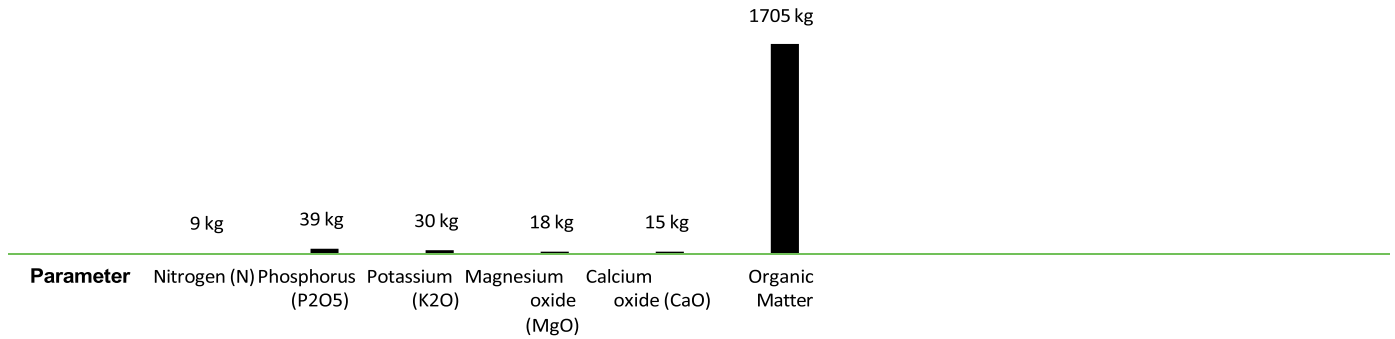
Sample Number : ATTON00591A22
 Field Name : Karwapa Maria

Date : 2022-09-08
 Crop Name : cowpea

Field Size : 1 ha
 Target Yield : 900 kg

Soil Texture : Loamy Sand

Actual Nutrient Need (in kg)



Suitable Crop Types



Fertilizer recommendations

Activities	Instructions	Best Option	First Alternative	Second Alternative
1 Before Planting	If Available	1704 kg Compost or Animal Manure		
2 At Planting	Place the fertiliser at the bottom of the planting holes, put 10 cm of soil on top, add the seed and cover the seed with soil.	180 kg 2.0.7(21) Nam and 135 kg Rock phosphate	180 kg 2.0.7(21) Nam and 230 kg SSP	180 kg 2.0.7(21) Nam and 80 kg TSP

Soil Status

Parameter	Unit	Analysis Result	Range Low	Range High	Low	Adequate	High
Total Nitrogen	g/kg	0.1	1	2	■		
Phosphorus (M3)	mg/kg	< 0	20	40	■		
Potassium (exch.)	mmol+/kg	0.1	1.5	3	■		
pH (KCl)	pH Value	4.8	6.0	7.2	■		
Total Carbon	g/kg	2.1	17	50	■		
Organic Carbon	g/kg	2.1	17	50	■		
Cation Exchange Capacity	mmol+/kg	36	75	200	■		
Calcium (exch.)	mmol+/kg	12.6	15	25	■		
Magnesium (exch.)	mmol+/kg	0.5	4.5	10	■		
Sulphur (exchangeable)	mmol-/kg		0	0			
Aluminium (exch.)	mmol+/kg	0.9	10	40	■		
Boron (exch.)	mmol+/kg	< 0	0.01	0.03	■		
Total Sodium	g/kg	2.3	3.1	13	■		
Total Silicium	g/kg	442	240	340			■
Zinc (exchangeable)	mmol+/kg	< 0	0	0			
Sand	%	85	0	0			
Silt	g/kg	11	0	0			
Clay	%	4	20	40	■		

Disclaimer Scanner

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