



**Fertility assessment and phosphorus sorption characteristics of
selected crop and grazing land soils in North West Province,
South Africa**

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ABSTRACT

The assessment of the fertility and phosphorus sorption characteristics of soils in crop and grazing land areas in North West Province of South Africa is crucial for developing appropriate management strategies that promote nutrients replenishment, improve soil physical and chemical and biological conditions, and sustainable use of the soils. The research was initiated due to continuous declining soil fertility, impacting negatively on crop and animal production. Assessing soil physical and chemical indicators and phosphorus sorption characteristics in smallholder crop farm, commercial crop farm and communal grazing lands is crucial to promoting increase productivity and food security. The objectives of this study were to determine selected physical and chemical indicators that affect soil fertility, clay mineralogy and phosphorus sorption characteristics of the selected soils. This was done by analysing soils from selected smallholder crop farms, commercial crop farms and communal grazing land. A total of 180 soil samples randomly collected from 0 – 15 cm, 15 - 30 cm and 30 - 45 cm depths were analysed using routine soil analysis methods. Thirty-six soil samples were used for mineralogical study using XRD and 360 samples for sorption study by batch sorption method. Results of the soil physical and chemical indicators significantly ($p \leq 0.05$) varied across location, land use and soil depth. The highest WHC (57.49%), BD (1.41g/cm^3), TP (66.06% and silt/clay (1.81) values were recorded from the study. The highest means for pH- H_2O , pH-KCl and ΔpH (7.19, 6.14 and 1.14), EC (0.13 dS/m), OC (1.82%), N (1.67 %), P (12.35 cmol/kg), K (415 cmol/kg), Ca (2870 cmol/kg), Mg (493 cmol/kg), Al (1.43 cmol/kg), S (0.84 %), EA (0.87 cmol/kg), CEC (18.31 cmol/kg), Cu (5.94 mg/kg), Fe (60.5 mg/kg), Mn (137.1 mg/kg) and Zn (17.23 mg/kg). Thirteen different mineral phases were identified in the study area: quartz, magnesioferrite, kaolinite, calcite, biotite, dolomite, muscovite, portlandite, nacrite, rutile, albite, brucite and pyrochroite. Quartz (71.2 to 99.4%), kaolinite (0.5 to 16.3%), muscovite (0.7-11.6%), albite (3.2-5.9%), Nacrite (0.1-1.8%), magnesioferrite (0.1-1.6%), portlandite (0.1-0.6%), calcite (0.3-1.2%), biotite (0.1-1.2), dolomite (0.1-1.1%), rutile (0.1-1.2%), brucite (0.5%) and pyrochroite (0.2 %). The sorption maxima of the soils ranged from 70 to 5769 mg P kg^{-1} and binding energy ranged from -28.8542 to 3.808 mg^{-1} . The coefficients of determination (R^2) values of 0.5734 to 1.0 were observed in this study. The slope and intercept ranged from 1.7332 to 18.812 and -51.435 to 111.76. The SPR ($P_{0.2}$) values of 1.04 to 400 mg/kg were recorded. Phosphorus adsorption capacity decreased in the order of Itsoseng commercial crop farm (LC) > Mathopstad commercial crop farm (RC) > Mathopstad communal

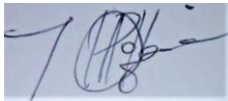
grazing land (RG). The study confirmed that LC (20%) clay required more P fertilisation than the other soils. Generally, most of the soil physical and chemical indicators fell within the acceptable limits, except available P and OC were low to medium. In addition, variability of the measured soil physical and chemical indicators helps explain eventual abnormalities of the results of future studies. According to findings in this study, adequate fertilisation and good crop/ soil management must be practiced based on the soil variability in the research area. This would help improve the productivity and fertility of the soils within the research area for sustainable crop production.

Keywords: fertility assessment, physical and chemical indicators, clay mineralogy, phosphorus sorption, South African soils

DECLARATION

I, Payout Tugwell Ogboin, hereby declare that this research entitled “Fertility assessment and phosphorus sorption characteristics of selected crop and grazing land soils in North West Province, South Africa” was carried out by me and all sources quoted or used are indicated and acknowledged by means of complete referencing and that this study has not been submitted to any other institution for a degree or higher qualification.

Payout Tugwell Ogboin

A handwritten signature in blue ink, appearing to read 'P. T. Ogboin', is shown within a light blue rectangular box.

DEDICATION

This research is dedicated to my kind wife, Julia Arabebe Ogboin and my understanding children who missed me a lot when I was undertaking this study. Their patience enabled me to complete the work in time.

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LIST OF ABBREVIATIONS AND SYMBOLS

a	Slope
Al	Aluminium
APAP	Agricultural Policy Action Plan
ATP	Adenosine triphosphate
B	Boron
b	intercept
C	Carbon
C:N	Carbon Nitrogen ratio
Ca	Calcium
CAS	Chrome Azuro-S
CCF	Commercial crop farm
CEC	Cation exchange capacity
CGL	Communal grazing land
Co	Cobalt
Cu	Copper
DAP	Di-ammonium phosphate
DNA	Deoxyribonucleic acid
DTPA	Diethylene triamine penta acetic acid
FAO	Food and Agricultural Organization
Fe	Iron
I	Intensity factor
ICDD	International Centre for Diffraction Data
K	Potassium
k	Binding energy or sorption affinity constant
KCl	Potassium chloride
Lsd	Least significant difference

Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NDA	National Development Plan
Ni	Nickel
NWP	North West Province
P	Phosphorus
PBC	Phosphorus buffer capacity
PDF	Powder diffraction file
PSA	Particle size analysis
Q	Quantity factor
RIR	Reference intensity ratio
RNA	Ribonucleic acid
S	Sulphur
SA	South Africa
SAS	Statistical Analysis System
SEF	Soil evaluation factor
SFI	Soil fertility index
SHCF	Smallholder crop farm
Smax	Sorption maxima
SOC	Soil organic carbon
SPR	Standard phosphorus requirement
SSA	Sub-Saharan Africa
WHC	Water holding capacity
XRD	X-ray diffraction
Zn	Zinc

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background information

Soil fertility refers to the ability of soil to sustain agricultural plant growth, i.e. to provide plant habitat and result in sustained and consistent yields of high quality. It also refers to the soil's ability to supply plant/crop nutrients in the right quantities and qualities over a sustained period of time (Abreha, 2013; Brady & Weil, 2002a). Proper soil fertility management entails managing not just the nutritional status of soil for crop production but the totality of soil physical, chemical and biological properties of soils that affect its intended use for crop cultivation, construction, wetland, aquaculture, waste disposal, etc. (Brady & Weil, 2002a). Fertile soils increase yield, produce high quality crops and reduce overall cost of production. However, soil could lose its fertility through deterioration of the physical and chemical properties resulting in the decline in its chemical fertility attributes particularly soil organic matter, cation exchange capacity (CEC) and plant mineral nutrients supply (Hartemink, 2006). The most commonly discussed degradation processes are vegetation degradation, water and wind erosion, salinisation, soil compaction and crusting, and soil nutrient depletion (Hartemink, 2006).

The causes and consequences of soil fertility loss and the consequent land degradation vary from region to region, mainly in terms of localised intensity, ecosystem characteristics, culture, economics and political will (Reynolds *et al.*, 2003). There is global concern over soil fertility management, especially with the decline in agricultural productivity and recent increases in food prices and food insecurity in developing countries. Despite the generally poor soil conditions and climatic factors compared with international situations, Laker (2005) argues that South Africa has a highly successful commercial agricultural sector. This is attributable to the highly technical and good infrastructural support base, most especially within the commercial agricultural subsector. The South African agricultural sector is, however, dualistic in nature comprising (i) commercial farmers, and (ii) subsistence and emerging farmers. Land use, soil fertility and agricultural productivity vary greatly among these two groups of farmers (FAO, 2005).

South Africa (SA) has a wide array of soils that range from shallow with small life sustaining capacities to highly weathered profiles that recycle and support large vegetation, crop and animal production (Laker, 2003). In the North West Province (NWP), key limiting factors to agricultural productivity are low soil fertility (Laker, 2005) resulting in land degradation, and limited to nonavailability of water, which is quite frequent. The NWP is the sixth largest province in South

Africa and covers a total land area of 116 320 km², with 56.8% of its land used for grazing while crop production only accounts for 28.3% of land use (Masigo & Matshego, 2002).

South African soils, similar to the other agricultural soils of the semi-arid regions, are generally low in available Phosphorus (P). Several authors have reported independently that about 60% of South African agricultural soils are deficient in plant available P (Schoeman and Van der Walt, 2004) and P deficiency is one of the most common nutritional stresses in SA (Henry & Smith, 2006). The authors also reported that P is one of the nutritional factors most inhibiting crop productivity, which must be supplemented by application of fertilizer to obtain optimal crop yield. Unfortunately, the cost of P fertilizers is the highest of all input nutrients in South Africa (Henry & Smith, 2006). Phosphorus fertilization and its efficiency in improving soil P for crop production and better management of P fertilizers can be achieved by studying the P sorption behaviour of agricultural soils to establish the standard phosphorus requirement (SPR) of the soils (Afsar *et al.*, 2012). This study, therefore, assessed the status of soil fertility indicators and P sorption characteristics on selected smallholders, commercial crop farms and communal grazing land soils in the NWP to identify key indicators for improvement. This information contributes to promoting better and sustainable soil management and land use practices to increase agricultural productivity.

1.2 Statement of the problem

Agricultural activities in most farming communities are under pressure in many parts of Africa due to declining soil fertility. This has a negative impact on crop and animal production (Amuyou & Kotingo, 2015). In many parts of Sub-Saharan Africa (SSA), the problem of increasing land degradation with the attendant negative effects on soil quality and agricultural production continues to escalate. The problem is exacerbated by overgrazing, intensive harvesting of wood for fuel, erosion, uncontrolled bush fires, reduction in the length of fallow period and increased pressure on land for settlement expansion and other purposes (Bationo *et al.*, 2007; Bekunda *et al.*, 2010). Smallholder and commercial crop farms and grazing land areas across South Africa are currently experiencing considerable biomass and yield loss due to significant loss in soil quality arising from soil fertility decline, among other causes (Du Preez *et al.*, 2011; Nell *et al.*, 2001). Among the key problems associated with decline in soil fertility is inappropriate use of land and fertilisers (Kutu, 2012), and degradation all constituting the growing threat to agricultural activities in many parts of South Africa (Du Preez *et al.*, 2011).

South African agricultural soils are inherently low in carbon, soil organic matter content, sulphur (S), and particularly phosphorus (P), which is one of the key limiting nutrients to crop production (Mandiringana *et al.*, 2005; Swanepoel *et al.*, 2014). Most of these soils are inherently categorised by poor resilience, poor nutrients reserves and low water holding capacity (Snyman & Du Preez, 2005). Hence, poor and inappropriate management and land use practices on such soils could be devastating with little chance of recovery once the degradation has begun (Laker, 2005) while detailed information regarding the state of fertility status including the sorption characteristics of majority of these soils on crop and grazing land areas in the NWP are limited.

1.3 Justification for the study

As envisaged by the government of South Africa 2030 National Development Plan (NDP), the study seeks to contribute to food and nutrition security. The national aspiration on food security through increased and sustainable agricultural productivity by farmers, especially the smallholder and emerging farmers, represents a key consideration in the NDP, and this research provides support in the short-to-medium term government priorities and the Agricultural Policy Action Plan (APAP) by assessing the fertility status of the soils. Approximately 80% of the country's available land area is used for agricultural production and predominantly regarded as marginal for crop production, with less than 13% considered as fertile while less than 3% is considered as high potential land (Goldblatt, 2010).

The NWP is one of the country's leading key grain producers where one third of the country's maize grains are produced thus, contributing immensely to the country's food production. The province is also recognised for rearing diverse animals because of the availability of adequate grazing lands. Despite the Province's potential to significantly contribute to the country's food production, there is little information on the overall fertility status of soils especially for emerging and small-scale farmers and several available community farmlands. Assessing the fertility status and sorption characteristics of soils in crop and grazing land areas in NWP is thus crucial for developing the most appropriate management strategies that could promote nutrients replenishment, improve soil physical, chemical, and biological properties and promote sustainable use of these lands. Soil as a natural asset needs to be maintained and conserved. This is considered important in the wake of soil use for the numerous types of activities, including agricultural production to guarantee sustainable use for food security and engender economic sustainability of the farmers. Hence, this study contributes towards broadening the existing soil information database in the province which should benefit farmers in terms of decisions on

sustainable land use and management. This research is targeted at both the smallholder and commercial crop farmers to enhance the productivity of their farms.

1.4 Research Questions

The study sought to answer the following research questions:

- (i) What are the variations in soil physical indicators across different fields and how do they affect productivity of crops grown on them?
- (ii) What are the variations in soil chemical indicators across different fields and how do they support optimum growth of crops grown on them?
- (iii) What are the variations in mineralogical characteristics of the soils across different fields and how do these affect soil fertility?
- (iv) How does the distribution of the inherent P-sorption parameters of these soils vary across the fields?
- (v) How does the variation in the soil P-sorption parameters influence P fertiliser management on the fields for increased productivity?

1.5 Research Aim, Objectives and Hypotheses

1.5.1 Aim

The aim of this research was to assess the fertility status and phosphorus sorption characteristics of soils in selected areas of the North West Province, South Africa, and proffer sustainable soil fertility management strategies.

1.5.2 Specific Objectives

The specific objectives of the research were designed to:

- (i) determine the soil physical indicators (Bulk density, Total porosity, water holding capacity, Particle size distribution) across the different fields.
- (ii) determine the soil chemical indicators (Soil pH, OC, TN, P, K, S, Al, CEC, Ca, Mg, Cu, Fe, Mn and Zn) across the different fields;
- (iii) provide detailed mineralogical characteristics of the soils across different fields.
- (iv) assess the P release and sorption parameters as well as the sorption characteristics of selected soils from the fields.

1.5.3 Hypotheses

Literature information on the fertility status and phosphorus sorption characteristics of smallholder communal grazing farmlands in NWP are scanty while the few commercial farmers that have the resources to undertake such assessment often do not make such data/information readily available. Hence, this research was guided by the following research hypotheses:

- (i) There is no variation in soil physical indicators across the different fields.
- (ii) There is no variation in soil chemical indicators across the different fields.
- (iii) There is no variation in the mineralogical characteristics of the soils across the different fields.
- (iv) There is no difference in available phosphorus and P-sorption characteristics of the selected soils from the fields.

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CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Soil is a collection of natural bodies on the earth's surface supporting or capable of supporting crops and showing properties resulting from the integrated effects of climate and living organisms on parent rock as condition by relief and time, (Brady & Weil, 2002b; Sannappa & Manjunath, 2013). Soil is a friable material in which plant roots find a foothold and nourishment and other conditions for growth. Soil fertility is one of the many characteristics that makes it important in crop production (Brady & Weil, 2002b).

Soil fertility is a measure of the soil's ability to sustain satisfactory crop growth, both in the short and long-term. This fertility is determined by a set of indicators interacting between the soil's physical environment, chemical environment and biological activity (Brady & Weil, 2008b). There is no standard method for measuring soil fertility, but measurements of nutrient availability, salinity, soil acidity and soil organic carbon (SOC) are generally considered adequate to distinguish soils in terms of fertility (Schjonning *et al.*, 2004). According to Brady & Weil (2002b), plant essential nutrients are classified into non-mineral and mineral nutrients. The former includes carbon (C), oxygen and hydrogen. The latter is further subdivided into primary, secondary and micro-nutrients. Primary nutrients include nitrogen (N), phosphorus (P) and potassium (K). Secondary nutrients are calcium (Ca), magnesium (Mg) and sulphur (S). Essential micronutrients are boron (B), manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), nickel (Ni), cobalt (Co), and molybdenum (Mo). Each of the nutrients plays an important role in plant growth, development and quality. There is a minimum range (critical level) for each nutrient below which it is deficient and above which it is toxic (Uchida, 2000). An important concept in chemical soil fertility is nutrient balance, which is centred on Liebig's law of minimum (Brady & Weil, 2008b). The law states that *"if one of the essential elements is deficient or lacking, plant growth will be poor, even when all the other elements are abundant. If the deficient element is supplied, growth will be increased up to the point where the supply of that element is no longer the limiting factor."*

Most agricultural soils in South Africa have low soil fertility (Mandiringana *et al.*, 2005; Mills & Fey, 2003), as well as high silt and low soil organic matter (SOM) contents and are under pressure as an increasing number of farmers make a living based on what the land can offer to growing crops (Mandiringana *et al.*, 2005). Du Preez *et al.* (2011) reported that changes have

taken place in the fertility status of soils in South Africa due to different land uses. The changes in the fertility status of South African soils, as reported by Mandiringana *et al.* (2005) and Swanepoel *et al.* (2014) linked directly to a general drop in organic matter, declining N, soil acidity, expanding extent of saline and alkaline areas and low P.

Soil organic matter (SOM) is recognised as a major attribute of soil fertility that dates to the beginning of agriculture. SOM is on the decline in South Africa (Weil & Magdoff, 2004). In addition, Du Preez *et al.* (2011) reported that South African soils are characterised by very low organic matter levels, about 58% of the soils contain less than 0.5% - 2% organic carbon and only 4% contain more than 2% organic carbon. A study has shown that micro-nutrients concentrations in South African soils of poor resource farmers are generally lower than those of range lands ((Herselman & Steyn, 2001).

Laker (2005) reported that soil samples obtained from land reform programmes across four developing farming districts of Vryburg, Lichtenburg, Klerksdorp and Brits in North West Province had low P levels (< 10 cmol/kg Bray-P), with a mean value of 2 cmol/kg. A study on plant nutrient status of soils of the Lusikisiki area in the Eastern Cape Province by Bühmann *et al.* (2006a) reported that the soils are extremely low in P and K. While Ca content are acceptable and magnesium (Mg) content is high, Ca:Mg ratios are low, particularly in the lower parts of the profiles. Cation exchange capacity (CEC) and base status in the A horizons are more strongly associated with organic carbon than with the clay content and nature of the clay fraction. Generally, the fertility status of agricultural soils in South Africa is very low in nutrients in the communal areas where subsistence agriculture is practiced because of inadequate nutrient inputs with P being one of the nutritional factors inhibiting crop production (Mandiringana *et al.*, 2005; Bühmann *et al.*, 2006b; Du Preez *et al.*, 2011).

Many of the soils are also suspected to have high P sorption capacities, particularly those from high rainfall areas which tend to be acidic with low to medium base status. Mandiringana *et al.* (2005) reported that almost 100% of the garden and field soils in three Transkei districts (Elliotdale, Umtata and Mt Fletcher districts) were acidic, indicating that they had the potential to fix added P. Studies on P sorption for some South African soils reported by Henry and Smith (2002) indicated that majority of the soils had high sorption capacities ranging from 500 to 1197 mg P kg⁻¹ of soil. Their study reported that the highest sorbers were weathered red or yellowbrown clays with high oxalate aluminium content, which is now described as short-range order iron and aluminium (SRO), especially in soils with a humic-horizon, such as Inanda, Kranskop

and Magwa forms. Therefore, only a small proportion of added P is present as P ions in the soil solution and available for plant uptake and increased productivity (Mandiringana *et al.*, 2005).

2.2 Soil Fertility Indicators of Crop and Grazing Land

Soil fertility indicators are measurable soil properties that influence the capacity of the soil to perform specific functions (Carter, 2002; Pathak *et al.*, 2005). The number of soil fertility characteristics depend on the scale of the assessment (i.e., field, farm, watershed, or region) and the soil functions of concern. They could show significant changes between 1-3 years, with 5 years being the upper limit to usefulness (Pathak *et al.*, 2005). It has been proposed by Herrick *et al.* (2002) that soil fertility indicators are predictive, to the extent that they reflect early changes in ecological processes and indicate if a significant change is likely to occur or not, though it is difficult to measure (Cannon & Winder, 2004). However, it still needs to be regularly evaluated, because nearly all land uses depend on healthy soil functions (Adamu *et al.*, 2014).

Owing to its complex and multi-functional nature, soil fertility cannot be measured or expressed by a single quantitative indicator. Soil fertility assessments are therefore either qualitative (e.g. expressed as light, moderate, severe) or quantitative referring to specific aspects such as the degree of alteration of certain soil properties or amount of soil nutrient loss; or to the loss of specific ecosystem services; or to its reduced potential to provide certain ecosystem services (e.g. to produce crops) (Bhardwaj *et al.*, 2011). Generally, soil fertility is the function of its physical, chemical and biological properties on which we have both qualitative and quantitative information to formulate appropriate fertility management programmes.

Many factors are responsible for the fertility of any given soil and those are generally called indicators. The factors include agro-climatic, hydrogeology, and cropping practices (Hartemink, 2006). The necessity for regular investigation of soil in order to evaluate its fertility is further heightened because land use and management could change the capacity of the soil to function properly in order to be productive (Adamu *et al.*, 2014). There are three basic processes through which soil fertility could be degraded namely, physical (erosion); chemical (salinisation, alkalinity, nutrient deficiency and heavy metal contamination) and biological (which borders on loss of organic matter) (Hartemink, 2006). Assessing soil fertility implies measuring physical, chemical, and biological soil indicators (Saley Moussa, 2007) and using these measured values to detect changes arising from land use change and management practices (Campos *et al.*, 2007).

Many chemical, physical, and biological properties of the soil have been proposed as indicators to assess the fertility status of soils. Fertility status and suitability assessment of soils for the production of maize at Solomon Mahlangu Campus farm, Morogoro, Tanzania, made by Adamu *et al.* (2014), reported on Total N, Available P, K, Ca, Mg, Na, EC, CEC, Exch. Acidity, Base saturation, Org.C, pH, Cu, Zn, Fe, and Mn as minimum data set of physical, chemical, and biological indicators for determining soil fertility.

2.3 Soil Physical Fertility Indicators

Soil physical indicators determine the capacity of the soil to provide plants with a support base, moisture, nutrients and air. Soil physical indicators varied and the success or failure of any agricultural project depends on the indicators of interest. The occurrence and growth of many plant species are closely related to soil physical indicators. These indicators determine the soil's water and air supplying capacity to plants and animals. Soil physical indicators strongly influence the fertility status and productivity of soils. The physical indicators such as structure, texture, bulk density, water holding characteristics and soil aeration are critical in crop production (Estefan *et al.*, 2013). Generally, the physical environment of the soil influences the nature of the chemical and biological reactions in the soil necessary for optimum plant growth (Rasool *et al.*, 2007).

2.3.1 Soil Texture

The relative size range of soil particles is expressed by the term texture and qualitatively, this refers to the relative proportions of the different particle size fractions i.e., sand, silt and clay specifically (Brady & Weil, 2013). They are the building blocks for the soil and can have a large effect on soil properties. Sands have a smaller surface area ($0.1\text{--}0.01\text{ m}^2/\text{g}$) and tend to be less chemically and physically active or reactive. Clays have a high surface area of $5\text{--}750\text{ m}^2/\text{g}$ depending on clay type and can have a high amount of chemical and physical activity (McKenzie *et al.*, 2004). Soil texture rating of the relative amounts of sand, silt or clay is $<10\%$ = very low, $10\text{--}25\%$ = low, $25\text{--}40\%$ = moderate, $40\text{--}50\%$ = high and $>50\%$ = very high (Hazelton and Murphy, 2007a). For instance, $<10\%$ clay indicates very low level of clay; $>50\%$ silt indicates very high level of silt.

Soil texture is the most fundamental quantitative physical indicator controlling the exchange, retention and uptake of water, nutrients and gases in the soil. It is a master soil indicator that influences most other properties and processes (Binkley & Fisher, 2012). It influences water infiltration and retention, soil aeration, nutrient absorption, microbial activities, tillage and

irrigation practices. It is also an indicator of other soil features such as type of parent material, homogeneity and heterogeneity within the profile, migration of clay and intensity of weathering of soil materials or age of soil (Lilienfein *et al.*, 2000).

Soil texture is naturally permanent in nature and it is an inherent attribute of soil and the one most often used to characterise its physical make-up (Brady & Weil, 2008b). In spite of the type of land use, it was reported by Kiflu and Beyene (2013) that the different land use types do not have effect on the soil texture, since texture is an inherent soil property that might not be influenced in a short period. However, the effect of texture on nutrient and water holding capacity, OM level and decomposition, aeration, infiltration rate, drainage and/or permeability and workability can be modified by soil structure, nature of the clay minerals, OM and lime content (Glover *et al.*, 2000).

If soil texture is considered as a permanent indicator, management systems may contribute indirectly to changes in particle size distribution, particularly in the surface horizons as a result of clay movement through illuviation, clay removal through sheet and rill erosion, and mixing of soils of the surface and subsurface horizons during mechanical tillage activities (Wakene & Heluf, 2001). Lower clay content was reported in cultivated land than forest and grazing lands, and the reason for low clay in surface layers of cultivated lands might be attributed to selective removal of clay from the surface by erosion and illuviation (Tessema *et al.*, 2011). The same authors also reported that silt content was significantly higher in cultivated land than the other land uses, implying that the land under cultivation is more susceptible to erosion than the adjacent forest and grazing lands if the subsurface soil do not have evidence of clay illuviation.

2.3.2 Bulk Density (BD)

Soil BD is a ratio of the mass (oven-dry weight) of soil to the bulk volume expressed in grammes per cubic cm (g/cm^3) or tons per cubic meter (t/m^3). Soil BD varies among soils of different textures, structures, and organic matter content. Within a given soil type, it can be used for the determination of degree of soil compaction and lessivage. It is used as a measure of soil structure, for calculating soil pore space and as indicator of aeration status and water content. Changes in soil bulk density affect a host of other properties and processes that influence water and oxygen supply (Schoenholtz *et al.*, 2000; Estefan *et al.*, 2013).

Bulk density normally decreases as mineral soils become finer in texture. The effect of bulk density on soil condition and plant growth therefore depends on soil texture. According to

Estefan *et al.* (2013), average bulk density of fine textured mineral soils usually ranges from about 1.0 and 1.5 g/cm³, and sandy soils from 1.3 to 1.7 g/cm³. Basically, an increase in soil OM lowers bulk density while compaction increases bulk density. The authors also reported that BD of organic soils are usually lower than mineral soils and may be as low as 0.4g/cm³. Soils with low and high bulk density exhibit favourable and poor soil physical conditions respectively (Chimdi *et al.*, 2012).

Soil bulk density is highly affected by soil management practices such as land use type and soil management practices. Any factor that influences soil pore space also affects the bulk density. For instance, intensive cultivation increases bulk density resulting in reduction of total porosity. A study reported that the BD of cultivated soils was higher than the bulk density of forest soils (Lemenih, 2004; Workneh & Glatzel, 2008; Chimdi *et al.*, 2012; Mojiri *et al.*, 2012). This might be attributed to the impact of frequent tillage and decline in OM content of the soils. Other authors also indicated that bulk density increased significantly with increasing cultivation period (Lemenih *et al.*, 2005). On the other hand, relatively higher soil BD was observed in the soils at higher elevation compared to those at lower elevation (Abreha, 2013), which is attributed to the existence of relatively lower OM accumulation in the lower elevation site or poor soil organic matter management or accumulations are of sandy nature.

2.3.3 Total Porosity

The percent bulk volume of a soil not occupied by solids is called the total porosity of that soil. The porosity of a soil or the amount of pore space influences its physical and chemical properties such as percolation, infiltration, aeration, and redox status of the soil. In soils, the amount of pore space (porosity) can be obtained from its bulk density and particle density measurements (Estefan *et al.*, 2013).

Total porosity is the ratio of total volume of pore spaces to the total volume of soil, and it is an index of the relative pore space in the soil. Its value generally ranges from 30 (in compacted subsoil) to more than 60% in well-aggregated, high OM surface soils (Brady & Weil, 2002b). Coarse textured soils tend to be less porous than fine-textured soils, though the mean size of individual pores is greater in coarse-textured soils. However, in clayey soils, the porosity is highly variable as the soil alternately swells, shrinks, aggregates, disperses, compacts and cracks (Brady & Weil, 2008b). Soil porosity is a measure of the ratio of non-capillary and capillary pores in soils; it may be a sensitive indicator of management induced physical change that leads to water and air imbalances (; Schoenholtz *et al.*, 2000; Estefan *et al.*, 2013).

2.4 Soil chemical fertility indicators

2.4.1 Soil reaction (pH)

Soil reaction (pH) is defined as the negative log of the hydrogen ions (H^+) activity in the soil solution (Brady & Weil, 2002b). In other words, pH is a measure of acidity or alkalinity of a soil that gives an indication of the activity of the hydrogen ion (H^+) and hydroxyl ion (OH^-) in a soil/water solution. The pH ranges normally found in soils varies from 3 to 9. Soil pH is also an indicator of the chemical processes that occur in the soil and is a guide to likely nutrient deficiencies and/or toxicities (Hazelton & Murphy, 2007b). Hydrogen ion concentration (pH) and nutrient availability in soils is presented in Figure 2.1.

Many chemical reactions that influence nutrient availability are induced by the soil chemical environment and principally by soil pH (Schoenholtz *et al.*, 2000). Soil pH has an important role in determining several chemical reactions in soils and influencing plant growth as it consequently affects the activity of soil microorganisms. It also affects the availability of most of the essential plant nutrients, because of its relationship to solubility and rates of decomposition and particularly the micronutrients such as Fe, Zn, Cu and Mn (Alley & Vanlauwe, 2009). Whenever soil pH is low, availability of both macro and micronutrients is affected and the population and activity of organisms responsible for transforming nutrients from the organic and/ or atmospheric pool to plant available forms may be reduced (Fernández & Hoefft, 2009).

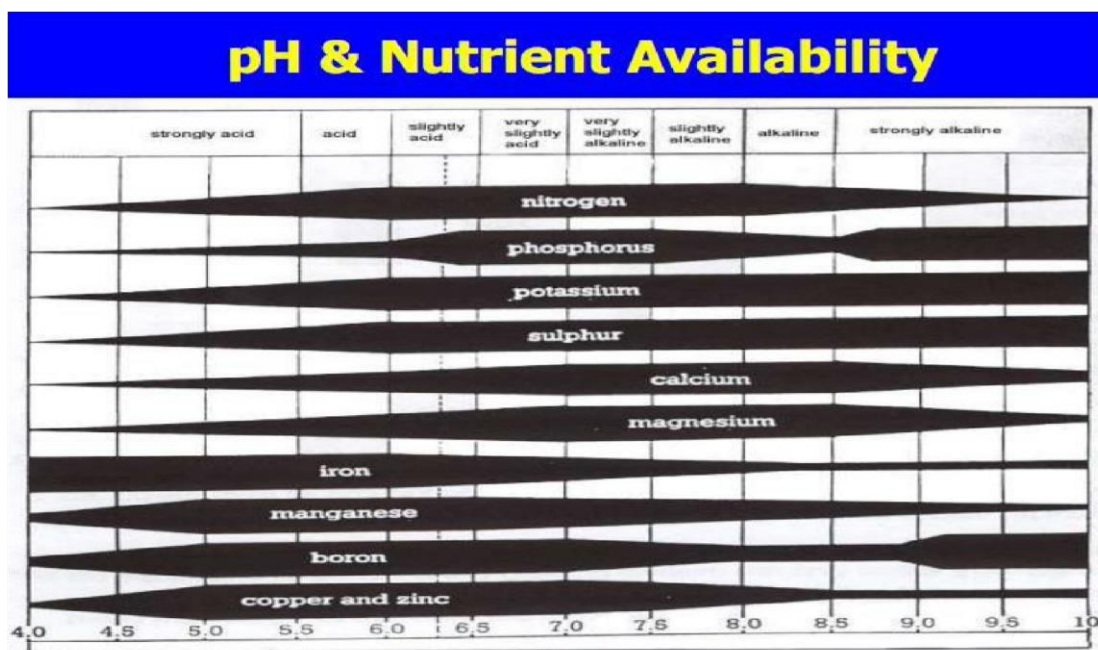


Figure 2.1: Hydrogen ion concentration (pH) and nutrient availability in soils (Brady & Weil, 2008c).

Most of the macronutrients exhibit maximum availability at pH values between 6.5 and 7.5. Although metallic ions are generally less available above pH 7, some are available even at pH values lower than 4, especially the micronutrients. Optimum availability of nutrients for most plants appears to be between pH 6 and 7 (slightly acid to neutral). However, pH may not be the only determinant of nutrient availability in soil (Brady & Weil, 2002b).

Soil acidity (low pH) is common in all regions where precipitation is high enough to leach significant quantities of cations (Ca^{2+} , Mg^{2+} , K^{+} and Na^{+}) from the surface layers of soil. However, acidity is a naturally occurring phenomenon. Agricultural practices such as the removal of plant residues, removal of organic anions and excess cations from the farm, decomposition of organic materials, application of acid forming commercial fertilisers are likely to accelerate soil acidification (Brady & Weil, 2002b). Changes in land use type also affect soil pH.

Research reported by different scholars indicates that soil pH can be affected significantly by land use (Abbasi and Rasool (2005); (Abreha, 2013). Emiru and Gebrekidan (2013) found that soil pH was higher in soils under forest land use but this generally becomes small in cultivated land soils. According to these authors, the lower pH in the cultivated field could be attributed to the depletion of basic cations by crop harvest. Besides that, continuous use of ammonium-based fertilisers such as DAP, and urea in cereal based cultivated fields and its oxidation by soil microbes produces strong inorganic acids. These strong acids in turn release H ions to the soil solution and lower soil pH. On the other hand, the high pH of soils from the forest land might be attributed to the ameliorating effect of the high accumulation of OM. This ameliorating effect of soil OM could be due to the combined effect of the continuous release of basic cations from OM, deposition of basic cations at the surface by the relatively deep root forest trees from the subsoil and the specific adsorption of organic anions on hydrous Fe and Al surfaces and the corresponding release of hydroxyl ions (Brady & Weil, 2013). Critical limits for interpreting pH levels in soils are presented in Table 2.1.

In addition, Rengel (2003) reported that trees and shrubs play a role in minimising soil acidification through the development of deep root systems capable of taking up bases such as Ca and Mg from deep layers of the soil profile and returning them to the topsoil as leaf litter containing excess basic cations. Contrary to Yimer *et al.* (2007) Rengel (2013), reported high pH values for croplands as compared to forestlands. In coarse (sandy) textured soil, steep slope and higher rainfall areas there is high loss of base forming cations down the soil profiles, even

beyond sampling depths, through leaching and drainage into streams in runoff generated from accelerated erosion. This in turn enhances the activity of Al^{3+} and H^+ in the soil solutions, which reduces soil pH regardless of the type of land use (Emiru & Gebrekidan, 2013).

Table 2.1: Critical limits for interpreting pH levels in soil

Class	pH level
Ultra-acid	< 3.5
Extremely acid	3.5 - 4.4
Very Strongly acid	4.5 - 5.0
Strongly acid	5.1 - 5.5
Moderately acid	5.6 - 6.0
Slightly acid	6.1 - 6.5
Neutral	6.6 - 7.3
Slightly alkaline	7.4 - 7.8
Moderately alkaline	7.9 - 8.4

Source: Esu (2010).

2.4.2 Electrical Conductivity (EC)

Electrical conductivity (EC) is a measure of salinity and soil salinity refers to the concentration of soluble inorganic salts in the soil (Estefan *et al.*, 2013). Excessive accumulation of soluble salts converts soils to salt affected soils and the process leading to build-up of salts is common in arid and semi-arid regions where rainfall amount is in short supply to leach soluble salts. Electrical conductivity of soil is highly dependent on climatic conditions of the area. In soils of sub-humid tropics where there is sufficient rainfall to flush out base forming cations from the root zone, EC is usually low. Salinity is an important measurement since it reflects the extent to which the soil is suitable for growing of crops. However, salinity affects plants at all stages of development and for some crops, sensitivity varies from one growth stage to another. While salinity is largely a concern in irrigated areas with saline soils, it is often less important in rainfed agriculture. The values of 0 to 2 ds/m are within the safe for all crops while the yields of very sensitive crops are affected between 2 to 4 ds/m. On the other hand, many crops are affected between 4 and 8 ds/m while tolerant crops grow reasonably well above 8 ds/m. Nevertheless, higher EC value hinders nutrient uptake by increasing the osmotic pressure of the nutrient solution, waste nutrients, and this increases discharge of nutrients into the environment, resulting in environmental pollution (Bohn *et al.*, 2002).

2.4.3 Soil Organic Carbon (SOC)

Soil organic carbon is the major component (approximately 58%) of soil organic matter. It plays an important role in agricultural production and in a range of other soil functions. It is acknowledged as the most useful single characteristics of soil fertility (Initiative, 2011). For many years it was assumed by many advocates of intensive farming that soil carbon was not a limiting factor in crop yields because studies failed to show otherwise. Of late, however, research has shown that once soil carbon falls too low, optimum crop yields cannot be achieved no matter how much fertiliser is used (Johnston *et al.*, 2009). Soil organic carbon (SOC) also improves the physical properties of soil that increase the extent to which it can absorb and hold water, making it available for later crop use. Other important properties influenced by SOC include the ability of soils to absorb minerals, including fertiliser nitrogen, without becoming more acidic. Soil organic matter is a major source of nutrients, which has ability to reduce leaching, enhances microbial biomass activity and the species diversity of soil fauna and flora (Brady & Weil, 2008b). Crops grown in soils with a low organic carbon level are also more susceptible to diseases (Altieri & Nicholls, 2003; Magdoff & Weil, 2004).

Depletion of organic carbon in agricultural soils accelerates soil fertility degradation (Brevik *et al.*, 2015) and between 42 - 78 billions of tonnes of carbon have been lost from soils over the last century due to degradation. The SOC is mostly emitted into the atmosphere as carbon dioxide (CO₂) and other greenhouse gases (GHGs) with negative implications for climate change and food production (Lal, 2004). In England and Wales, the total estimated organic carbon loss from the soil each year is 5.3 million tonnes, corresponding to a mean rate of 0.6% of the existing soil carbon content (Bellamy *et al.*, 2005; Graves *et al.*, 2015).

Soil microbial life only makes up 5% of soil organic matter (Camenzind *et al.*, 2023) but it is very important in relation to maintaining or enhancing SOC levels. It is responsible for the decomposition of crop and livestock waste and any added organic material, which once fully decomposed constitutes the soil's stable organic matter. This slowly increases or decreases over time according to farming systems, temperature, soil type and other factors, but un-decomposed organic matter rapidly oxidizes to carbon dioxide and is therefore of little value to crop production (Johnston *et al.*, 2009).

In soils with high clay fraction, SOC levels do not fall indefinitely, but instead fall to a lower equilibrium level. In contrast, light and sandy soils containing little clay are less able to resist soil carbon decline which can fall to extremely low levels where the soil is incapable of

supporting livestock or growing crops (Johnston *et al.*, 2009). This is an important point, which applies in particular to some soils in Africa, with under inappropriate farming systems have the potential to degrade rapidly (Elias & Fantaye, 2000). Critical values for OC interpretation in soils are: < 10 g/kg low, 10-15 g/kg medium and > 15g/kg high (Landon, 2014).

2.4.4 Cation Exchange Capacity (CEC)

Cation exchange capacity is the total number of negative charges per unit weight of soil. The quantity of positively charged ions (cations) that a mineral soil or similar material can accommodate on its negatively charged surface is expressed as milli-ion equivalent per 100g of soil or more commonly as milliequivalent (meq) per 100g or cmol/kg (Troeh & Thompson, 2005). Thus, CEC is a measure of soil fertility and nutrient retention capacity. The CEC of a soil mainly depends upon the mineralogy and different types of clay a soil can hold in variable amount or the ability of the soil solid phase to attract and store or exchange cationic nutrients with the soil solution phase thus rendering them available to plants through exchange reactions (Kumar & Mohan, 2021). It is one of the dominant factors in measuring soil fertility which affects exchange of ions on the clay surface (Abera & Belachew, 2011). This gives an indication of the type of clay minerals present in the soil, its capacity to retain nutrients against leaching, determines how often and how much lime must be applied and determines how plant nutrients other than lime can be applied in assessing the fertility and environmental behaviour of the soil. Generally, the chemical activity of the soil depends on its CEC.

The CEC is strongly affected by the nature and amount of mineral and organic colloids present in the soil. Soils with large amounts of clay and OM have higher CEC than sandy soils low in OM. It was reported by Brady and Weil (2002b), that in mineral soils, the clay fraction is largely responsible for cation exchange properties. Gelaw *et al.* (2014), reported on major soils of some dry land areas of north-east Ethiopia, that the highest CEC value (56.70 cmolc kg⁻¹) was recorded in the surface layer of Kobo Eutric Vertisols and can be considered very high for tropical soils. Ayele *et al.* (2014) reported that CEC status in Abaya Chamo Lake Basin ranges between 33.81 – 47.83 cmol/kg.

The same authors above also reported that CEC is highly correlated with organic matter content of the soil, which in turn is affected by different soil management practices such as intensive cultivation, fertilisation and changes in land use. In addition, due to intensity of human activity, there was a drastic loss of CEC in the surface than in the subsurface layers of the soils of Senbat watershed, western Ethiopia (Nega *et al.*, 2006). The processes that affect texture, such as clay

and OM due to land use changes also affect CEC of soil. The soil CEC values in agricultural land uses decreased mainly due to the reduction in organic matter content (Yitbarek *et al.*, 2013). The authors reported that conversion of natural forest land into cultivated lands caused losses of CEC. Esu (1991) reported that values of < 6 is low, 6-12 medium and > 12 cmol/kg high and are the critical limits for interpreting CEC in soils of lower Benue basin Nigerian.

2.4.5 Total Nitrogen

Nitrogen (N) is an important indicator essential for plant nutrition. It is found primarily in organic forms in soils and more in soils and plants in the anionic form and is responsible for serious environmental problems (Brady & Weil, 2002c).

Nitrogen is the first mineral nutrient that is relatively needed in greater amount by all crops (Alley & Vanlauwe, 2009). On the other hand, it is one of the most deficient elements in the tropics for crop production and considered the most limiting nutrient for plant growth in arid and semi-arid ecosystems (Havlin *et al.*, 2016). This is presumably due to leaching loss of the plant available negatively charged nitrate-N (Abera *et al.*, 2012) and loss of ammonium-N either through immobilisation by microorganisms, fixation in to clays or soil OM or its rapid nitrification.

Change in land use type also results in significant effect on the content of total N. Nitrogen is lost very rapidly in the form of nitrous oxide, the most persistent and potent, in terms of global warming, of all the major greenhouse gases. A study in the Netherlands found that taking nitrogen losses into consideration increased the net greenhouse gases (GHG) impact of converting grassland to crop production by 50%, with an associated soil fertility decrease and disruption of nutrient cycles (Vellinga *et al.*, 2004).

Generally, the total N under forest land was higher than those under cultivated field soils (Abera & Belachew, 2011; Tessema *et al.*, 2011; Chimdi *et al.*, 2012). The total N content of a soil is directly associated with its OC content and its amount on cultivated soils is between 0.03% and 0.04% by weight (Havlin *et al.*, 2016). Total N values of < 0.1 is considered as low, 0.1 to 0.2 is medium and > 0.2 g/kg is high (Landon, 2014).

2.4.6 Available Phosphorus

Available phosphorus in soils can be defined as the concentration of P in soil solution which is readily available for the plant and microbial use or demands. Soil solution is the main source of P for plants and microbes. The major P is present in the form of inorganic orthophosphates (H_2PO_4^-

or HPO_4^{2-}). However, when it is depleted by plants and micro-organisms, it has to be replenished from a combination of inorganic, organic and microbial pools (Condrón & Tiessen, 2005; Sims & Sharpley, 2005).

Phosphorus is known as the master key to agriculture, because lack of available P in soils limits the growth of both cultivated and uncultivated plants (Foth & Ellis, 1997). Following N, P has more widespread influence on both natural and agricultural ecosystems than any other essential nutrient. In most natural ecosystems, such as forests and grasslands, P uptake by plants is constrained by both the low total quantity and its very low solubility in the soil (Brady & Weil, 2002b). It is the most commonly plant growth limiting nutrient in tropical soils next to water and N (Kirkby & Johnston, 2008; Marschner, 2011). Erosion tends to transport predominantly the clay and OM fractions of the soil, which are relatively rich in P fractions. Thus, compared to the original soil, eroded sediments are often enriched in P by a ratio of two or more (Brady & Weil, 2002b). According to Foth & Ellis (1997), natural soil contains from 50 to over 1,000 mg of total P per kilogramme of soil and of this quantity, about 30 to 50% may be in inorganic form in mineral soils.

The main sources of plant available P are the weathering of soil minerals, the decomposition and mineralisation of soil OM and commercial fertilisers. Most of the soils in South Africa, particularly Nitisols and other acid soils, are known to have low P contents, not only due to the inherently low available P content, but also due to the high P fixation capacity of the soils (Henry & Smith, 2006). Oxisols, Ultisols, Vertisols and Alfisols are generally low in total P while Andosols are generally high in P content (STAFF, 2004). Available P in the soil is categorised as low when it is < 10 mg/kg, medium (10-20 mg/kg), and > 20 mg/kg high (Landon, 2014).

2.4.7 Exchangeable Potassium

Potassium (K) is an essential nutrient for plant growth and occupies third position after nitrogen and phosphorus. It enhances resistance to disease and drought in plants. It also helps to develop fruit size, flavour and texture (Brady & Weil, 2002b; Marschner & Rengel, 2012).

Potassium is present in the soil in three forms namely; relatively unavailable, slowly available or fixed, and readily available (exchangeable) (Al-Zubaidi *et al.*, 2008). Generally, 90-98% of total soil K is found in relatively unavailable form whereas only 1 to 10% of the soil K is the slowly available from clays and hardly 0.1-2% is readily available to plants (Buchholz & Brown, 1993). Feldspars and micas contain most of the soil K. Plants cannot use the K in this crystalline-

insoluble form. The exchangeable K maintains equilibrium with the K in solution and the addition of exchangeable and solution K makes up the available K. Exchangeable K is widely used for evaluating the soil K status and prediction of crop K requirements (Samadi, 2006). The research work of Ajiboye and Ogunwale (2008) reported that exchangeable K alone cannot be used as the basis for evaluating K availability under intensive cropping. It was noticed that those soils which were considered sufficient in exchangeable K were unable to maintain that condition for long under intensive cropping with high yielding varieties.

The level of K in soil is termed low when it is < 60 mg/kg; medium (60-100 mg/kg) and high, when the readily available K is >100 mg/kg (Naseem *et al.*, 2012). Potassium in combination with Ca and Mg is also very significant to assessing quality of agricultural soils. There is cation antagonism that exists between Ca, Mg and K such that high levels of one or more of these nutrients can result in decrease of another, despite sufficient soil levels (Wacal *et al.*, 2019). The Ca/K ratio around 13:1 is approaching ideal condition. Available K is the potassium held in the soil solution (soluble K₂O) by soil organic matter and non-fixing clay particles in an exchangeable form (Al-Zubaidi *et al.*, 2008). It is absorbed by plants in large amounts than any other nutrients except N. According to Anthes and De Schutter (2018), available K is involved in the working of more than 60 enzymes, in photosynthesis and the movement of its products to storage organs, water economy and provides resistance against a number of pests, diseases and stresses.

Mineral weathering followed by organic matter mineralisation is the major source of potassium in soils (Brady & Weil, 2008b). However, mineral weathering rates are usually slow compared to plant needs. On the other hand, organic matter decomposition releases ions much faster than mineral weathering, but most of the ions released react with the soil solid phase before they can be absorbed by plants or assimilated by microorganisms (Bohn *et al.*, 2002). Plant residues and wood ashes contain several percent K and are important sources of this element (Foth, 1990).

Although the total K content of soil is usually many times greater than the amount taken up by a crop during a growing season, only a small fraction of it is available to plants (Havlin *et al.*, 2016). Potassium content and its availability varies with type of parent material, degree of weathering, management practices, OM content and clay content as well as type (Ayele *et al.*, 2013). Available K availability increases with OM content, as reported by Singh and Mishra (2012) and it might be due to creation of favourable soil environment with presence of OM.

2.4.8 Exchangeable Calcium (Ca) and Magnesium (Mg)

Calcium is the dominant exchangeable cation in many soils except alkaline soil that contains sodium and acidic soils holding larger amounts of H and Al (Prasad & Power, 1997). Calcium is important for enzyme functioning and it is an essential constituent of cell wall structure and in transport of metabolites (Brady & Weil, 2008b; Hepler, 2005). The release of Ca or Mg from the exchange complex and their availability to crops depends upon the total Ca or Mg supply, the type of clay mineral present, the CEC of soil, percentage saturation of CEC with exchangeable Ca or Mg, soil pH and the ratio of Ca^{2+} or Mg^{2+} to the other cations in the soil solution. Though different crops have varying optimum ranges of nutrient requirements, the response to calcium fertiliser is expected from most crops when the exchangeable calcium is less than 0.2 cmol(+)/kg of soil, while 0.5 cmol(+)/kg of soil was the deficiency threshold level in the tropics for magnesium (Díaz *et al.*, 2011).

Calcium improves soil crust, structure and quality as well as reduces soil salinity, erosion and phosphorous loss. It promotes root and leaf development and helps to create a healthy environment for plant growth. Calcium at optimum level reduces disease in most plants (Dordas, 2009). Imbalance of Ca leads to tight hardpan soils, which restrict the flow of air and water through the soil profile (Naseem *et al.*, 2012).

Magnesium (Mg) is the second most abundant exchangeable cation in soils. The concentration of Mg in the lithosphere is 2.1% and only 0.5% is in the soil, and three quarters of the Mg has been lost by weathering during soil formation (Selassie *et al.*, 2014).

Magnesium is one of the secondary nutrients needed by plants for metabolic and physiological activities. Magnesium forms part of the chlorophyll molecule and relates to movement of phosphorus in soil and directly involved in photosynthesis (George *et al.*, 2002). The total Mg content in soil is a product of climate, parent material, and maturity of the soil (Mokwunye & Melsted, 1972). According to Prasad and Power (1997), exchangeable Mg generally constitutes 4 to 20% of the CEC. Magnesium usually increases with increasing percentage of soil clay. Both exchangeable Ca and Mg usually account for more than 60% of the exchangeable cations on soil with pH 5.5 or higher. However, the exchangeable Mg is lower. Magnesium deficiency causes the loss of healthy green colour of leaves because of shortage of chlorophyll in plant. Magnesium is a mobile element in the plant, so the concentration of Mg usually decreases from top to bottom of the plant. It also decreases according to plant maturity. Ca/Mg ratio is an important parameter

to evaluate soil for agricultural purpose. A good soil has Ca:Mg between 5-8 with 6.5 as an ideal condition (Naseem *et al.*, 2012).

2.4.9 Exchangeable Aluminium (Al)

Aluminium is one of the most abundant metals in the earth's crust, but its availability depends on soil pH. Aluminium is not considered an essential element, despite its abundance (BojórquezQuintal *et al.*, 2017). Aluminium is one of the soil indicator sources contributing to soil acidity and about 40% of the world's arable soils are acidic and may be subject to the effects of Al toxicity (Havlin *et al.*, 2016). Aluminium is one of the main factors limiting fertility of most soils and impedes crop development (Kochian *et al.*, 2004).

Aluminium toxicity is an important factor in soil fertility decline caused by acidification of the soil solution (Bose *et al.*, 2015). Soil acidification leads to increasing concentrations of aluminium and to decreasing concentrations of the base cations (BC) K, Ca and Mg in the soil solution (van Schöll *et al.*, 2004; Gupta *et al.*, 2013). At pH values lower than 4, dissolved Al is present as Al^{3+} , which is toxic to plants (Kochian *et al.*, 2005). Symptoms of Al toxicity include halted root growth and Ca and Mg deficiencies, resulting in reduced growth. Impaired root growth results from inhibited cell division and cell elongation, for which disruption of regulatory processes in the cytoplasm and the plasma membrane are considered key factors (Kopittke & Blamey, 2016). Increasing the concentration of Ca and Mg in the soil solution can reduce Al toxicity (van Schöll *et al.*, 2004).

2.4.10 Micronutrients in soil

The concentration of micronutrient elements in soil is a consequence of weathering that releases micronutrients from the host minerals during soil formation (Brady & Weil, 2008b). The availability and solubility of soil micronutrients is largely dependent on their distribution in soil and by other physical and chemical properties of the soil such as clay content, pH, organic matter, CEC, phosphorus level and soil management practices (Kabata-Pendias, 2011; Vijayakumar *et al.*, 2011). It was reported that Fe and Mn are more available under acidic soil conditions, while Mo is more available under alkaline soil conditions, and at low pH, Mo is adsorbed by Fe and Al oxides, as well as silicate clays (Brady & Weil, 2008b).

Micronutrients are essential and required by plants in very minor amounts as related to macronutrients. The minimum requirements of micronutrients in the soil for optimum plant growth ranged from 2 - 11 kg/ha. If micronutrient elements are not available sufficiently, plants

suffer from physiological stresses caused by inefficiency of several enzymatic systems and other related metabolic functions (Kumar & Babel, 2013) and higher concentrations may cause crop toxicities. The term applies to nutrient elements that are contained in plant tissues in amounts less than 100 mg/kg (Foth & Ellis, 1997) and the six essential micronutrients that exist as cations in soils unlike boron and molybdenum are zinc (Zn), copper (Cu), iron (Fe), nickel (Ni), cobalt (Co), and manganese (Mn) (Brady & Weil, 2008b).

Chekol and Mnalku (2012) reported that availability of micronutrients is negatively related with soil P. Vijayakumar *et al.* (2011) and Nazif *et al.* (2006) reported that soil micronutrients are positively related with soil OM and clay, while negative relations with sand particles. This is because the high retention of moisture induces the diffusion of these nutrient elements. According to the same authors, the concentrations of Fe, Mn, Cu and Zn are negatively correlated with soil pH. Their solubility, availability and plant uptake are more under acidic conditions (pH of 5.0 to 6.5). Vijayakumar *et al.* (2011) reported that the presence of OM may increase the availability of certain micro and macro nutrients in the soil.

2.5 Soil Mineralogy

Soil mineralogy refers to the composition of the solid inorganic part that controls the physical and chemical processes in soils. It is one of the principal soil forming factors (Jenny, 1994) and a major determinant of basic soil functional properties. Soil mineralogy has a deep influence on the dynamic behaviour of soils namely the gains, losses, transformation and translocation of inorganic and organic substances. Therefore, understanding soil mineralogy is critically important for assessing functional soil properties, such as interactions with nutrients, nutrient quantity (stock) and availability (intensity or strength of retention by soil), sorption of metals, organics and nutrients to mineral surfaces, fertiliser response, water storage, erosion susceptibility and provision of sites for microbial and faunal activities. These properties in turn determine the fertility of agricultural soils, environmental and engineering qualities (Brady & Weil, 2008b).

Soil minerals are inorganic compounds with physical, chemical, and crystalline properties. They are classified into primary or secondary minerals, silicates and non-silicates, crystalline and noncrystalline. Silicate minerals are dominant in most soils, while, other mineral groups include: sulphides, oxides and hydroxides, halides, sulphates, carbonates and phosphate (Esu, 2010). Mineral particles make up about 50% of the volume of most soils and knowledge of the different

minerals present in a soil and the chemical composition of these minerals are important to the understanding, use and management of the soils (Brady & Weil, 2008b).

Soil minerals play an important role on the suitability and behaviour of soils. They make available physical support for plants, add to soil structure formation and supply many soil nutrients, (Brady & Weil, 2008b; Bühlmann *et al.*, 2004; Mandiringana *et al.*, 2005) and act as sorbents of several environmental pollutants. Therefore, soil mineralogy is essential to understanding land use and is often a key to solving specific agricultural problems.

2.6 Phosphorus (P)

Phosphorus is a naturally occurring nutrient element found in soils and it is derived from the weathering of igneous, sedimentary and metamorphic rocks, which release phosphorus containing minerals, apatite and other phosphate minerals into the soil (Brady & Weil, 2008b; Gichangi *et al.*, 2008; Troeh & Thompson, 2005). Phosphorus occurs naturally in combination with other elements to form phosphates. Phosphates are very complex and many forms are found in soils, water, plants, animals and man (Johnston & Steen, 2000). The primary P minerals weather with time and release P into the soil and exist because of anthropogenic processes. This happens due to the addition of inorganic P fertilisers and organic fertilisers (manures) to improve the fertility of soils (Troeh & Thompson, 2005).

Phosphorus is considered one of the most limiting nutrients in agricultural soils because most of its compounds are insoluble or strongly bound to soil particle surfaces (Suthiphasilp, 2009). The formation of these insoluble phosphates depend on the complex dynamics of P in soils, which involve several physical and chemical (sorption/desorption) and biological (immobilisation/mineralisation) reactions (Havlin *et al.*, 2016). The rate and direction of these reactions are influenced by the properties of soil and microbiological components (Campbell & Edwards, 2001). Phosphorous is one of 18 nutrient elements essential for plant growth and all other known life forms (Brady & Weil, 2008a). An adequate supply is required in agricultural soils to meet the demands for crop growth and grazing animals' health (Daly *et al.*, 2015).

Phosphorus is involved in most major metabolic processes, e.g. it plays a major role in energy transfer as adenosine triphosphate (ATP). As phospholipids, phosphorus is part of cell membranes and as part of nucleotides. It is a major component in the construction of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). In addition, plants are dependent on phosphorus to secure energy production in photosynthesis (Faucon *et al.*, 2015; Ruttenger, 2003;

Smil, 2000). Due to these reasons, the importance of phosphorus in agriculture and food production cannot be over-stressed.

Phosphorus application has become an essential part of crop production systems to produce adequate food and fibre for human consumption. The importance of maintaining adequate P supply to crops has long been recognised for developed agriculture (Withers *et al.*, 2001). Phosphorus in soils is influenced not only by parent material and land management but also the soils sorption and desorption characteristics (Börling *et al.*, 2001).

2.6.1 The Role of Phosphorus in Plants

Phosphorus is one of three macronutrient elements absorbed from the soil by plants and it is essential for seed formation, cell division, flowering and fruiting, root development, strengthening of straw and making plants resistant to diseases (Ayub *et al.*, 2002). It is responsible for energy transformation in cells of both plants and animals. As such it is necessary for normal transformation of carbohydrates in plants, the changing of starches to sugar (Niamatullah *et al.*, 2011). As a major component of DNA and RNA, it contributes to the genetic character of biological matter. It is a constituent of certain lipids, which are helpful in the maintenance of the cell membrane in plants (Masood *et al.*, 2011).

Phosphorus is essential for photosynthetic processes by which plants derive energy from the sun to produce carbohydrate molecules, i.e., sugars. These are transported to the plants' storage organs such as the root of sugar beet or wheat grain, rice, maize and potato tuber where the sugars are converted to starch. This process is crucial to all life and is the first step in producing food, feed and fibres (Mullins, 2009; Melenya *et al.*, 2015). Phosphorus is stored in seeds and grains in order to develop the first roots and shoots during germination (Bomans *et al.*, 2005). Phosphorus further improves the shoot strength and crop quality (necessary for the development of seeds, fruits and leaves) and is a component necessary in the process of N-fixation by legumes (Brady & Weil, 2008b).

Shortage of P causes a decrease of tillering and branching, reduces plant growth and also limits root growth and reduces the ultimate crop yield (Gichangi *et al.*, 2008). Phosphorus deficiency during the early developmental stage of plant growth manifests in stunted growth. This slows the growth of leaves and then reduces photosynthesis (Sato, 2003; Fageria, 2016). Due to the ability of phosphorus compounds to move from older leaves to younger leaves and developing buds, the symptoms of P deficiency start from the older leaves then progresses toward the youngest ones.

Severe phosphorus deficiency leads to inhibition of root growth. It affects the yield, the quality of fruit and the formation of seeds and delays the harvest time. Generally, phosphorus-deficient plants are stunted and develop poor root systems and thin stems. Fruit trees deficient in P have fewer and shorter shoots and malformed fruits and seeds. Thus, not only are the yields poor but crop quality is also poor where P is severely deficient (Uchida, 2000; Zahedifar *et al.*, 2010).

2.6.2 The Importance of Phosphorus in Animals

Phosphorus is an essential element for animal growth and milk production. It contributes to many vital functions in metabolic processes of soft tissues, maintenance of stable conditions for biological reactions, maintenance of appetite, optimal growth, fertility and bone development; and prevention of bone disease such as rachitis (Brasnett, 2002). The average daily nutritional requirements for animals in terms of phosphorus are about 85-95 g per day for dairy cattle, and 35- 40 g per day for beef cattle. Feeds which contain high amounts of phosphorus include rape seed meal, by-products from the milling industry and animal products like fish and bone meal. Animals digest only a small part of the phosphorus in this material and the rest is lost through dejection. This dejection leads to concentrations of P in manure as compared to the fodders (Johnston & Steen, 2000).

2.6.3 Phosphorus Cycle in Soils

Phosphorus is a sparse macronutrient and is efficiently recycled in natural ecosystems and its cycling in nature includes the physical, chemical, and microbiological processes that determine the forms of P, its availability to plants and its transport in runoff or via leaching (Campbell & Edwards, 2001a). The processes and different P pools that make up the cycle are illustrated in the Figure 2.2.

Phosphorus in soils originates from the weathering of residual minerals and from other sources e.g., inorganic fertilisers, animal manure, plant residues and industrial waste (Campbell & Edwards, 2001b), Brady & Weil, 2008b). Phosphorus is released into the soil solution phase in forms that are available for plant uptake. This occurs through the following processes that are reversible: (1) dissolution of primary and secondary minerals; (2) desorption of P from clays, oxides and minerals; and (3) mineralisation of P in organic materials to inorganic forms. Precipitation and sorption of dissolved P are reversible chemical processes that regulate soil solution P concentrations (Brady & Weil, 2008b).

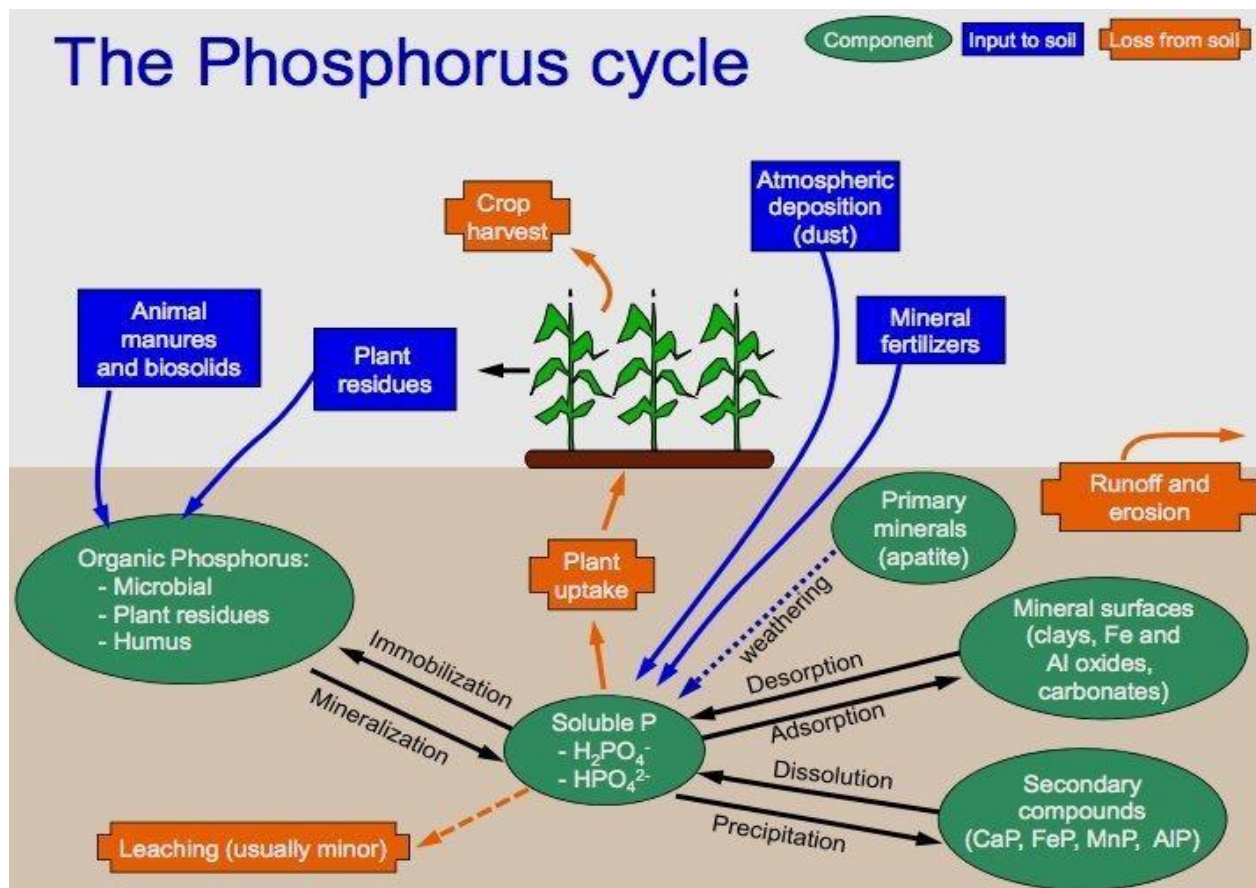


Figure 2.2: Phosphorus cycle presenting different forms of P and their interrelationships (Campbell & Edwards, 2001b)

Orthophosphate forms in soil solution at different pH levels are presented in Figure 2.3. The orthophosphate (phosphorus) in soil solution is either a monovalent (H_2PO_4^- in acid soils) or a divalent anion (HPO_4^{2-} ; in alkaline soils) (Hiradate *et al.*, 2007). These phosphate ions in the soil solution are readily absorbed by plants and animals can utilise the P in plants. The P is ultimately returned to the soils as organic phosphates in either plant or animal residues. These are slowly released as inorganic phosphate during mineralisation by microbial biomass or may be incorporated into more stable organic materials and become part of the soil organic matter (Whitelaw, 1999).

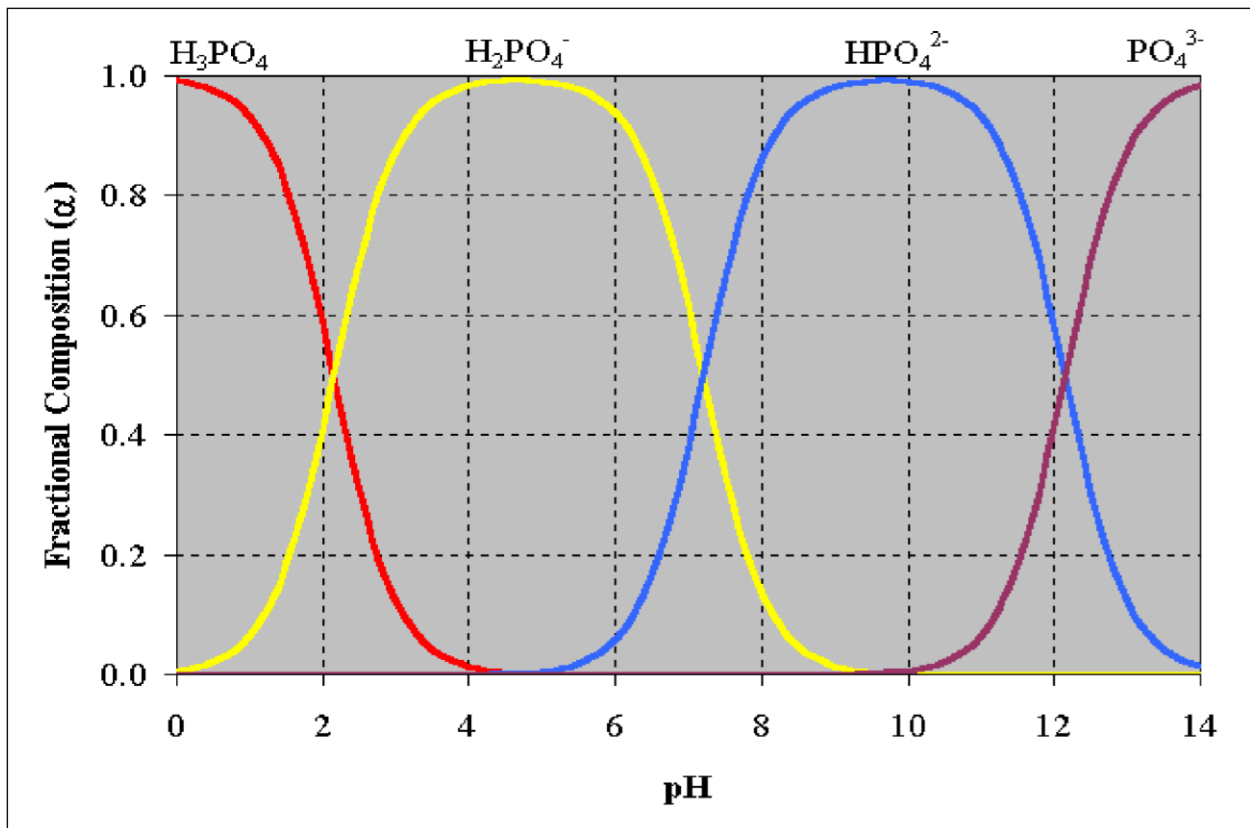


Figure 2.3: Orthophosphate forms in soil solution at different pH levels (van Loon & Duffy, 2017).

The process of mineralisation or immobilisation is carried out by soil microorganisms and is highly influenced by soil moisture, temperature, aeration, pH, cultivation intensity and P fertilisation (Brady & Weil, 2008b). Mineralisation and immobilisation processes are most rapid in well-drained and warm soils (Busman *et al.*, 2002). Mineralisation and immobilisation rates depend on the C:P ratio of residues in the soil. Immobilisation occurs when the C:P ratio exceeds 300:1 while mineralisation is rapid when the C:P ratio is less than 200:1. These processes are in approximate balance when the C:P ratio ranges between 200:1 and 300:1 (Campbell & Edwards, 2001a). It is estimated that up to 50% of the P currently circulating in the global cycle is from anthropogenic sources (Manahan, 2017).

Phosphorus in the soil can be potentially lost through several transport processes in the form of either particulate P or dissolved P. This results in higher levels of P available to organisms like algae in streams, lakes or rivers and the ultimate effect is eutrophication of the water sources (Litaor *et al.*, 2005).

Havlin *et al.* (2016), Frossard *et al.* (2004), classified phosphorus availability using the concepts of intensity factor, quantity factor and capacity factor. The intensity factor gives the concentration of phosphate that is readily dissolved in the soil solution. The quantity factor describes the total amount of phosphorus that is in the soil and may be dissolved and taken up by the plants eventually. The capacity factor expresses the capacity of soils to stabilise the magnitude of the intensity factor even when the quantity factor changes. The relationship between the intensity and quantity factor may provide information on the ability of the soil to resupply nutrients for crop uptake (Brady & Weil, 2008b).

2.6.4 Phosphorus Sorption and Desorption in Soils

The inherent properties that influence the sorption and desorption of native or added P in soil are the effect of pH, greatest degree of P sorption occurs at very low and very high soil pH levels. As pH increases from below 5.0 to 6.6, the Fe and Al phosphates become soluble. As a general principle in mineral soils, phosphorus sorption is at its lowest and plant availability is highest when soil pH is maintained in the range of 6.0 to 7.0 (Shigaki *et al.*, 2006; Havlin *et al.*, 2016). As the soil pH drops from greater than 8 to below 6, Ca phosphate compounds increase in solubility. The nature and amount of minerals present, primary and secondary mineral P solubility, cation effects, anion effect, effect of P saturation, organic matter, texture, moisture, soil temperature and mineralogical composition of the soil (Brady & Weil, 2008b; Muindi *et al.*, 2015) are some of the other properties of P sorption and release.

If large amounts of P accumulate in soil, the capacity of the soil to sorb additional P can be saturated, which may lead to an increased risk for P losses through leaching and surface runoff (Brady & Weil, 2008b). A common way of estimating P sorption capacity is to measure the amount of P sorbed by the soil at different P additions and to construct sorption isotherms. From the isotherms, several sorption indices can be calculated (Fox & Kamprath, 1970).

Sorption reactions and phosphorus buffer capacity (PBC) of soils play important roles in both agronomic and environmental aspects of P management. Sorption isotherms are used to characterise the retention of P and the PBC of soil (Yli-Halla *et al.*, 2002). The capacity of the soil to sorb P significantly influences plant responses to applied P fertilisers and the calibration of soil tests for P. Therefore, knowing the ability of the soil to sorb and desorb (release) P is not only required in providing an accurate estimate on the P fertiliser requirements of soils but also generates accurate information about the fate of applied P fertiliser over time. It is also crucial

for understanding the differences in interaction of P with the soil matrix and quantification of P fluxes between the soil solid and solution phases (Szara & Sosulski, 2012).

2.6.5 Phosphorus Forms and Their Reactions in Soils

Phosphorus is the eleventh most abundant element in the earth crust and its average concentration in the soil has been estimated at 0.1 % W/W. It occurs in the soil almost utterly as phosphate or more specifically as orthophosphate, with an ionic form of PO_4^{3-} . The global phosphorus cycle shows that P is found in the atmosphere in association with dust particles (VanLoon & Duffy, 2017). Terrestrial phosphorus is composed of a number of specific minerals including apatite [$\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$] and vivianite [$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$]. A large part of phosphorus in soil is sorbed to soil particles or incorporated into soil organic matter. The organic part consists of undecomposed biotic residues, microbes and humic matter in the soil, whereas inorganic forms are usually associated with Al, Fe, Ca, Mn and Mg compounds of different solubility. The retention and release of P is controlled by either sorption-desorption or precipitation-dissolution reactions, depending on the environment in the soil or sediment (Havlin *et al.*, 2016).

Phosphorus occurs in the soil in numerous inorganic and organic forms. Inorganic phosphorus (Pi) includes minerals, secondary precipitates formed with Ca, Fe, Al, Mn, Mg and free phosphate ions (HPO_4^- , HPO_4^{2-} , PO_4^{3-} all denoted here as $\text{PO}_4\text{-P}$) attached to sorption surfaces or dissolved in soil water. Organic phosphorus (Po) includes a group of organic molecules having P as part of their structure. Orthophosphate esters are Po compounds having an ester link joining $\text{PO}_4\text{-P}$ to organic moiety. These are further divided into mono and diesters according to the number of ester groups attached to each $\text{PO}_4\text{-P}$. The largest group of Po in most soils is the monoesters (Turner *et al.*, 2002), including sugar phosphates, phosphoproteins, mononucleotides and inositol phosphates.

The inorganic and organic forms of P can be divided into three major pools that are in dynamic equilibrium (Richter *et al.*, 2006): soil solution P, labile P and non-labile P (occluded P pools). The soil solution and labile P represent the available forms of P for immediate crop uptake (Negassa & Leinweber, 2009) and consist of phosphate in the soil solution or phosphate that can be released rapidly or mineralised from inorganic and organic soil compounds (Vandecar *et al.*, 2009). The slowly cycling active P pool is the pool from which P can easily be converted to the labile P pool (Richter *et al.*, 2006). Slowly cycling P is phosphate sorbed onto mostly colloidal soil particles, inorganic and organic phosphate that has reacted with elements such as aluminium

(Al₂) or iron (Fe₂) and calcium (Ca₂), and more stable organic P. The occluded P pool remains in the soil for years without being available to plants and has little impact on soil fertility (Havlin *et al.*, 2016). The occluded pool is represented by inorganic compounds that are very insoluble and organic compounds that are resistant to mineralisation by microorganisms in the soil (Brady & Weil, 2008b).

The organic P is divided into three groups. The first group is the inositol phosphates which constitutes 10 to 50 percent of the total organic P in soils. It is composed of the phosphate esters including all sugar-like molecules which are mostly very stable in alkaline conditions and are likely to react with higher molecular weight compounds. The second group is constituted of phosphate found within nucleic acids (Scheffe & Tymms, 2013). This can be sorbed by silicate clays and humic acids. Most organic phosphates are associated with the fulvic acid fraction of soil organic matter. Organic P compounds can be mineralised and immobilised by soil microorganisms or by plants (Brady & Weil, 2008b).

Diesters including nucleic acids, phospholipids and teichoic acid and aromatic compounds generally occur in smaller concentrations in soil than monoesters. Phosphates form a group of Po that contains a C-P bond. Polyphosphates complicate the simple division of P into organic and inorganic pools since most of them are inorganic but are of biological origin. However, polyphosphates such as ADP and ATP are, chemically, organic compounds (Brady & Weil, 2008b; Bünemann *et al.*, 2008).

Generally, the inorganic forms of P can reach up to 90% of the total P in agricultural soils. The total P in soil depends on the available P fraction and plant uptake. It ranges generally between 0.20 to 2.0 g kg⁻¹ in agricultural soils (Havlin *et al.*, 2016). Only 0.1 percent of the total soil P is available for plants usually as orthophosphate ions, inorganic polyphosphates and organic P (Brady & Weil, 2008b). The soluble P can be readily extracted by water or salt solutions. Solution and labile P are the P fractions that are normally taken up by crops and it is chemically mobile, exchangeable and reactive in soil and water. The labile or more bio-available phosphate is adsorbed to the surface of silica, calcium carbonate, or other soil minerals. The non-labile part corresponds to a fraction of P which is not available for plants due to complexation with metal oxides and hydroxides or bound within mineral compounds e.g. apatite (Daly *et al.*, 2001). Labile and non-labile soil phosphates react to form calcium bound phosphate and iron or aluminium bound phosphate. Non-labile phosphorus is usually incorporated within the matrices of Fe and Al minerals and is quite insoluble in soils (Havlin *et al.*, 2016).

2.6.6 Phosphorus Extraction Methods

About four major forms of soil P are distinguished, i.e., P dissolved in soil water, P sorbed to surfaces of clay minerals or Fe and Al oxides, P in primary phosphate minerals and P in organic substances and living organisms. According to these various P forms, different methods of extracting P have been developed. In routine soil testing many different extraction methods are in use today, i.e. H₂O, CaCl₂, LiCl₂, Trong, Olsen, Bray 1 & 2, Melich 1 & 3, Calcium-acetatelactate (CAL), Fe-oxide Pi, Oxalate, Dithionate, HCl, Ambic 1 & 2 and others (Abbasi & Rasool, 2005; Hue & Fox, 2010; Wuenscher *et al.*, 2015).

Various P extraction methods using acids, organic and inorganic complexing agents, or alkaline solutions have been developed and the extractants often extract all or part of the labile P, which is available to plants during their growth cycle, plus an undefined proportion of other forms of soil P (Kovar & Pierzynski, 2009). It is because several soil properties influence P extraction, which is not surprising since there is not one best extractant for all conditions. It has also been reported widely that P sorption isotherms have a distinct advantage over extraction methods in predicting the efficiency of plants to utilise the P that is available (Hue & Fox, 2010).

2.6.7 Phosphorus Status of South African Agricultural Soils

Soils in South Africa are naturally low in phosphorus, and most cropping systems on these soils require supplemental phosphorus to maximise their yield (STAFF, 2004). Research recognises that applying fertiliser phosphorus increases crop growth and yields on soils that are naturally low in phosphorus and soils that have been depleted through crop removal. Consequently, crop fertilisation remains the greatest hope of phosphorus in agriculture today (Mullins, 2009).

Agricultural crop production levels under the smallholder systems of South Africa are reportedly low due to poor natural soil fertility coupled with low usage of organic and inorganic fertilisers with P being one of the nutritional factors limiting crop production (Laker, 2005a; Mandiringana *et al.*, 2005). Mandiringana *et al.* (2005) also reported that almost 100% of the garden and field soils in three Transkei districts of Elliotdale, Umatata and Mt Fletcher districts were acidic, indicating that they had the potential to sorb added P. Studies on P sorption for some South African soils reported by Henry & Smith, (2002); Henry & Smith, (2006) that majority of the soils had high sorption capacities ranging from 500 to 1197 mg P kg⁻¹ of soil. Their studies showed that the highest sorbers were weathered red or yellow-brown clays with high oxalate (amorphous) aluminium content, especially in soils with a humic-horizon (Mandiringana *et al.*,

2005). Many of the soils, also found in most parts of NWP, are also suspected to have high P sorption capacities, particularly those from high rainfall areas which tend to be acidic with low to medium base status. In South Africa, inorganic P fertiliser costs are highest of all nutrients yet its deficiency in soils must be supplemented by inorganic P fertiliser addition (Henry & Smith, 2006).

2.6.8 Phosphorus Sorption and Sorption Isotherms

Sorption is the movement of materials or molecules from one phase to another. There are two types of sorption namely ‘Adsorption’ and ‘Absorption’. Adsorption is a surface phenomenon whereby molecules of a substance are attracted to the surface while the absorption takes place when the molecules are distributed uniformly in the bulk of the interaction phase (i.e. dispersed throughout the bulk of the absorbing material) (Wankasi, 2013). In other words, adsorption is the net accumulation of chemicals at the interface between solid phase and aqueous solution phase which determines the availability of native soil nutrients and the rate of nutrients to be applied to soil as fertilisers. Phosphorus adsorption is the process in which phosphorus ions are held on active sites of soil surfaces (Khan *et al.*, 2010).

Soils have the property of holding or binding molecules on their surfaces. When a molecule approaches a soil surface, it encounters a net attractive potential because the molecules on the surface are under the influence of unbalanced forces, whereas molecules within the soil are subjected to equal forces in all directions. This behaviour is usually more intense in the case of soil solid compared to liquids. Sorption takes place in order to reduce the unbalanced forces that attract each other, thereby reducing surface free energy of the soil solid (Brady & Weil, 2008a).

Sorption isotherms play an important role in the study of soil phosphorus which has been used to estimate phosphorous concentration in aqueous phase of soil, energy of phosphorous adsorption, maximum value of its adsorption by soil, buffer strength of soil against phosphorous concentration variations in solution and equilibrium state between phosphorous in aqueous and solid phases and their relationship (Olsen & Watanabe, 1957; Onweremadu, 2007). The isotherms can be described as the equilibrium relationship between the amounts of adsorbed and dissolved phosphate at constant temperature in quantitative terms. They are explained by fitting the isotherms and their mathematical descriptions using Langmuir, Freundlich, or Temkin, isotherm models (Hoseini & Taleshmikael, 2013; Khan *et al.*, 2010). Their use also allows summarising results and reducing the sorption data to comparable values. These models can

discriminate soils based on their ability to sorb P from soil solutions. They also give an insight into the strength of P-adsorption on the surface of a particular soil (Wolde *et al.*, 2015).

2.6.9 Standard Phosphorus Requirement (SPR) of Soils

This is an approach that uses standard fertiliser P requirement (SPR) concept. It represents an effort directed at improving the empirical processes of calibrating soil P tests for fertiliser P recommendations based on soil P status. The hypothesis of this approach to estimating P requirements is that fewer costly field experiments are required if SPR values can be successfully predicted from the sorption data. The SPR of crops has been defined as the concentration of P in solution known to be non-limiting to plant growth (Henry & Smith, 2004). Lopez-Hernandez *et al.* (1987) reported that for a given climate and provided that the soil contains sufficient clay (5% or more) to ensure adequate reserves of labile P, the standard P requirement applies and it is a crop constant and independent of soil texture and clay mineralogy. Henry and Smith (2003) reported that the standard P requirement decreases with increasing additional P. This shows that P-isotherms are useful for making fertiliser recommendations as they are sensitive enough to differentiate between low and high P status in the same soils and respond to build-up of the soil P content by fertilisation. The data obtained from P isotherms may be used to optimise P application based on plant needs while at the same time minimising possible P loss to surface waters through runoff.

The amount of P to be added to maintain an equilibrium concentration of 0.2 mg P l⁻¹ (P 0.2) in soil solution is a threshold for many crops, over which no response to P is observed (Beckwith, 1965). Though the P concentration required by plants varies, P 0.2 (mg P kg⁻¹) has been used as a standard for comparing P requirements of different soils (Duffera & Robarge, 1999). In some instances, however, it is necessary to determine fertiliser P requirement at other P concentrations besides 0.2 mg P (Bray P-1) as the critical value is dependent on plant species and agronomic factors (Fox, 1981). In South Africa, a standard or external P requirement factor of 0.11 mg P has been reported as suitable for low to moderately P fixing soils of the tobacco growing areas of Kwa-Zulu-Natal (Henry & Smith, 2006). Regrettably, information on fertilizer P requirements of soils of NWP are scanty in the literature thus the importance of the current study.

2.7 The Causes of Soil Fertility Decline in South African Farmland

To meet the food demands of a rapidly growing population, vast areas of land are being cultivated under intensive systems and large areas of grass and forest lands overgrazed and deforested in the process. Land use changes and soil management also have a marked effect on soil fertility

(Aluko and Fagbenro, 2000), mainly in the conversion of natural ecosystem to farm land which results in decline of soil physical, chemical and biological processes (Jamal *et al.*, 2010). Khalili *et al.* (2011) reported that prolonged intensive cultivation of crops resulted in the deterioration of plant nutrients worldwide. Deforestation and cultivation of virgin tropical soils often lead to depletion of N, P, sulphur (S) and other plant nutrients due to nutrients mining and poor soil management that lead to aluminium (Al), iron (Fe) and manganese (Mn) toxicity which increase soil acidity (Aluko & Fagbenro, 2000; Pound & Jonfa, 2005). The decline of SOM is the basic cause of fertility degradation in soils: all the chemical, physical and biological problems follow a decline in organic matter content. Some of the factors that have contributed to the decline in SOM in South African soils are cereal production under monoculture, intensive tillage, and virtual absence of crop rotation systems in the commercial sector and overgrazing (Pound & Jonfa, 2005; Kotzé *et al.*, 2013; Dlamini *et al.*, 2014).

Soil fertility in South Africa is declining because of soil loss, nutrient and organic matter (OM) depletion (Mandiringana *et al.*, 2005; Abreha, 2013; Kotzé *et al.*, 2013). Soil acidity is also recognised as a serious problem in most agricultural soils of South Africa and the single most significant cause of soil fertility decline (Barnard & Du Preez, 2004). Some soils in South Africa are naturally acidic, especially those that are poorly buffered in high rainfall areas. This problem is largely caused by anthropogenic activities (continuous cropping, prolonged cultivation of cereal crops, deforestation and overgrazing, intensive cultivation of crops, soil mismanagement, bush burning and industrial mining activities resulting in declining levels of organic matter). In addition, the application of excessive amounts of reduced forms of nitrogenous fertilisers is a major contributor to the decline in soil fertility in South African farmlands (Barnard & Du Preez, 2004).

2.8 Agricultural Implications of Low Soil Fertility in South Africa

Low soil fertility contributes to food insecurity and malnutrition, the biggest risk factor for human illness and disease (Clair & Lynch, 2010; DeFries *et al.*, 2012). Soils with low fertility contribute to human malnutrition in two important ways: firstly, they reduce crop yields, causing food scarcity and results in protein energy malnutrition. Secondly, crops produced on nutrient poor soils typically have low tissue concentrations of trace elements (Clair & Lynch, 2010; Sánchez, 2010).

Impoverished soil fertility threatens food production in many parts of world including South Africa where smallholder farming is practiced (Mafongoya *et al.* (2006) and the problem is

exacerbated by a wide range of biophysical, chemical and socio-economic factors. The geological origin of the parent materials may have contained few nutrient bearing minerals. Nutrient depletion and nutrient balances are negative for many cropping systems, indicating that farmers are mining their soils (Mandiringana *et al.*, 2005; Yusuf & Yusuf, 2008; Fanadzo *et al.*, 2010; Dube *et al.*, 2012).

In the Eastern Cape province, poor soil fertility is attributed to low geological reserves of essential plant nutrients, low soil organic matter (SOM) levels, continuous monoculture (without adequate nutrient replenishment) and tillage induced soil erosion (Mandiringana *et al.*, 2005). Improvements in SOM could result in several benefits in these soils, including improved soil nutrient storage capacity, nutrient availability, biological activity, soil structure and resistance to erosion (Brady & Weil, 2008b).

The problem of soil fertility decline has become endemic in critical ecosystems like South Africa. Farmers in marginal ecosystems often plough the soil, denying the soils fallow periods essential for soil regeneration. This has led to soil crisis and farmers are aware that soil crisis cascades into food crises (FAO, 2009). This affirms the point that achieving adequate food security is a necessary step towards the alleviation of poverty, hunger and sustainable economic growth which are all important components of the NDP in SA. South Africa has a highly successful commercial agriculture, despite generally poor soil fertility and climatic factors compared with international situations. However, there is cause for concern with regards certain fertility trends (Laker, 2005b). The same author also reported that agricultural soils of the NWP are renowned for their low fertility due to continued mining of nutrients and poor agricultural practices that have consequently reduced yield and nutritional quality of produce (Laker, 2005b).

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CHAPTER THREE

PHYSICAL FERTILITY INDICATORS OF SOILS OF SELECTED CROP FIELDS AND GRAZING LAND IN NORTH WEST PROVINCE OF SOUTH AFRICA

3.1 Abstract

Physical fertility indicators represent the foundation for expressing chemical fertility of the soils fundamental to plant growth. This study assessed the soil physical fertility indicators of twelve different farmlands with distinct land use types and soil characteristics. One hundred and eighty surface and sub-surface soil samples were collected from four districts, distributed randomly across smallholder crop farm, commercial crop farm and communal grazing land, and analysed for selected physical indicators including bulk density (BD), total porosity (TP), water holding capacity (WHC), particle size distribution (PSD) and silt/clay ratio. Computed mean values of these parameters were compared with established critical limits. The findings showed that soil texture belongs to three textural classes: loamy sand, sandy loam and sandy clay loam. Results of the soil physical indicators significantly ($p \leq 0.05$) varied across location, land use and soil depth. The values of WHC range from 57.71% in Communal grazing land (CGL) to 63.7% in smallholder crop farm (SCF), BD range from 1.27 g/cm³ in SCF to 1.33 g/cm³ in commercial crop farm (CCF), TP range from 49.85% in CCF to 52.10% and silt/clay ratio range from 1.22 in CCF to 1.40 in CGL. The soil physical fertility indicators of the various farmlands suggest that sustainable agricultural production could be practiced based on the critical limits.

Keywords: land use types, critical limits, bulk density, soil porosity, water holding capacity, soil texture.

3.2 Introduction

Physical fertility indicators of soil refer to the ability of the soil to provide water, air, and spaces to the root environment of plants (Glinski, 2018). It could also be described in terms of its texture (particle size distribution), bulk density, particle density, porosity, water holding capacity, moisture content, temperature, friability and other parameters (Brady & Weil, 2013). Agricultural production depends much on the physical fertility indicators of soil and mainly those specific indicators relating to water holding and transmission capacities (Indoria *et al.*, 2017). Most physical fertility indicators of soil have important effects on the chemical and biological soil indicators, and these in turn influence plant growth (Delgado & Gómez, 2016). The composition of physical fertility indicators of soil can impede or foster root development, shoot

emergence and has effects on nutrient supply and pH (Rogers, 2015). It also plays a functional role in supporting capability of crops, movement, retention, availability of water, nutrients to plants, the penetration of roots, flow of heat and air (Phogat *et al.*, 2015).

Soil physical indicators closely relate to agricultural land use types, cropping systems and their management practices (Agbede, 2010; Yuan *et al.*, 2020). There is serious concern that agricultural production could change physical fertility indicators of soils, as successful agricultural production requires the sustainable use of soil physical indicators (Indoria *et al.*, 2017). However, soil physical fertility indicators, including resilience characteristics, can decline rapidly within a short time (Brady & Weil, 2002). Arable farmlands in the North West Province (NWP) currently face the problem of soil physical fertility decline due to overgrazing, poor soil management and erosion (Moussa, 2007). In combating the on-going soil physical fertility problems with concerted efforts towards enhancing crop yield through bearable use of soil resources, there is need to determine the status of the soil physical fertility indicators of the different land use types. This knowledge of the soil physical fertility indicators is essential in defining and improving soil management practices to achieve optimum agricultural production (Dexter, 2004; Indoria *et al.*, 2017). However, little information is available on the physical fertility of the study area. Therefore, this study assessed the soil physical fertility indicators across the different fields studied. We hypothesized that there is no variation in soil physical indicators across the different fields in the study areas.

3.3 Materials and Methods

3.3.1 Description of the Study Area

The study was conducted on farmlands located in four districts of NWP of South Africa where crop cultivation and animal grazing are practiced. The districts are Dr Ruth Segomotsi Mompati (Taung) in the west, Ngaka Modiri Molema (Itsoseng) in the central part, Bojanala (Mathopetstad) in the eastern part and Dr Kenneth Kaunda (Ventersdorp) in the south of the province (Figure 3.1). Geographical co-ordinates of the study area span between 24 38' 10" S and 26 27' 7" S latitude, 22 37' 44" E and 28 57' 20" E Longitude. North West Province is situated in the extreme national border part of South Africa and shares precincts with four other Provinces: Northern Cape to the west, Free State to the south, Gauteng and Limpopo to the east and an international border with Botswana to the north. The province is also fringed by the Kalahari Desert in the west (READ, 2014). It is the sixth largest of the nine provinces in South

Africa, and covers a total land area of 116 320 km² (Walmsley & Walmsley, 2002), representing

9.7% of the total surface area of South Africa (Masigo & Matshego, 2005). The area is relatively uniform in terrain with flat topography in the western and central parts and rolling topography in the east while the altitude ranges between 800 to 1100 m (Mangold *et al.*, 2002).

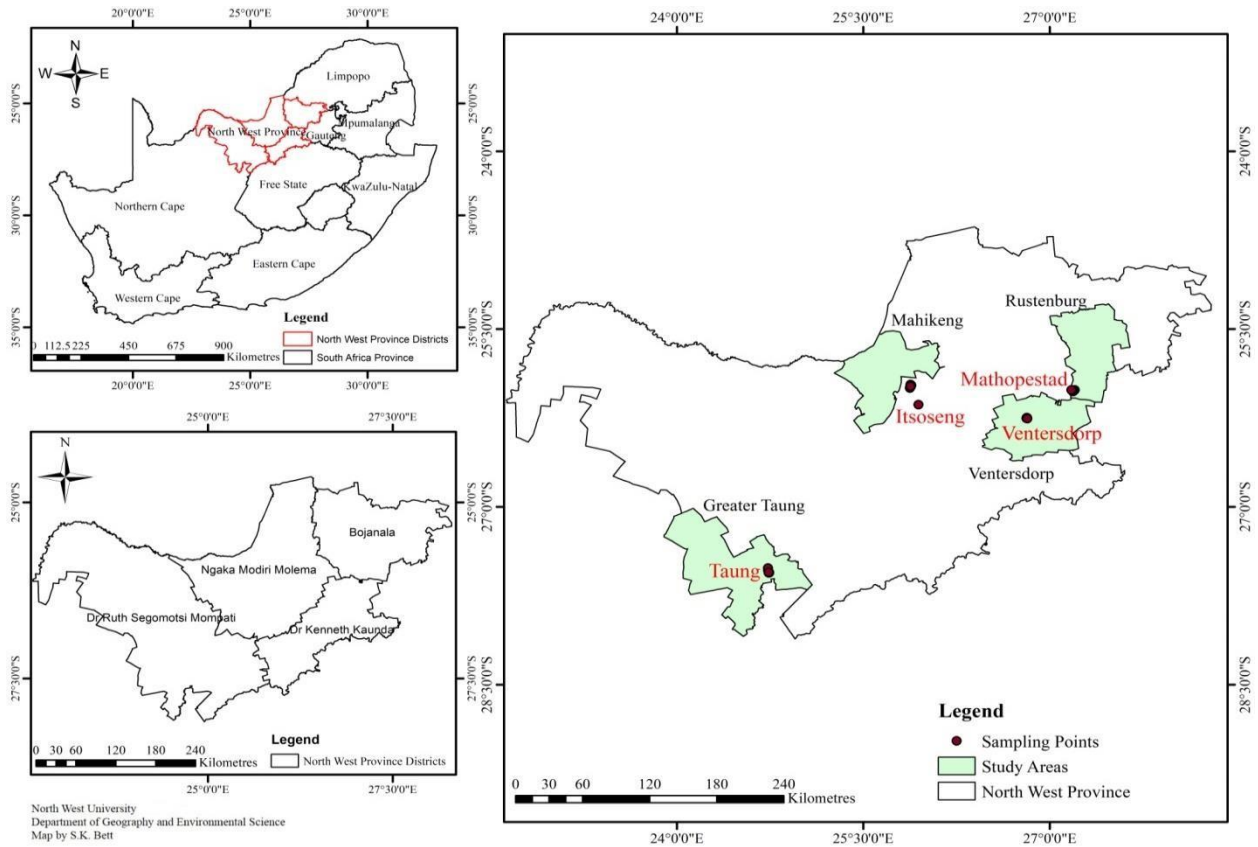


Figure 3.1: Map of the study area in North West Province of South Africa

3.3.2 Climate of the Province

The province is semi-arid with rainfall pattern varying from east to west, with the eastern part of the region being wetter than the western part of the region. Three different rainfall regimes are distinguished annually in the North West Province: 600 to 700 mm in the east, between 500 to 600 mm in the central, 400 to 500 mm in the west and less than 300 mm in the Kalahari area (Sanchez, 2002); Moussa, 2007).

The mean annual pan evaporation of North West Province is about 1800mm (Mangold *et al.*, 2002). Temperatures vary between extremes of -6.0° in the winter and 40°C in summer with an average of 19°C . The average mid-summer maximum temperatures vary from the high twenties to thirties (degrees Celsius) while the minimum in winter usually varies in the teens (Mangold *et al.*, 2002; Walmsley & Walmsley, 2002).

3.3.3 Vegetation

About 71.35% of the vegetation of NWP falls within savannah biome while the remainder falls within the grassland biome (Walmsley & Walmsley, 2002). There are four major ecological zones in the province: (i) the Highveld in the South-east, (ii) the Bushveld in the north-east, (iii) the Middleveld as a narrow zone between the Highveld and the Bushveld and (iv) Kalahari Desert in the west (Walmsley & Walmsley, 2002; Mucina & Rutherford, 2006).

3.3.4 Geology and Agricultural Activities in North West Province

The province comprises an ancient geological heritage which is rich in minerals and artefacts. The north eastern and north central regions are largely dominated by igneous rock formations. Ancient igneous volcanic rocks dating back to the Ventersdorp age are dominant formations in the western, eastern and southern regions of the province, whereas sedimentary rocks of the Quaternary period occur in the north western part (Moussa *et al.*, 2009; Venter *et al.*, 2012). These formations constitute the parent materials from which the soils are derived.

Agricultural activities in the province are pasture and forestry, cattle ranching and wildlife related tourism (Masigo & Matshego, 2002). Irrigated agriculture is widely practiced in association with ostrich and chicken farming (Kasirivu *et al.*, 2011). The major crops across the province are maize (*Zea mays L.*), sunflower (*Helianthus annuus*), groundnuts (*Arachis hypogaea*), sorghum (*Sorghum vulgare*) and vegetables such as spinach (*Spinacia oleracea*), cabbage (*Brassica oleracea*), beetroot (*Beta vulgaris*), and onions (*Allium cepa*) (Materechera, 2010).

3.3.5 Soils of the Study Area

Soils of the study area are largely shifting sands in the north-western region with plinthic catena of yellowish-brown sandy loams characterising the south and eastern regions. The soil in the central region is dominated by red or brown non-shifting sands with rock as well as weakly developed lime soils associated with dolomite formations. The south-western region is characterised by undifferentiated rock and lithosol, shallow soils containing coarse fragments and rock at depths less than 30 cm. The north-eastern region has lithosols of arenaceous sediments. The southern and central regions are dominated by black and red clay as well as ferrisiallitic sands, loams, and clay. The drier western region is characterised by red to yellow arenosols, while the southwest has calcareous sands, loams and arenaceous lithosols (De Villiers and Mangold, 2002). The clays are either alluvial or derived from dolerite outcrops, Mispah and Arcadia soil forms while the sandy loams are derived from granite (Materechera, 2016). There

are many intergradations within and between these broad types. The predominant soil profiles are made up of orthic topsoil with red apedal B-horizon which, according to the local classification system, belongs to the Hutton formandare characteristically similar to a Ferric Luvisol (Group & Macvitar, 1991; WRB, 2006).

3.3.6 Soil Sample Collection

Soil sample collection was made from one smallholder crop farm, one commercial crop farm and one communal grazing land area in each of the four districts, Mathopetad (Bojanala), Itsoseng (Ngaka Modiri Molema), Ventersdorp (Dr Kenneth Kaunda) and Taung (Dr Ruth Segomotsi Mompati (Figure 3.1). Twelve farms across all districts were sampled randomly and georeferenced. Table 3.1 presents the list of the study locations with the geo-references of the sampling points and land area. Soil samples were collected from 5 sampling points in each site, using a soil auger and hand trowel at a depth of 0-15cm, 15-30cm and 30-45cm. The samples were bagged, labelled and transported to the laboratory for analysis. The air-dried samples were crushed with a mortar and pestle, sieved through 2 mm sieve, and bagged with proper labelling.

A total of 180 soil samples were collected for this study.

3.3.7 Laboratory determination of the soil physical indicators

The processed soil samples were used to determine the selected soil physical fertility indicators namely bulk density, porosity, particle size and water holding capacity.

3.3.8 Procedures for physical analysis

Soil samples collected were subjected to selected critical physical determinations that relate to soil fertility management with the following specific procedures.

3.3.9 Bulk Density (BD) and Total Porosity (TP) Determination

Bulk density determination was based on the method described by Estefan *et al.* (2013) using a core method. The core sampler with a diameter of 5.2 cm and 10.2 cm height was driven into the soil, far enough to reach the sampling depth and filled the inner cylinder with soil without compacting the sample. The soil sample was carefully removed, bagged and taken to the laboratory. The wet weight of the soil samples was taken and recorded. Samples were then dried at 105°C in the oven to a constant weight after which the bulk density and total porosity were recorded. Total porosity was computed from the equation $PS (\%) = PD - BD / PD \times 100$.

Table 3.1: Soil Sample Location/ Sampling Points and Land Area

Study Location	Sampling Unit	Number of samples	Land Area (ha)	Land Area of study (%)	Cropping history/ vegetation cover
MATHOPES TAD	SCF S 26° 00' 47.3" E 027° 12' 05.7"	Sampling units comprises five sampling points namely.RS1 – RS5 (5)	.5	0.4	The farm has been under maize, beans and vegetable production for some time and was fallow for about 2 years before sampling. Cattle manure was applied while it was under cultivation.
	CCF S26° 01' 23.7" E027° 11' 30.3"	RC1 - RC 5 (5)	10	8	Booyskaal commercial crop farm was cultivated with sunflower maize a year ago. Fertiliser application was done with KAN (36:32.78) NPK (8:1:0) and NPK+Zn (6:22:1:31).
	CGL S26° 01' 23.7" E027° 11' 30.3"	RG1 - RG5 (5)	20	16	Communal grazing land was gently sloppy and flooded during the summer rainy season.
ITSOSENG	SCF S26° 08' 15.2" E025° 56' 40.0"	LS1 – LS5 (5)	.5	0.4	The area was for vegetable production but fallow for the about 2 years:
	CCF S25° 59' 25.6" E025° 52' 47.9"	LC1 – LC5 (5)	10	8	Area planted a year ago with sunflowers. Fertiliser was applied NPK (3:2:3), manure and lime ammonium nitrate (LAN) were used for top-dressing.
	CGL S25° 58' 53.0" E025° 52' 50.1"	GL1 – LG5 (5)	20	16	Land area was for cattle and sheep grazing and covered with grasses, small shrubs and a few trees.
VENTERSD ORP	SCF S26° 14' 53.4" E026° 48' 54.8"	KS1 – KS5 (5)	2	1.6	Smallholder crop farm was a stony area and last planted with sorghum, beans, cabbage, tomatoes, spinach and carrot a year ago. NPK (3:2:1) fertiliser was applied when under cultivation. Stones and gravel were encountered at 30-45cm depth.
	CCF S26° 14' 57.8" E026° 49' 04.3"	KC1- KC5 (5)	10	8	Ventersdraai commercial crop farm was for maize production and was under continuous cropping. It was planted twice yearly with NPK. (4:2:1) fertilizer application made.
	CGL S26° 15' 04.7" E026° 48' 46.6"	KG1 – KG5 (5)	20	16	The communal grazing area was covered with grasses and shrubs and a few small trees.
TAUNG	SCF S27° 32' 05.5" E024° 44' 06.3"	TS1 – TS5 (5)	2	16	Tshenolo coop smallholder crop area was planted with cabbage and carrot a year ago. Fertiliser application was made during planting with NPK (2:3:1).
	CCF S27° 33' 16.6" E024° 44' 17.4"	TC1 – TC5 (5)	10	8	MS 2.1 (Ipelegeng) was planted with maize/ barley and groundnuts a year ago. Fertiliser was applied on the farm, NPK (7:2:1).
	CGL S27° 33' 23.0" E024° 44' 28.1"	TG1 – TG5 (5)	20	16	Land area was sparsely covered with grasses, shrubs and a few trees.
TOTAL HECTRAGE		60	134		

3.3.10 Particle Size Analysis (PSA)

Particle size determination was by hydrometer method as described by Okalebo *et al.* (2002). Fifty (50) gm air-dried 2 mm sieved soil sample was weighed into 400 ml polyethene bottle and 25 ml of 5% of sodium hexametaphosphate (calgon) dispersing solution, 200 ml of tap water was added and covered with a lid and mixed thoroughly. Samples in well-labelled bottles with cork were transferred into a reciprocal shaker followed by 30 minutes of shaking for dispersion. Thereafter, the dispersed content of each sample bottle was completely transferred and washed into one litre cylinder and made up to a litre mark with distilled water. The content of the cylinder mixed at least 10 times through end to end with the palms and the cylinder placed on the bench and the time immediately noted. After 15 seconds, a hydrometer was gently placed into the suspension and hydrometer reading taken after 40 seconds with the temperature reading simultaneously recorded; and this gives the weight of silt and clay in the 1 litre suspension. After 2 hours, the hydrometer and temperature readings were recorded, temperature correction was made using the table as in Okalebo *et al.*, (2002) and calculations were made to obtain the different size fractions to obtain the value for sand, silt, and clay under standard temperature.

3.3.11 Water Holding Capacity (WHC)

Soil water holding capacity (WHC) was determined using the method as described by Estefan *et al.* (2013). Thoroughly air-dried 2 mm soil sample was mixed and 100 g weighed into a filter paper in a funnel attached to a conical flask. The funnel filled with 100 ml of water using a graduated measuring cylinder until the sample was covered. The amount of water added was recorded and left to set until the sample was fully saturated. Water was drained into a conical flask for about 24 hours and the amount of water collected in the flask was measured with a graduated measuring cylinder and recorded. Water holding capacity was calculated using the formula: Water Holding Capacity (ml/l) = Water retained (ml)/100ml sample x10.

3.3.12 Data analysis

Evaluation of the physical fertility indicators of soils in the study area was made on the parameters from the laboratory analyses. In other words, the results of the laboratory analyses were compared with critical levels for different classes of the respective parameters in evaluating the physical fertility indicators of soils. Data on laboratory analysis on soil samples were subjected to a one-way analysis of variance (ANOVA). Mean separation was done using Duncan multiple range test and correlation analysis was performed to determine the degree of association

between the measured parameters. Statistical tests were conducted using GenStat Release Version 10.3 DE software package.

3.4 Results

3.4.1 Physical indicators of the soils from different land use types

The key selected physical indicators of soils that relate to fertility such as texture, silt/clay ratio, water holding capacity, bulk density, and total porosity results are presented in Table 3.2. The measured contents of these indicators were significantly different across the four locations ($p \leq 0.05$), land use types and soil depths. Soil samples at Taung had the highest mean sand content (73.16%) while soils from Ventersdorp had 57.90% sand content. The mean sand content in soils at Itsoseng and Mathopestad were not significantly different ($p \geq 0.05$). Soil samples obtained at Ventersdorp had the highest silt proportion (24.96%), which was significantly different from the other locations. On the other hand, mean clay content in soils at Mathopestad was significantly higher than soils at all other locations while the silt/clay ratio was highest at Taung (1.81) and differed significantly at other locations. The highest mean TP of 66.06% in soils recorded was at Mathopestad, which differed significantly from the values recorded at other locations with the lowest value of 53.67% recorded at Taung.

The recorded mean soil BD differed significantly across the different locations with the highest value (1.41 g/cm^3) in soil samples collected at Taung, which was not statistically different from soil samples collected at Ventersdorp. However, soils from Mathopestad had the least mean BD value of 1.13 g/cm^3 . The recorded mean WHC of 57.49% in soils at Mathopestad was highest and differed significantly from the measured mean values at other locations with the least mean value of 46.89% recorded in the soil sample at Taung.

There was a significant variation in the three primary soil particles (sand, silt and clay) across the land use types ($p \leq 0.05$). The highest recorded mean sand content of 67.35% was on the communal grazing land (CGL) while the lowest mean value of 62.06% was on smallholder crop farm (SCF). The highest mean silt content of 19.14% was in SCF and the least recorded silt content value of 16.61% was in CCF. Although there was a significant variation in the mean clay content across land use types, the difference in mean clay content obtained in CCF and SCF was statistically the same but the highest value of 18.89% was SCF. The highest recorded silt/clay ratio of 1.40 was from CGL while the least ratio of 1.22 was on CCF. The TP values differed significantly across the variety of land uses with the highest mean value of 63.67% obtained in SCF and the least value of 57.71% in CGL. There was no significant difference in the mean BD

values measured across the land use types but CCF recorded the highest mean BD of 1.33 g/cm³ while SCF recorded the lowest value of 1.27 g/cm³. There was a significant variation in WHC ($p \leq 0.05$) across land use types.

Table 3.2: Effect of variation in location, land use types and soil depth on mean values of measured soil physical indicators

Treatments	Sand %	Silt %	Clay %	Si/C Ratio	TP %	BD g/cm ³	WHC %	STC
Locations								
Itsoseng	63.10b	19.14b	17.48b	1.19c	63.83b	1.29b	51.47b	SL
Mathopestad	64.72b	10.35d	24.92a	0.60d	66.06a	1.13c	57.49a	SCL
Taung	73.16a	15.94c	11.25c	1.81a	53.83d	1.41a	46.89c	SL
Ventersdorp	57.90c	24.96a	17.22b	1.54b	57.67c	1.39a	47.70c	SCL
LSD (0.05)	2.37	2.14	2.12	0.27	1.53	0.09	3.31	
Land use types								
CCF	64.75b	16.61b	18.38a	1.22	59.67b	1.33	49.85b	SL
CGL	67.35a	17.05b	15.89b	1.40	57.71c	1.31	50.72a	SL
SCF	62.06c	19.14a	18.89a	1.24	63.67a	1.27	52.10a	SL
LSD (0.05)	2.05	1.85	1.84	NS	1.33	ns	2.87	
Soil depth (cm)								
0 – 15	65.88a	18.54	15.64b	1.56a	59.88a	1.31	50.89	SL
15 – 30	65.60a	17.08	17.40b	1.28b	60.33a	NA	NA	SL
30 – 45	62.68b	17.17	20.12a	1.01c	60.83a	NA	NA	SL
LSD (0.05)	2.05	ns	1.84	0.24	ns	na	na	

Main effect means within a column followed by the same letters are not significantly different from each other at $p \leq 0.05$; NS = not significant; STC = soil texture class; SL = sandy loam; SCL= sandy clay loam; TP = total porosity; CCF = commercial crop farm; CGL= communal grazing land; SCF= smallholder crop farm; NA = not applicable.

There was a significant variation in the three primary soil particles (sand, silt and clay) across the land use types ($p \leq 0.05$). The highest recorded mean sand content of 67.35% was on the communal grazing land (CGL) while the lowest mean value of 62.06% was on smallholder crop farm (SCF). The highest mean silt content of 19.14% was in SCF and the least recorded silt content value of 16.61% was in CCF. Although there was a significant variation in the mean clay content across land use types, the difference in mean clay content obtained in CCF and SCF was statistically the same but the highest value of 18.89% was SCF. The highest recorded silt/clay ratio of 1.40 was from CGL while the least ratio of 1.22 was on CCF. There was no significant difference in the mean BD values measured across the land use types but CCF recorded the

highest mean BD of 1.33 g/cm³ while SCF recorded the lowest value of 1.27 g/cm³. There was a significant variation in WHC ($p \leq 0.05$) across land use types.

There was significant variation in sand content at various soil depths with the recorded highest mean sand content of 65.88% obtained at the surface 0 - 15 cm depth while the least value of 62.68% was at 30 - 45 cm depth. There was no significant variation in silt content at soil depth but the highest mean value of 18.54% was at 30 – 45 cm depth while the lowest value of 17.07% was at 15 - 30 cm depth.

There was significant variation in clay content at soil depths. The highest recorded mean clay of 20.12% was at 30 - 45 cm while the least mean value of 15.64 % was at 0 - 15 cm depth. Silt/clay ratio was significantly different across depth and the highest (1.56) obtained at 0 - 15 cm and lowest (1.01) at 30 - 45 cm depth. Total porosity was not statistically significant at soil depths although, the highest recorded mean content of 60.83% was at 30 – 45 cm and the least (59.88%) was at 0 - 15 cm depth. Highest BD and total porosity values of 1.33 g/cm³ in CCF and 52.10 % in CGL respectively were in the surface soils. Generally, the soil textural classes were sandy loam at both Itsoseng and Taung but sandy clay loam at both Mathopestad and Ventersdorp while the different land use types are dominated by sandy loam textural class at the surface 0– 30 cm depths but sandy clay loam texture at depths beyond 30 cm.

3.4.2 Interaction effect of location, land use and soil depth on physical indicators of soil

Interaction effect of location, land use types and soil depth on TP and sand fraction are presented on Table 3.3 and appendix 1-3. The TP was significantly influenced by interaction effect of location, land use and soil depth. The highest mean TP of 70.50% was in soil sample obtained at 0 – 15 cm soil depth at Itsoseng under SCF and the least value of 49.50 % was at Taung CGL from 0 – 15 cm depth. Sand particle distribution was highest (80.8%) at Taung at 0 - 15 cm depth. Conversely, the least sand (54.1%) was observed at Ventersdorp CGL at 30 – 45 cm depth.

Table

3.3: Interaction effect of location, land use and soil depths on TP and sand particles in soils from North West Province

Land use	Location	TP (%)			Sand (%)		
		0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
CCF	Itsoseng	60.5ghijk	62.0efgh	64.0cdefgh	62.5efghijkl	58.2hijkl	56.2l
CGL		61.0ghij	59.5ghijklm	60.0ghijlmk	68.8cdefg	71.7bcd	66.0defghi
SCF		70.5a	67.0abcde	70.0ab	62.4efghijkl	62.0efghijkl	60.8fghijkl
CCF	Mathopestad	61.5fghij	63.5defgh	66.5abcdef	65.1defghijk	70.0bcde	62.4efghijkl
CGL		65.0bcdefg	67.0abcde	64.5cdefg	65.2defghijk	66.3defgh	59.4hijkl
SCF		70.0ab	69.0abc	67.5abcd	69.3cdef	65.4defghij	59.4hijkl
CCF	Taung	50.5pq	53.5nopq	53.0opq	76.8abc	75.6abc	77.6ab
CGL		49.5q	49.0q	48.5q	80.8a	81.2a	80.4a
SCF		58.5hijklmn	60.5ghijk	61.5fghij	62.4efghijkl	62.8efghijkl	60.8fghijkl
CCF	Ventersdorp	59.5ghijklm	60.5jklmno	61.0ghij	59.2hijkl	57.2ijkl	56.8jkl
CGL		55.0kmnop	56.5ijklmno	57.0ijklmno	58.1hijkl	56.4kl	54.0l
SCF		57.0ijklmno	56.0kmnop	56.5ijklmno	60.5ghijkl	60.5ghijkl	58.5hijkl

Interaction effect within a column followed by the same letters is not significantly ($p \geq 0.05$) using Duncan's multiple range test at $p \leq 0.05$, CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

The interaction effect of location, land use and soil depth on silt and clay samples are presented on Table 3.4. Smallholder crop farm at Ventersdorp obtained the highest (26.5%) silt at 30 – 45 cm depth, the least silt value (4.4%) was obtained in CCF at Mathopestad at 15 – 30 cm depth and there was significant variation across location, land use and soil depth. The highest (30.6%) clay was observed at Mathopestad CCF at 30 - 45 cm depth and the lowest value (5.8%) was recorded at Taung CGL at 0 – 15 cm depth. Clay significantly varied across location, land use and soil depth.

Table

3.4: Interaction effect of location, land use and soil depths on silt and clay particles in North West Province

Location	Land use	Silt (%)			Clay (%)		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	19.9abcdeghi	21.6abcdegh	19.5abcdeghij	18.16cdegh	20.2bcdegh	22.6bcdegh
	CGL	17.3cdeghijkl	14.5ghijklmn	18.6bcdeghijk	13.8hijkl	13.8hijkl	15.4ghij
	SCF	22.2abcdegh	21.00abcdegh	18.2bcdeghijk	15.4ghij	17.0deghi	21.5bcdegh
Mathopestad	CCF	7.5mno	4.4o	7.8no	26.9ab	25.7abc	30.6a
	CGL	14.2hijklmn	11.0klmno	16.6deghijkl	20.7bcdegh	22.6bcdegh	24.4abcde
	SCF	12.3ijklmn	9.9lmno	10.4lmno	18.4cdegh	24.7abcd	30.3a
Taung	CCF	16.2efghijkl	16.6deghijkl	12.2ijklmn	7.5lm	7.8klm	10.2ijklm
	CGL	15.0ghijklm	13.0ijklmn	11.8ijklmn	5.8m	7.0lm	8.2jklm
	SCF	24.2abcd	18.60bcdeghijk	15.8fghijkl	13.4hijkl	18.5cdegh	23.4abcde
Ventersdorp	CCF	23.8abcde	26.1ab	25.0abc	16.6fghi	16.6efghi	18.2cdegh
	CGL	24.1abcd	23.4abcde	25.0abc	17.8deghi	20.2bcdegh	21.0bcdegh
	SCF	25.7ab	24.9abc	26.5a	13.8hijkl	14.6hijk	16.2fghi

Interaction effect within a column followed by the same letters is not significantly ($p \geq 0.05$) different using Duncan's multiple range test at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

The consideration of data pertaining to silt: clay ratio and interaction effect clearly indicated that location, land use and soil depth was significant (Table 3.5). The highest silt: clay ratio (3.7) was recorded at 0 - 15 cm depth at Taung CGL and the least value (0.2) obtained at Mathopestad CCF from 15 – 30 cm depth.

Table

3.5 Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

West Province

Location	Land use	Silt/Clay ratio		
		Depth (cm)		
		0-15	15-30	30-45
Itsoseng	CCF	1.1defghijkl	1.2defghij	0.8fghijkl
	CGL	1.4cdefgh	1.1defghijkl	1.2defghi
	SCF	1.6cdefg	1.4cdefgh	0.9efghijkl
Mathopestad	CCF	0.3ijkl	0.2jl	0.2ijkl
	CGL	1.0defghijkl	0.8fghijkl	1.0efghijkl
	SCF	0.9fghijkl	0.5hijkl	0.5hijkl
Taung	CCF	2.7ab	2.4abc	1.056defghijkl
	CGL	3.7a	2.0bcd	1.4cdefgh
	SCF	1.9bcde	1.2defghijk	0.7ghijkl
Ventersdorp	CCF	1.6cdefg	1.7cdefg	1.4cdefgh
	CGL	1.5cdefgh	1.2defgh	1.2defghi
	SCF	1.9bcde	1.8bcdef	1.6cdefg

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

3.4.3 Relationship between Soil Physical Properties

Correlation analysis results of the physical parameters presented in Table 3.6 indicate that clay had highly significant positive relationship with WHC ($r = 0.628$, $p < 0.01$), and TP ($r = 0.523$, $p < 0.01$) while it had negative relationship with BD ($r = -0.523$, $p < 0.01$), sand ($r = -0.595$, $p < 0.01$), and silt ($r = -0.328$, $p < 0.01$). The relationship between silt and BD was significant and positive ($r = 0.296$, $p < 0.05$) however, it had an inverse relationship with porosity ($r = -0.269$, $p < 0.05$), WHC ($r = -0.157$, $p < 0.05$), and sand ($r = -0.552$, $p < 0.01$). Sand had a positive relationship with BD ($r = 0.226$), negative relationship with porosity ($r = -0.226$) and both were not significant but had a highly significant negative relationship with WHC ($r = -0.552$, $p < 0.01$). The relationship between WHC and porosity was highly significant and positive ($r = 0.648$, $p < 0.01$) but this had a highly significant negative relationship with BD ($r = -0.648$, $p < 0.01$). Porosity also had highly significant negative relationship with BD ($r = -1.000$, $p < 0.01$). Silt/Clay had highly positive significant relationship with BD ($r = 0.408$, $p < 0.01$), sand ($r = 0.197$, $p < 0.01$), silt ($r = 0.566$, $p < 0.01$) and had highly negative significant relationship with porosity ($r = -0.408$, $p < 0.01$), WHC ($r = -0.501$, $p < 0.01$) and clay ($r = -0.761$, $p < 0.01$).

Table 3.6: Pearson's Correlation matrix between soil physical properties

	BD	Porosity	WHC	Sand	Silt	Clay	Silt/Clay
BD	1	-1.000**	-.648**	0.226	.296*	-.523**	.408**
Porosity		1	.648**	-0.226	-.296*	.523**	-.408**
WHC			1	-.425**	-.157*	.628**	-.501**
Sand				1	-.552**	-.595**	.197**
Silt					1	-.328**	.566**
Clay						1	-.761**
Silt/Clay							1

** Correlation is significant at the 0.01 level (2-tailed).

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

3.5. Discussion

3.5.1 Physical fertility indicators of the soils

Physical indicators of soils generally include particle size, bulk density, porosity, aggregate stability, and others. These affect processes such as erosion, aeration, runoff, infiltration rate and water retention (Schoenholtz *et al.*, 2000). A soil is considered physically poor when it shows low rates of water infiltration, enhanced surface runoff, poor cohesion, low aeration, poor root density and difficulty for mechanization (Dexter, 2004). Soil texture is an important factor influencing the balance between water and gases, but it is very stable along time, independent of the soil management. Therefore, bulk density and total porosity can reasonably represent the effects of soil use and management on the water/air relationships (Beutler *et al.*, 2002).

The textural composition of the soils (sand, silt and clay) differs across different locations. The soils at Itsoseng and Taung appeared similar texturally but, the indicators differed statistically. This suggests that soils may have similar textural classes but different properties. This means that soil must be properly evaluated based on physical indicators rather than textural classification, which provides only a broad categorisation rather than specific and unique features of the soils. The distribution of sand, silt and clay fractions were influenced by effect of location, land use and soil depth. Soil particle size distribution ratings as reported by Hazelton and Murphy (2016) grouped textural composition ratings as low (10 – 25%), moderate (25 – 40%) and high (> 40%). Hence, according to the ratings, sand was rated high in the study, which has serious implication for water retention and the general physical fertility of these soils. Taung communal grazing land recorded the highest amount of sand particles at 0 – 15 cm depth and significantly differed from all other locations and land use types but had no statistical difference at soil depth. The higher sand content of the soils could be attributed to the granite (igneous) parent material

over which they are formed or may be possibly influenced by physical and pedogenic process in the location. Generally, soils from Taung area had more sand than all other locations. It could be inferred that these soils have developed in recently deposited soil materials such as alluvium (Bruandi *et al.*, 2005). The result is in line with Saley Moussa (2007) who reported that soils from western Bophirima area of NWP was dominated by sand particles and low in silt and clay fractions. The physical fertility of these soils is low hence unable able to retain much water for crop production, except when amended with organic matter.

Effect of location, land use and soil depth on silt and clay are shown in Table 3.2. Silt was rated low, while clay was rated low to moderate in the study area. The highest silt content was observed at Ventersdorp smallholder crop farm. Silt content was rated low at all depths and locations and was significantly higher at 30 – 45 cm depth. The highest clay was observed at Mathopstad commercial crop farm at 30 – 45 cm depth and was influenced by soil depth but rated moderate. The content of clay increased with depth. In terms of soil physical fertility, these soils have higher water holding capacity and less porous and can retain water for crops growth. The higher clay in Mathopstad could be due to in-situ weathering of the parent materials. Although Essoka and Esu (2003) attributed increase in clay with soil depth indicating that clay had moved down the profile by lessivage, it is more probable that the increase in clay content reported in the current study could be attributed to residual clay accumulation rather than illuvial accumulation due to a lower precipitation that is often recorded in this Province. In general, the distribution of sand, silt and clay were irregular in the different locations and land use types, which could be attributed to the different tillage practices made in the area.

It was observed from the statistical analysis that location, land use and soil depth exerted significant effect on silt/clay ratio (Tables 3.2 and 3.5). This observation was however, unexpected since silt/clay ratio is a pedological feature that is more related to weathering. Highest silt/clay ratio was recorded at Taung CGL at 0 – 15 cm depth and significantly higher than other locations and depths. As reported by Egbuchua and Ojobor (2011), silt/clay ratios of any given soil below 0.15 was an indication that such soil was of old parent material, while those above 0.15 were of young parent materials or with low degree of weathering. It is factual that all the soils recorded silt/clay ratio of more than 0.15 confirming that the soils were of young parent materials or with low degree of weathering and has good potential for weathering to release nutrients in future, but if the parent material has high quartz content it would be resistant to weathering. Silt/clay ratio is a pedological feature that is more related to weathering and parent

material compositions. Soil with high silt/clay ratio can affect the physical fertility by retaining water in the soil and physically support plants growth. Soils high silt/clay ratio was reported by Nwaka and Kwari (2000) that in sandy soils, high silt/clay ratio may be related to the coarse texture of the parent material and youthfulness of the soil. The silt sized particles in the different depths indicated that the soils have potential for weathering to release nutrients for plant use in the future.

3.5.2 Structural Indicators of the Soils

Structural indicators of soils are the major soil physical attributes affected by organic matter and the physical indicators such as water holding capacity, bulk density, porosity, aeration, water infiltration and retention are very pertinent in crop production (Dexter, 2004). Effects of location, land use and soil depth on TP of the study area are presented in Table 3.3. The significant effects of location, land use and soil depth on TP could be attributed to the differences in soil particle distribution and organic carbon content. The highest value was observed at SCF Itsoseng at 0 – 15 cm depth and this significantly differed across soil depth. The diverse land uses differed in their TP due to the variations in sand, silt and clay contents. Similar research results were reported by Wakene (2001) that TP is influenced by particle size distribution. This result confirms Evanylo and McGuinn (2009) who reported that soils with high TP provide more plant-available water, but soil texture also determines what portion of the soil water is available to plant including aeration and root movements. The same authors also reported that clayey soils hold the most while sandy soils the least and loamy soils intermediate amounts of water. However, loamy soils provide the most plant available water because much of the water in the small pores in clayey soils is held too tightly to be available to plants (Indoria *et al.*, 2017).

The bulk density (BD) values obtained in the area are shown in Table 3.2 and were ideal for normal crop growth compared with the ideal bulk densities (g/cm^3) developed by Evanylo & McGuinn, 2009). The ratings are in the order of sand, loamy sand < 1.60, sandy loams, loams < 1.40, sandy clay loam, clay loam < 1.40, silts, silt loams < 1.30, sandy clays, silky clays, some clay loams (35 – 45%) < 1.10 and clays (> 45% clay) < 1.10 as ideal bulk densities for crop growth. Taung recorded the highest BD but was not significantly higher than at Ventersdorp. Soils with high bulk density cause restrictions to root growth, poor movement of air and water through the soil (Gleason *et al.*, 2008). Generally, soils with low bulk densities have favourable physical conditions for plant growth (Chaudhari *et al.*, 2013).

The highest WHC recorded at Mathopestad and might be attributed to its high clay content, which has implication for the soil physical fertility as it promotes good crop production and impact on the pore size distribution in soil. Pore size distribution provides the ability to store root zone water and air necessary for plant growth (Indoria et al., 2017). High clay content impacts on soil WHC and the TP (Brady & Weil, 2013). The soil TP is influenced by the the proportion of soil particles and structural, depending on bio-pores and as macro-structure. The macro- structure is easily affected by land use and soil management (Dexter, 2004). However, the least value of total porosity was obtained at Ventersdorp. Generally, the soils are within range for normal crop growth. (Brady & Weil, 2013). Soil porosity affects soil aeration, water permeability and tree root growth and is an important index of soil physical fertility (Brady & Weil, 2013). Soil porosity and bulk density showed an opposite trend of change, that is, the bulk density decreased, and the porosity increased (Indoria et al., 2017).

3.6 Conclusion

The study showed that majority of the soil physical fertility indicators across the different locations, land use types and soil depths can support crop growth despite their variations which might have been influenced by the land use types, management practices and environmental factors such as climate and topography. Particle size distribution, WHC, BD and TP in the study area were ideal for normal crop growth.

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CHAPTER FOUR

CHEMICAL FERTILITY INDICATORS OF SOILS UNDER THREE LAND USE TYPES IN NORTH WEST PROVINCE, SOUTH AFRICA

4.1 Abstract

Information about soil chemical indicators in different land use types is crucial for promoting best and sustainable land management practices. This study assessed the current status of soil chemical fertility indicators on smallholder crop and commercial crop farms as well as communal grazing land at four locations. A total of 180 soil samples was randomly collected from three depths (0 - 15, 15 - 30 and 30 - 45 cm) for laboratory determination. Soil pH (H₂O and KCl), EC, percent OC, total N, available P, S, exchangeable cations (K, Ca, Mg, Al), exchangeable acidity, CEC and micronutrients (Cu, Fe, Mn, Zn) were analyzed. Results established significant ($p < 0.05$) variation in the content of these measured indices across locations, land use types and soil depth. The highest mean pH-H₂O (7.19), pH-KCl (6.14), Δ pH (1.14), EC (0.13 mS/m), OC (1.82%), N (1.67%), P (12.35 cmol/kg), K (415 cmol/kg), Ca (2870 cmol/kg), Mg (493 cmol/kg), Al (1.43 cmol/kg), S (0.84%), EA (0.87 cmol/kg), CEC (18.31 cmol/kg), Cu (5.94), Fe (60.5), Mn (137.1) and Zn (17.23 mg/kg) were recorded. Most of the measured values for the various farmlands were within the threshold levels for crop production. Soil fertility index ranged from 1383 at Taung communal grazing land to 4934 at Itsoseng smallholder crop farm. The soil evaluation factor ranged from 1363 at Taung communal grazing land to 4917 at Itsoseng smallholder crop farm. These values are considered as highly fertile for crop production when compared with the critical values. Pearson's correlation matrix confirmed both positive and negative correlation among the indices. These results have practical management implications for farmers to promote increased productivity.

Keywords: chemical indicators, land use types, smallholder, commercial, grazing land

4.2 Introduction

The growth, development and reproduction of crop plants depend on soil fertility. In turn, soil fertility is determined by the availability of macro and micronutrients in soil and other environmental factors (Havlin *et al.*, 2016). Soil fertility is defined as the capacity of a soil to supply all essential plant nutrients and water in adequate quantities and proportions for the growth and reproduction without toxic substances which could inhibit plant growth (Bot & Benites, 2005). Soil, as the basic medium for plant growth, has a direct influence on the harvest and quality of crops grown.

An assessment of the fertility of an agricultural soil can provide information about the productive potential. Auspiciously, producers can control fertility by managing the nutritional status of the soils (Flynn *et al.*, 2004). However, fertility status in soil is a hidden factor in plant growth, except when imbalances become so severe that visual symptoms are evident on the plant (Flynn *et al.*, 2004).

In South Africa, a general reduction in the yield of common crops in recent times has drawn the attention of stakeholders in the agricultural sector to this worrisome trend (Du Preez *et al.*, 2011; Nell *et al.*, 2001). Therefore, at present, the greatest challenge confronting the South African agriculture is to boost food production and productivity as well as sustainability of agriculture (Nafiu *et al.*, 2012). There are problems that impede these goals, raising serious concerns about national food security. These include declining soil fertility, increases in the cost of production and low diversity of production systems and water scarcity (Arifalo & Mafimisebi, 2011). Low fertility of South African agricultural soils is one of the major constraints in achieving high productivity (Materechera, 2010; Mills & Fey, 2003). In both rain-fed and irrigated systems, nutrient addition through inorganic and organic fertilisers remains low and most especially in smallholdings thus causing nutrient mining of native reserves over the years in South Africa (Mandiringana *et al.*, 2005; Mills & Fey, 2003). Low soil fertility reduces nutrient use efficiency and returns from capital invested in nutrients and other inputs (Sanchez *et al.*, 1997). Soils with low fertility weaken the foundation for high yielding sustainable farming and increases costs for rebuilding depleted soils (Arifalo & Mafimisebi, 2011).

Site-specific assessment of soil fertility status is integral to rational fertiliser use and dependable information can only be accomplished through planned programmes. Soil fertility assessment is the process of estimating the amount of native and residual nutrient elements which could be available for use by growing crops in a particular soil and the amount of fertiliser to be supplemented for profitable crop production (Sanchez *et al.*, 1997). Although soil fertility assessment is a powerful tool in supporting high productivity by way of rationalising nutrient use, its current impact on farm practice is elusive in smallholders' farms in NWP (Laker, 2005). To make it an effective and farmer-oriented service, it is imperative to make regular soil fertility assessments to identify the current fertility status and provide information regarding nutrient availability in soils. This could form the basis for fertiliser recommendations for optimising crop yields and maintaining optimum fertility in soil year after year.

For proper soil fertility management, the farmer should know what adjustments are necessary to optimise the soil productivity for enhanced crop production. Currently, data on chemical fertility status of soils from the selected study areas are scarce and limited to the old work by Cilliers *et al* (1998). Hence, this study focused on the determination of soil chemical fertility indicators of selected smallholder crop farms, commercial crop farms and grazing land soils of NWP to boost data and achieve sustainable utilization of the soils.

4.3 Materials and Methods

Chapter three sections 3.2.1 to 3.2.6 described the study area, climate of the province, vegetation, geology/agricultural activities and soil samples collection.

4.3.1 Chemical fertility indicators determination of the soil samples

Soil pH was determined in H₂O, 1M KCl solution and electrical conductivity (EC) using soil solution ratio of 1:2.5 as described by Okalebo *et al.* (2002). Organic C, total N and available S were analysed using the Automated Dumas dry combustion method and a TRUMEC LECO machine. Available P was determined using Bray 1 method as described by Estefan *et al.* (2013).

Cation exchange capacity (CEC) was determined by using 1N NH₄OAc (pH7) extracting solution as described by Estefan *et al.*, (2013). 1N NH₄OAc extract from the CEC determination was used for K determination as outlined by Estefan *et al.*, (2013) using Flame photometer. The determination of Ca and Mg were made as described by Jackson & Brown, (1964) using EDTA titration method. Exchangeable Aluminium was determined by the Aluminium Method as described by Non-Affiliated Soil Analysis Working Committee (Committee, 1990). Diethylene triaminepenta-acetic (DTPA) acid extracting solution was used as outlined by Estefan *et al.* (2013) for the extraction of micro-nutrients (Cu, Fe, Mn and Zn) and measured by atomic absorption spectrophotometry.

4.3.2 Soil Fertility Evaluation

Soil fertility index (SFI) and Soil evaluation factor (SEF) are indicators that commonly used to evaluate the soil fertility in a place. The SFI and SEF encompasses all the significant parameters of the soil, which indicate the soil fertility level. However, calculating SFI and SEF requires the laboratory measurement of multiple soil properties. Moran *et al.*, (2000) reported that values of Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF) when calculated can be used to quantify soil fertility. Computation of SFI (Moran *et al.* (2000) and SEF (Lu *et al.* 2002) to evaluate the fertility status of the soils on the different farms based on the following equations:

$$\text{SFI} = \text{pH} + \text{Organic matter (\% dry soil mass)} + \text{Available P (mg kg}^{-1} \text{ dry soil)} + \text{Exchg. K (cmol}_c\text{kg}^{-1}) + \text{Exchg. Ca (cmol}_c\text{kg}^{-1}) + \text{Exchg. Mg (cmol}_c\text{kg}^{-1}) - \text{Exchg. Al (cmol}_c\text{kg}^{-1}).$$

$$\text{SEF} = [\text{Exchg. K (cmol}_c\text{kg}^{-1}) + \text{Exchg. Ca (cmol}_c\text{kg}^{-1}) + \text{Exchg. Mg (cmol}_c\text{kg}^{-1}) - \log (1 + \text{Exchg. Al (cmol}_c\text{kg}^{-1})] \times \text{Organic matter (\% dry soil basis)} + 5.$$

4.3.3 Data analysis

The data was subjected to analysis of variance (ANOVA) to know the significant differences in chemical indicators of the different locations, land use types and soil depths. DMRT was used to separate significant means. The relationship between the selected soil chemical indicators were determined using Pearson's correlation analysis. Fertility of the soils was assessed using Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF). Data interpretation was also based on comparison with critical values in research. All statistical analyses were done by GenStat 11.1 (Genstat Eleventh Edition).

4.4 RESULTS

4.4.1 Chemical fertility indicators under different land use types at different depths and locations

Soil chemical indicators are the most important factors that affect soil fertility and determine the nutrient supply power of soils to crops and microbes. In this study, the key soil chemical indicators were analysed and these are presented in Tables 4.1 - 4.2. Soil pH-H₂O, pH-KCl and Δ pH significantly differed ($p \leq 0.05$) across the different locations (Table 4.1). The highest pH-H₂O (7.19), pH-KCl (6.14) and Δ pH (1.48) mean values were obtained in Mathopestad. Electrical conductivity (EC) and OC were significantly different at location. Considering the effect of location on EC and OC, the highest EC (0.13 mS/m) and OC (1.82%) was recorded at Mathopestad, Taung and these were significantly different. Total nitrogen (TN), available P and exchangeable K were significantly different at location. Highest TN (1.67%), AP (12.35) and Exch. K (415 mg/kg) values were observed in Taung, Ventersdorp and Taung. Soil pH-H₂O/KCl were significantly influenced by land use. The pH-H₂O recorded highest (7.03) in SCF and highest pH-KCl (6.08) value was also observed in SCF. Change in soil pH (Δ pH) was significantly influenced by effect of land use with highest (1.40) figure found in CGL. Electrical conductivity and OC were significantly different in land use type and the highest (0.15 mS/m at SCF and 1.51 % at CGL). Statistically, there was no significant variation in total nitrogen across land use types. Total nitrogen (TN) recorded (1.41 %) in CGL. Available P and

Table 4.1: Effect of land use types on soil chemical indicators at different depths from four locations in North West Province

Treatment	pH (H ₂ O)	pH (KCl)	Δ pH	EC (mS/m)	OC (%)	TN (%)	Av. P (mg/kg)	Exch K (mg/kg)
Location								
Itsoseng	6.92b	5.79b	1.14b	0.10a	0.82c	1.55ab	6.56b	315b
Mathopestad	6.70c	5.22c	1.48a	0.13a	1.57b	0.65c	6.48b	323b
Taung	7.19a	6.14a	1.05bc	0.10a	1.82a	1.67a	3.30c	415a
Ventersdorp	6.66c	5.67b	0.99c	0.08b	1.06c	1.37b	12.35a	144c
LSD (0.05)	0.14	0.15	0.15	0.03	0.24	0.21	2.12	66.5
Land use								
CCF	6.91b	5.78a	1.14b	0.13b	1.20b	1.26	7.74a	202c
CGL	6.66c	5.26b	1.40a	0.08c	1.51a	1.41	4.64b	269b
SCF	7.03a	6.08a	0.95c	0.15a	1.25b	1.26	9.14a	427a
LSD (0.05)	0.12	0.13	0.12	0.03	0.21	NS	1.84	57.6
Depth (cm)								
0 – 15	6.78b	5.67	1.11b	0.13	1.44	1.27	7.42	370a
15 – 30	6.91a	5.71	1.20a	0.10	1.25	1.30	7.11	287b
30 – 45	6.91a	5.73	1.19b	0.10	1.24	1.36	6.98	240b
LSD (0.05)	0.12	NS	0.12	NS	NS	NS	NS	57.6

Main effect means within a column followed by the same letters are not significantly different from each other at $p \leq 0.05$; NS = not significant, CCF = Commercial crop farm, CGF = Communal grazing land, SCF = Smallholder crop farm

Exchangeable K were significantly different in land use types. The highest available P (9.14) and exchangeable K (427 cmol/kg) were observed in SCF. Soil pH-H₂O was significantly different across soil depth and the highest pH-H₂O (6.91) was recorded at 15 -30 cm to 30 - 45 cm depths. However, soil pH-KCl had no significant difference at different soil depths. The highest pH-KCl (5.71) was recorded at 30 – 45 cm depth. The Δ pH had significant difference at soil depth and the highest (1.20) was observed at 15 – 30 cm depth. Electrical conductivity, OC, NT and AP had no significant difference at different soil depths. The highest (0.13 mS/m) EC, (1.44 %) OC were recorded at 0 -15 cm depth. Total N and AP highest (1.36 %) and (7.42 cmol/kg) AP were observed at 30 - 45 cm and 0 - 15 cm depths. Exchangeable K was significantly different at soil depths and highest value (370 cmol/kg) was obtained at 0 – 15 cm depth.

Soil pH-H₂O/KCl were significantly influenced by land use. The pH-H₂O recorded highest (7.03) in SCF and highest pH-KCl (6.08) value was also observed in SCF. Change in soil pH (Δ pH) was significantly influenced by effect of land use with highest (1.40) figure found in CGL. Electrical conductivity and OC were significantly different in land use type and the highest (0.15 mS/m at SCF and 1.51 % at CGL). Statistically, there was no significant variation in total nitrogen across land use types. Total nitrogen (TN) recorded (1.41 %) in CGL. Available P and

Exchangeable K were significantly different in land use types. The highest available P (9.14) and exchangeable K (427 cmol/kg) were observed in SCF. Soil pH-H₂O was significantly different across soil depth and the highest pH-H₂O (6.91) was recorded at 15 -30 cm to 30 - 45 cm depths.

However, soil pH-KCl had no significant difference at different soil depths. The highest (5.71) pH-KCl was at 30 – 45 cm depth. The Δ pH had significant difference at soil depth and the highest (1.20) was observed at 15 – 30 cm depth. Electrical conductivity, OC, NT and AP had no significant difference at different soil depths. The highest (0.13 mS/m) EC, (1.44 %) OC were recorded at 0 -15 cm depth. Total N and AP highest (1.36 %) and (7.42 cmol/kg) AP were observed at 30 - 45 cm and 0 - 15 cm depths. Exchangeable K was significantly different at soil depths and highest value (370 cmol/kg) was obtained at 0 – 15 cm depth.

The contents of exchangeable calcium (Ca), magnesium (Mg) and aluminium (Al) were significantly different across location (Table 4.2). The highest means of exchangeable Ca, Mg and Al under location were recorded at Itsoseng (Ca = 2870 cmol/kg), Mathopestad (Mg = 575 cmol/kg) and Taung (Al = 1.43 cmol/kg). Cation exchange capacity (CEC) significantly varied across location. In view of the effect of location, the highest mean (18.31 cmol/kg) was observed at Itsoseng. The contents of available micronutrients (Cu, Fe, Mn, and Zn) were significantly different across location (Table 4.2). Considering the main effect of location, the highest mean content of Cu (5.94 cmol/kg), Fe (60.5 cmol/kg) and Zn (17.23 cmol/kg) were recorded at Mathopestad and Mn (137.1 mg/kg) at Ventersdorp. Highest mean values of Ca (3232 cmol/kg) at SCF, Mg (520 cmol/kg) at SCF, and Al (0.93 cmol/kg) at CGL. Calcium, K and Al varied significantly across land use types. Available S and exchangeable acidity were not significantly different across land use but had (0.56 % and 0.51cmol/kg) means in SCF and CGL. Soil CEC varied significantly across land use types and highest (21.60 cmol/kg) in SCF. The micronutrients Cu, Fe, Mn and Zn significantly across land use. Results of land use also indicated that the highest contents of Cu, Mn and Zn (5.37, 124.5 and 14.92 mg/kg) were recorded in SCF and Fe (47.6) in CGL.

Table 4.2: Main effect of land use types on soil chemical indicators at different depths from four locations in North West Province

Treatment	Exch.Ca (cmol/kg)	Exch.Mg (cmol/kg)	Exch. Al (cmol/kg)	Avai.S (%)	Exch.Ac (cmol/kg)	CEC (cmol/kg)	Cu (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Zn (mg/kg)
Location										
Itsoseng	2870a	373b	0.36c	0.59a	0.11b	18.31a	2.95c	32.6b	111.0b	8.91c
Mathopestad	2341b	575a	0.35c	0.13ab	0.87a	17.43a	5.94a	60.5a	103.3b	17.23a
Taung	2247b	493a	1.43a	0.30bc	0.10b	16.43a	4.41b	36.0b	110.3b	5.02d
Ventersdorp	1631c	374b	1.09b	0.84a	0.18b	11.76b	5.12ab	36.0b	137.1a	12.48b
LSD (0.05)	362.6	107.4	0.1	0.4	0.69	2.34	0.86	7.44	10.29	1.81
Land use										
CCF	1890b	392b	0.76b	0.33	0.13	13.30b	3.98b	36.9b	124.0a	9.42b
CGL	1695b	449ab	0.93a	0.50	0.51	13.05b	4.47a	47.6a	97.0b	8.39b
SCF	3232a	520a	0.73b	0.56	0.31	21.60a	5.37a	39.3b	124.5a	14.92a
LSD (0.05)	314	93	0.09	NS	NS	2.03	0.75	6.44	8.91	1.57
Depth(cm)										
0 – 15	2377	433	0.84	0.42	0.36	16..52	4.50	42.1	116.9	10.86
15 – 30	2269	451	0.79	0.36	0.44	15.91	4.87	41.4	116	11.23
30 – 45	2171	478	0.80	0.62	0.15	15.53	4.44	40.4	113.4	10.64
LSD (0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Main effect means within a column followed by the same letters are not significantly different from each other at $p \leq 0.05$; NS = not significant, CCF = Commercial crop farm, CGF = Communal grazing land, SCF = Smallholder crop farm.

Exchangeable Ca, Mg and Al had no significant variation at different soil depths. Considering soil depths, the mean values of Ca, Mg and Al were at 0 - 15 cm (Ca 2377 cmol/kg), 30 - 45 cm (Mg 478 cmol/kg) and at 0 – 15 cm depth (Al 0.84 cmol/kg). Available S, EA and CEC also had no significant difference at soil depths. The S (0.62%) was observed at 30 – 45 cm, (0.44 cmol/kg) EA at 15 – 30 cm and (16.52 cmol/kg) CEC at 0 – 15 cm depths. There was no significant difference in micronutrients (Cu, Fe, Mn and Zn) at soil depths. The (4.87, 42.1, 116.9 and 11.23 mg/kg) contents of Cu, Fe, Mn and Zn were recorded at 15 - 30 and 0 - 15 cm depths.

4.4.2 Interaction effect of location, land use and soil depth on chemical indicators of soil

Interaction effect of location, land use and soil depth on chemical indicators of soil are presented in Tables 4.3 to 4.12. Interaction effect of location, land use and soil depth were significantly varied ($p \leq 0.05$) across soil chemical indicators. The highest pH-H₂O (7.40) was recorded at Ventersdorp SCF at 15 – 30 cm depth (Table 4.3).

Table 4.3: Interaction effect of location, land use and soil depth on pH-H₂O in North West Province

		pH H ₂ O		
		Depth (cm)		
Location	Land use	0-15	15-30	30-45
Itsoseng	CCF	7.24abc	7.28ab	7.27ab
	CGL	6.38jkl	6.57fghijk	6.36kl
	SCF	6.98abcdefgh	7.08abcdef	7.12abcde
Mathopestad	CCF	6.401jkl	6.54hijk	6.60efghijk
	CGL	6.88abcdefghij	6.96abcdefghi	6.95abcdefghi
	SCF	6.70efghijk	6.74cdefghijk	6.56ghijk
Taung	CCF	7.10abcde	7.32a	7.38a
	CGL	7.07abcdefg	7.31a	7.37a
	SCF	6.79bcdefghijk	7.12abcde	7.23abcd
Ventersdorp	CCF	6.46ijkl	6.62efghijk	6.72defghijk
	CGL	6.03i	6.0li	6.00i
	SCF	7.30ab	7.39a	7.38a

Interaction effect within a column followed by the same letters are not significantly different from each other at $P \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

Interaction effect of location, land use and soil depth were significantly different in pH-KCl and Δ pH (Table 4.4). The highest pH-KCl (6.52) was obtained at Itsoseng SCF at depth 30 – 45 cm and the highest Δ pH (2.01) was observed at Mathopestad CGL at 15 – 30 cm depth.

Table 4.4: Interaction effect of location, land use and soil depth on soil pH-KCl and Δ pH in North West Province

		pH KCl			Δ pH		
		Depth (cm)			Depth (cm)		
Location	Land use	0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	5.91bc	5.85c	5.82c	1.33cdefghi	1.43bcdefg	1.44bcdefg
	CGL	4.99d	5.11d	5.04d	1.39cdefg	1.45bcdefg	1.32cdefghij
	SCF	6.35abc	6.47ab	6.52a	0.63lmn	0.61lmn	0.60lmn
Mathopestad	CCF	4.65d	4.84d	4.81d	1.76abcd	1.70abcdef	1.79abc
	CGL	4.98d	4.95d	5.20d	1.90ab	2.01a	1.75abcde
	SCF	5.86c	5.90c	5.83c	0.83jklmn	0.84ijklmn	0.74klmn
Taung	CCF	6.36abc	6.35abc	6.33abc	0.74klmn	0.97ghijkl	1.04ghijkl
	CGL	6.15abc	6.16abc	6.15abc	0.92hijklm	1.16ghijk	1.22fghijk
	SCF	5.86c	5.93bc	5.97abc	0.93hijklm	1.17ghijk	1.26fghij
Ventersdorp	CCF	6.09abc	6.13abc	6.15abc	0.37n	0.48mn	0.56lmn
	CGL	4.82d	4.73d	4.79d	1.21fghijk	1.28efghij	1.20ghijk
	SCF	6.07abc	6.12abc	6.07abc	1.24fghij	1.27efghij	1.31defghij

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

Interaction effect of location, land use and soil depth on EC and OC are shown in Table 4.5. The highest EC (0.25 mS/m) was registered at Itsoseng SCF at 30 – 45 cm depth and % OC recorded highest (2.33 %) value was at 0 -15 cm depth in Taung CGL. Interaction effect of location, land use and soil depth on total nitrogen and available phosphorus are presented in Table 4.6. The highest content of TN (2.25%) was recorded at 30 – 45 cm depth at Taung SCF and available P highest (18.01 mg/kg) was observed at 0 – 15 cm soil depth at SCF Ventersdorp.

Table 4.7 depicts interaction effect of location, land use and soil depth on K and Ca. Smallholder crop farmlands at Mathopestad had the highest (854 mg/kg) K at 0 – 15 cm depth. The highest Ca (4168 cmol/kg) content was recorded at 0 - 15 cm depth at SCF Itsoseng.

5: Interaction effect of location, land use and soil depth on electrical conductivity and organic carbon in North West Province

Location	Land use	EC (mS/m)			OC %		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	0.07ef	0.05f	0.06f	0.889hijkl	0.88hijkl	0.78ijkl
	CGL	0.09def	0.09def	0.06f	0.902ghijkl	0.94ghijkl	0.89ghijkl
	SCF	0.25ab	0.25ab	0.2540a	0.814ijkl	0.53l	0.77jkl
Matthostad	CCF	0.09def	0.07f	0.0660f	1.28dfghijkl	1.21ghijkl	0.982ghijkl
	CGL	0.14abcdef	0.010def	0.0960def	2.14abcdef	1.61abcdefghij	1.16ghijkl
	SCF	0.23abc	0.19abcd	0.1440acdef	2.18abc	2.15abcd	1.38bcdefghijkl
Taung	CCF	0.19abcde	0.13cdef	0.1340cdef	2.15abcde	1.47abcdefghijk	1.74abcdefgh
	CGL	0.09def	0.05f	0.0420f	2.33a	1.50abcdefghijk	2.20ab
	SCF	0.15abcdef	0.07ef	0.0700ef	1.52abcdefghijk	1.66abcdefghj	1.77abcdefg
Ventersdorp	CCF	0.13cdef	0.13cdef	0.1060def	1.03ghijkl	0.86hijkl	1.07ghijkl
	CGL	0.04f	0.04f	0.0520f	1.32cdefghijkl	1.51abcdefghijk	1.54abcdefghijk
	SCF	0.08def	0.07ef	0.0540f	0.69kl	0.66kl	0.86hijkl

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

Table 4.6: Interaction effect of location, land use and soil depth on total nitrogen and available phosphorus in North West Province

		Tot. N %			Avail. P cmol/kg		
		Depth (cm)			Depth (cm)		
Location	Land use	0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	1.64abcde	1.60abcde	1.59abcde	6.50efgh	4.85gh	8.15cdefgh
	CGL	1.98abc	1.50abcde	1.71abcde	9.65bcdefg	7.05defgh	8.40cdefgh
	SCF	1.08e	1.16de	1.68abcde	4.20gh	2.13gh	8.10cdefgh
Mathopestad	CCF	0.33f	0.27f	0.41f	4.83gh	5.89fgh	2.74gh
	CGL	1.22cde	1.31cde	1.38bcde	1.99gh	1.80gh	2.54gh
	SCF	0.32f	0.34f	0.228f	7.89cdefgh	16.44ab	14.18abcd
Taung	CCF	1.72abcde	1.71abcde	1.544abcde	6.41efgh	4.25gh	4.52gh
	CGL	1.260cde	1.302cde	1.272cde	3.85gh	0.70h	1.95gh
	SCF	1.890abcd	2.114ab	2.252a	3.85gh	3.00gh	1.15h
Ventersdorp	CCF	1.335bcde	1.568abcde	1.368bcde	14.81abc	15.96ab	13.96abcde
	CGL	1.120de	1.274cde	1.536abcde	7.10defgh	5.90fgh	4.70gh
	SCF	1.282cde	1.480abcde	1.354bcde	18.01a	17.31a	13.36abcdef

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

7: Interaction effect of location, land use and soil depth on exchangeable potassium and calcium in North West Province

Location	Land use	Exch K (cmol/kg)			Exch Ca (cmol/kg)		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	318efghijk.	236fghijkl.	150jkl.	2645bcdef.	2741bcdef.	2849bcde.
	CGL	439defgh.	358defghij.	273efghijkl.	2041defgh.	1864efgh.	1585efgh.
	SCF	423defgh.	300efghijkl.	335defghijk.	4168a.	3766ab.	4169a.
Mathopestad	CCF	210ghijkl.	97kl.	89kl.	1494efgh.	1571efgh.	1484fgh.
	CGL	176ijkl.	126jkl.	96kl.	2193cdefgh.	2216cdefgh.	2132cdefgh.
	SCF	854a	694abc.	565bcd.	3655ab.	3738ab.	2585bcdefg.
Taung	CCF	267efghijkl	291efghijkl.	239fghijkl.	1726efgh.	1543efgh.	1674efgh.
	CGL	447defg	458def.	419defghi.	1934efgh.	1610efgh.	1532efgh.
	SCF	719ab	488cde.	403defghi.	3308abcd.	3349abc.	3550ab.
Ventersdorp	CCF	217fghijkl.	174ijkl.	134jkl.	1927efgh.	1559efgh.	1464fgh.
	CGL	199hijkl.	124jkl.	112jkl.	949h.	1003h.	1277gh.
	SCF	176ijkl.	97kl.	63l.	2482bcdefg.	2272cdefgh.	1748efgh.

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = small holder crop farm.

The interaction effect of location, land use and soil depth on Mg and Al are presented in Table 4.8. The Mg content had (1273 cmol/kg) in Mathopestad CGL at 30 – 45 cm depth. The (1.66 cmol/kg) Al content was observed at 0 - 15 cm depth at Taung CGL.

The interaction effects of location, land use and soil depth on S and CEC are presented in Table

4.9. The highest S (2.56%) was obtained at Ventersdorp SCF at 30 – 45 cm soil depth. The highest CEC value (26.18 cmol/kg) was obtained at Taung SCF at 30 - 45 cm depth. The interaction effect of location, land use and soil depth on exchangeable acidity is shown in Table 4.10. The highest exchangeable acidity (0.38 cmol/kg) was recorded at Ventersdorp CGL at soil depth 15 - 30 cm.

Table 4.8: Interaction effect of location, land use and soil depth on exchangeable magnesium and aluminium in North West Province

Location	Land use	Exch Mg (cmol/kg)			Exch Al (cmol/kg)		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	418de.	454de.	461cde.	0.38ij	0.19j	0.29ij
	CGL	288e.	280e.	249e.	0.38ij	0.64ghi	0.29ij
	SCF	331e.	398de.	481cde.	0.35ij	0.29ij	0.38ij
Mathopestad	CCF	272e.	256e.	269e.	0.38ij	0.26j	0.29ij
	CGL	870b.	1015ab.	1273a.	0.33ij	0.35ij	0.38ij
	SCF	431de.	398de.	392de.	0.51hij	0.38ij	0.26j
Taung	CCF	448cde.	401de.	396de.	1.44abc	1.34abcd	1.47ab
	CGL	219e.	224e.	262e.	1.66a	1.54ab	1.54ab
	SCF	770bcd.	825bc.	891b.	1.25bcde	1.31abcd	1.34abcd
Ventersdorp	CCF	436.de	452cde.	444cde.	1.09cdef	0.96efg	1.06def
	CGL	221e.	241e	251e.	1.44abc	1.41abcd	1.22bcde
	SCF	492cde.	462de.	370e.	0.80fgh	0.77fgh	1.09cdef

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = small holder crop farm.

9: Interaction effect of location, land use and soil depth on available sulphur and cation exchange capacity in North West Province

Location	Land use	Avail S (%)			CEC (cmol/kg)		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	0.24c	0.51bc	0.31c	17.56bcdefghi	18.12abcdefgh	18.49abcdefgh
	CGL	0.58bc	0.51bc	1.82ab	13.80efghij	12.66fghij	10.83ghij
	SCF	0.44bc	0.53bc	0.38bc	24.68abc	22.95abcd	25.69ab
Mathopestad	CCF	0.11c	0.12c	0.11c	10.48ghij	10.36ghij	10.00hij
	CGL	0.20c	0.10c	0.17c	18.83abcdefg	19.97abedcf	21.63abcde
	SCF	0.18c	0.09c	0.06c	24.08abc	23.82abcd	17.70abcdefghi
Taung	CCF	0.19c	0.23c	0.22c	13.09fghij	11.86fghij	12.29fghij
	CGL	0.37bc	0.24c	0.23c	12.72fghij	11.14ghij	10.98ghij
	SCF	0.63bc	0.30c	0.27c	24.79abc	24.84abc	26.18a
Ventersdorp	CCF	0.65bc	0.48bc	0.83bc	13.88efghij	12.05fghij	11.39fghij
	CGL	0.79bc	0.57bc	0.45bc	7.30j	7.68j	9.08ij
	SCF	0.62bc	0.62bc	2.56a	16.97cdefghi	15.49defghij	12.03fghij

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

Table 4.10: Interaction effect of location, land use and soil depth on exchangeable acidity

Location	Land use	Exch. Ac (cmol/kg)		
		Depth(cm)		
		0 – 15	15 – 30	30 – 45
Itsoseng	CCF	0.11bc	0.10c	0.10c
	CGL	0.12bc	0.14abc	0.18abc
	SCF	0.08c	0.07c	0.07c
Mathopestad	CCF	0.25abc	0.17abc	0.16abc
	CGL	0.28abc	0.23abc	0.28abc
	SCF	0.11bc	0.11bc	0.13bc
Taung	CCF	0.12bc	0.12bc	0.07c
	CGL	0.13bc	0.08c	0.11bc
	SCF	0.11bc	0.10c	0.10c
Ventersdorp	CCF	0.13bc	0.11bc	0.09c
	CGL	0.24abc	0.38a	0.36ab
	SCF	0.10c	0.10c	0.11bc

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

The interaction effects of location, land use and soil depth on micronutrients (Cu and Fe) are presented in Table 4.11. The value of Cu was highest (7.80 mg/kg) at Taung CGL at 15 – 30 cm soil depth and the highest (115.70 mg/kg) Fe content was obtained at Mathopestad CGL at 0 – 15 cm soil depth. The Interaction effect of location, land use and soil depth on Mn and Zn are presented on Table 4.12. The highest Mn (155.9 mg/kg) value was recorded at Ventersdorp SCF at 30 – 45 cm soil depth. The highest Zn (33.08 mg/kg) content was obtained at Mathopestad SCF at 15 – 30 cm soil depth.

Table 4.11: Interaction effect of location, land use and soil depth on copper and iron in North West Province

Location	Land use	Cu (mg/kg)			Fe (mg/kg)		
		Depth (cm)			Depth (cm)		
		0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	2.52d	2.58d	2.60d	27.10cd	28.50bcd	30.20bcd
	CGL	3.02cd	3.02cd	3.08cd	20.90d	20.20d	17.20d
	SCF	3.74bcd	3.02cd	2.96cd	49.90bc	55.60b	43.90bcd
Mathopestad	CCF	5.60abcd	5.50abcd	5.60abcd	38.00bcd	39.80bcd	40.50bcd
	CGL	4.88abcd	5.22abcd	5.40abcd	115.70a	102.60a	101.00a
	SCF	7.02a	7.12a	7.10a	35.30bcd	34.50bcd	36.80bcd
Taung	CCF	2.70d	2.78d	2.88cd	41.10bcd	42.10bcd	43.30bcd
	CGL	2.52d	7.80a	2.86cd	32.90bcd	33.00bcd	34.40bcd
	SCF	6.36ab	6.06abc	5.70abcd	30.80bcd	32.80bcd	33.50bcd
Ventersdorp	CCF	5.12abcd	4.88abcd	4.94abcd	37.30bcd	38.20bcd	36.90bcd
	CGL	5.28abcd	5.38abcd	5.22abcd	35.80bcd	28.90bcd	28.70bcd
	SCF	5.26abcd	5.10abcd	4.94abcd	40.30bcd	40.10bcd	38.10bcd

Interaction effect within a column followed by the same letters is not significantly different from each other at ≤ 0.05 ; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

Table 4.12: Interaction effect of location, land use and soil depth on manganese and zinc in soils in North West Province

		Mn (mg/kg)			Zn (mg/kg)		
		Depth (cm)					
Location	Land use	0-15	15-30	30-45	0-15	15-30	30-45
Itsoseng	CCF	115.5bcdfe	123.2abcdef	119.3abcdef	8.52cdefghij	8.62bcdefghij	8.52cdefghij
	CGL	101.4cdefghi	104.2cdefgh	86.0fghi	8.24cdefghij	7.94defghij	8.36cdefghij
	SCF	115.1bcdef	111.6bcdef	122.6abcdef	9.64bcdefghi	10.58bcdefghi	9.74bcdefghi
Mathopestad	CCF	116.5bcdef	112.1bcdef	112.0bcdef	13.34bcde	12.94bcdef	8.78bcdefghij
	CGL	71.8ghi	69.7hi	66.6i	7.22defghij	7.98defghij	6.84efghij
	SCF	136.9abcd	134.1abcd	109.9cdef	32.48a	33.08a	32.40a
Taung	CCF	130.3abcd	122.8abcdef	124.1abcdef	2.70j	2.78j	2.88j
	CGL	106.4cdefg	99.4defghi	91.7efghi	4.02ij	6.10ghij	5.68hij
	SCF	105.3cdefgh	106.2cdefg	106.9cdefg	7.58defghij	7.22defghij	6.20fghij
Ventersdorp	CCF	137.3abcd	135.9abcd	139.3abc	13.94bcd	15.24b	14.80bc
	CGL	126.6abcde	123.0abcdef	126.8abcde	13.34bcde	12.60bcdefg	12.36bcdfehg
	SCF	140.0abc	149.4ab	155.9a	9.28bcdefghij	9.66bcdefghi	11.14bcdefgh

Interaction effect within a column followed by the same letters is not significantly different from each other at $p \leq 0.05$; CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm.

4.4.3 Pearson's correlation analysis of the soil indicators

Correlation analyses of the chemical indicators are presented in Table 4.13. Soil pH-H₂O and pH-KCl had a positive significant correlation ($r = 0.674^{**}$), while pH-KCl showed negative correlation ($r = -0.667^{**}$) with Δ pH. Electrical conductivity correlated negatively ($r = -0.520^{**}$) with Δ pH and significantly positively correlated ($r = 0.453^{**}$) with pH-KCl. Organic carbon showed significant positive correlation ($r = 0.193^{**}$) with electrical conductivity. Total nitrogen showed positive significant relationship ($r = 0.159^{*}$) with pH-H₂O and negative significant relationship ($r = -0.220^{**}$) with electrical conductivity. Available phosphorus observed negative significant relationship with nitrogen ($r = -0.194^{**}$) and Δ pH ($r = -0.348^{**}$) and had positive significant correlation with electrical conductivity ($r = 0.227^{**}$) and pH-KCl ($r = 0.225^{**}$). Exchangeable potassium found positively correlated with organic carbon ($r = 0.402^{**}$), electrical conductivity ($r = 0.516^{**}$), pH-KCl ($r = 0.321^{**}$) and had a negative significant ($r = -0.392$) relationship with Δ pH. Exchangeable aluminium recorded positive significant correlation with

total nitrogen ($r = 0.269^{**}$), organic carbon ($r = 0.286^{**}$), pH-KCl ($r = 0.186^*$), and had negative significant relationship with electrical conductivity ($r = -0.201^{**}$) and ΔpH ($r = -0.182^*$). A positive significant correlation was observed between exchangeable calcium and exchangeable potassium ($r = 0.514^{**}$), electrical conductivity ($r = 0.590^{**}$), pH-KCl ($r = 0.509^{**}$), pH-H₂O ($r = 0.289^{**}$) and significant negative relationship with exchangeable aluminium ($r = -0.279^{**}$) and ΔpH ($r = -0.395^{**}$). A significant positive correlation was also observed in exchangeable magnesium with exchangeable calcium ($r = 0.333^{**}$), total nitrogen ($r = 0.182^*$), electrical conductivity ($r = 0.150^*$), pH-KCl ($r = 0.196^{**}$) and pH-H₂O ($r = 0.370^{**}$). Cation exchange capacity observed positive significant relationship with exchangeable magnesium ($r = 0.621^{**}$), exchangeable calcium ($r = 0.943^{**}$), exchangeable potassium ($r = 0.483^{**}$), organic carbon ($r = 0.170^*$), electrical conductivity ($r = 0.558^{**}$), pH-KCl ($r = 0.487^{**}$), pH-H₂O ($r = 0.357^{**}$), however, it had negative significant relationship with exchangeable aluminium ($r = -0.262^{**}$) and ΔpH ($r = -0.296^{**}$). Available copper showed significant negative correlation with total nitrogen ($r = -0.181^*$), pH-KCl ($r = -0.161^*$) and pH-H₂O ($r = -0.178^{**}$). Positive significant correlation was found between available zinc and available copper ($r = 0.421^{**}$), cation exchange capacity ($r = 0.150^*$), exchangeable calcium ($r = 0.194^{**}$), exchangeable potassium ($r = 0.382^{**}$), available phosphorus ($r = 0.416^{**}$), electrical conductivity ($r = 0.272^{**}$), also had negative significant correlation with aluminium ($r = -0.247^{**}$), nitrogen ($r = -0.486^{**}$), ΔpH ($r = -0.282^{**}$) and pH-H₂O ($r = -0.318^{**}$). Available Mn had a significant positive correlation with zinc ($r = -0.208^{**}$), aluminium ($r = 0.155^*$), phosphorus ($r = 0.316^{**}$), pH-KCl ($r = 0.259^{**}$) but negative significant correlation with magnesium ($r = 0.222^{**}$) and ΔpH ($r = -0.289^{**}$). Significant negative correlation was observed between available iron and manganese ($r = -0.285^{**}$), aluminium ($r = -0.235^{**}$), potassium ($r = -0.148^*$) and obtained significant positive correlation with cation exchange capacity ($r = 0.184^*$), magnesium ($r = 0.456^{**}$), electrical conductivity ($r = 0.160^*$), ΔpH ($r = 0.222^{**}$) and pH-H₂O ($r = 0.174^*$).

Table 4.13: Pearson's correlation matrix for various soil chemical indicators

Parameters	pH H ₂ O	pH KCl	Δ pH	EC	Org C	Tot N	Avail P	Exch K	Avail S	Exch Al	Exch Ca	Exch Mg	CEC	Cu	Zn	Mn	Fe
pH H ₂ O	1	0.674**	0.101	0.088	0.042	0.159*	-0.045	0.039	-0.007	0.068	0.289**	0.370**	0.357**	-0.178*	-0.318**	0.058	0.174*
pH KCl		1	-0.667**	0.453**	0.087	0.140	0.225**	0.321**	0.036	0.186*	0.509**	0.196**	0.487**	-0.161*	-0.029	0.259**	-0.035
ΔpH			1	-0.520**	-0.075	-0.028	-0.348**	-0.392**	-0.056	-0.182*	-0.395**	0.110	-0.296**	0.038	-0.282**	-0.289**	0.222**
EC				1	0.193**	-0.220**	0.227**	0.516**	0.017	-0.201**	0.590**	0.150*	0.558**	-0.023	0.272**	0.073	0.160*
Org C					1	-0.047	-0.097	0.402**	-0.128	0.286**	0.108	0.143	0.170*	0.038	0.079	-0.031	0.08
Tot N						1	-0.194**	-0.114	0.054	0.269**	0.054	0.182*	0.098	-0.181*	-0.486**	-0.025	-0.100
Avail P							1	0.116	0.119	-0.073	0.115	-0.093	0.065	0.063	0.416**	0.316**	-0.113
Exch. K								1	0.003	0.028	0.514**	0.005	0.483**	0.136	0.382**	-0.019	-0.148*
Avail S									1	0.052	0.014	-0.031	0.000	-0.028	-0.015	0.039	-0.106
Exch. Al										1	-0.279**	-0.124	-0.262**	0.052	-0.247**	0.155*	-0.235**
Exch. Ca											1	0.333**	0.943**	-0.014	0.194**	0.020	0.035
Exch. Mg												1	0.621**	0.111	-0.095	-0.222**	0.456**
CEC													1	0.041	0.150*	-0.069	0.184*
Cu														1	0.421**	0.073	0.019
Zn															1	0.208**	-0.062
Mn																1	-0.285**
Fe																	1

*, **implies correlation is significant at 0.05 and 0.01 level, respectively (2 tailed test).

The computed values of SFI and SEF are presented in Table 4.14. The SFI values ranged from 1383 at Taung communal grazing land (CGL TNG) to 4958 at Mathopstad smallholder crop farm (SCF MTD) while SEF values ranged from 1363 at CGL TNG to 4934 at SCF MTD.

Table 4.14: Soil fertility index and Soil evaluation factor

Land use	Depth(cm)	SFI	SEF
CCF ITG	0 – 15	3396	3376
CGL ITG	0 – 15	2785	2763
SCF ITG	0 – 15	4934	4917
CCF MTD	0 – 15	1989	1971
CGL MTD	0 – 15	3251	3234
SCF MTD	0 – 15	4958	4934
CCF VTD	0 – 15	2457	2435
CGL VTD	0 – 15	2613	2593
SCF VTD	0 – 15	4809	4791
CCF TNG	0 – 15	2602	2574
CGL TNG	0 – 15	1383	1363
SCF TNG	0 – 15	3176	3145

CCF = commercial crop farm, CGF = communal grazing land, SCF = smallholder crop farm, ITG = Itsoseng, MTD = Mathopstad, VTG = Ventersdorp, TNG = Taung.

4.5 Discussion

4.5.1 Chemical fertility Indicators of the Soils

Soil chemical fertility indicators must have not only the capacity to provide nutrients for plants, but also retain or extract harmful chemical elements to the environment and plant growth under the changing conditions prevailing in a region. Soil pH, CEC, OC and nutrients are the main chemical indicators used in soil fertility assessment, especially when considering the capacity of the soil in supporting high yield crops (Kelly *et al.*, 2009). The soil chemical indicators can also be useful in considering the soil's capacity for sustaining forest production and sustainability, maintaining nutrient cycling, plant biomass and OM (Schoenholtz *et al.*, 2000). In this research, the most important soil chemical indicators that relate to soil fertility were carefully analysed and presented in Tables 4.1 – 4.2. Soil pH-H₂O and pH-KCl were significantly affected ($p \leq 0.05$) by the interaction effects of location, land use and soil depth where the highest was observed at Ventersdorp SCF at 30 -45 cm depth but not significantly higher than at Taung CCF and CGL (Table 4.1). Although relatively high pH values were obtained in the study area, this was attributed

to the presence of soluble bases, particularly calcium, magnesium and potassium, it could also be from the parent material from where the soil formed (Hazelton & Murphy, 2016). According to the class ratings of soil pH established by Jones Jr (2002), soils with pH values between 5.0 – 5.5 are strongly acidic, 5.6 -6.0 as moderately acidic, 6.0 – 6.5 as slightly acidic, 6.6-7.2 as neutral and 7.3-7.8 as slightly alkaline. Using these classes, the soils of the study area fell within the slightly acidic to neutral pH-H₂O and strongly acidic to slightly acidic in pH-KCl. The soil pH was rated as generally suitable for most crops. Wong *et al.* (2001) reported that the optimum pH for most crops fall between 6.0 and 7.0 and nutrients are more available at about pH 5.5 - 6.5. According to Brady & Weil (2013), a pH range of 5.5 to 7.0 is the preferred range for most crops because it is the range for the overall optimum availability of plant nutrients. Changes in hydrogen ion (ΔpH) values have been used to estimate the level of negatively charged clay colloids in soils (Alemayehu *et al.*, 2014). Generally, the value of ΔpH is positive, negative, or neutral, depends on the net surface charge of the soil. A positive ΔpH shows the presence of negatively charged soil colloids (Survey, 1993). The positive values show that the soils were all negatively charged. According to

Alemayehu *et al.* (2014), ΔpH values for a soil that is positive, shows the presence of considerable amount of negatively charged clay colloids. In this research, ΔpH in pH-H₂O and ΔpH -KCl were positively charged for all the soils (Table 4.1 and 4.4). The positive ΔpH values mean that the soils were relatively young, supporting the silt/clay ratio values shown in Table 4.1. The EC confirmed that the soils in the study area were not saline (Table 4.1) since the measured values were well below 1 mS/m. There was significant variability across and along the different locations and land use. As reported by Molin & Faulin (2013), electrical conductivity varies with differences in soil salinity, clay content and cation exchange capacity, clay minerals, pore size and distribution, organic matter and temperature. Electrical conductivity values of 0 to 2 ds/m are safe for all crops. Yields of very sensitive crops are affected between 2 to 4 ds/m. Many crops are affected between 4 and 8 ds/m; while tolerant crops grow reasonably well above that level (Bohn *et al.*, 2002; Daliakopoulos *et al.*, 2016). The low EC values recorded for these soils could be traced to parent materials of the soils (Abate *et al.*, 2014).

The results of organic carbon in the soils from the study are presented in Tables 4.1 and 4.5. The organic carbon ratings presented by Ravikumar (2013), rated organic carbon concentration for soils as < 0.5% (low), 0.5 - 0.75% (medium), > 0.75% (high). Based on the ratings above, soils from the study area ranged from 0.2 to 1.82% and rated as medium to high OC ratings.

Interaction effects of location, land use and soil depth were significantly influenced by organic carbon. The medium to high organic carbon levels of the study area could be attributed to the level of return of litter or agricultural residues added to the soils. The amount of OC in the soils could also be attributed to soil texture, climate and the current land use and management practices. According to West & Post (2002), land use types and agricultural management can increase or decrease soil OC. Kutu & Diko (2011) reported similar results in their research on mineralogical considerations in soil fertility management on selected farmlands in Limpopo and North West Province, South Africa. There was a slight variation in distribution of organic carbon across the locations and land uses. This variation in the amount of organic carbon was attributed to the differences in crop residue decomposition rate (Tsui *et al.*, 2004). According to Mzuku *et al.* (2005), higher organic carbon content is likely to contribute to increased aggregation and therefore increase soil aggregate stability. Despite mineral soils having low organic matter content; organic carbon is critically important to many aspects of soil fertility and plant growth. Soil organic carbon can range from less than 1 percent in many tropical, arid and semi-arid soils to 5 percent or more in temperate regions or under forest vegetation (Jahn *et al.*, 2006). Organic carbon also accounts for high soil nitrogen and phosphorus contents (Jahn *et al.*, 2006; Jamaluddin *et al.*, 2013).

Total N results are presented in Table 4.1 and 4.6. The total N contents of the studied soils were directly associated with organic C contents across the locations. The total N content in all locations, except Mathopestad, were higher, which is attributed to higher organic C contents. The higher total N content in the soils may be attributed to long-term cultivation coupled with frequent burning of crop residues (a common land clearing practice for cultivation) which accelerated the rapid turnover rates of organic materials under cultivation since total N in the soils is closely associated with organic C. Studies by Habtamu *et al.* (2009); Alemayehu *et al.* (2014) reported that bush burning and removal of crop residue significantly reduce soil organic carbon and total N contents as cultivated and uncultivated land were compared. The rating of total N < 0.1% as very low, 0.1 to 0.2% low, 0.2 to 0.5% medium, 0.5 to 1% high and > 1% as very high N status according to Landon (1991) as cited by Omar (2011). Hence, based on the information data generated from this study, N rating is high to very high in these wetland soils.

Available P results are presented in Table 4.1 and 4.6. According to 2007 South African fertilizer Handbook cited reported by Jacobs *et al.* (2018), soil available P level of < 5 mg/kg is low, 5 – 20

mg/kg is medium, while >20 mg/kg is high with 25 mg/kg considered optimum. Thus, the available P of soils in the study area qualified for very low to medium rating. The low to medium available P values observed in the soils of the study areas aligned with earlier results by Barnard and Du Preez (2004), which is attributed to P sorption or fixation, low level of application, removal through crop harvest, and soil erosion. Roberts *et al.* (2003) and Kutu (2012) also reported the poor P status reflects the low inherent P availability, as well as the low level of fertilization practiced by the farmers, along with the capacity of the soils to fix P strongly. There was a significant effect of location, land use and soil depth on available P and the highest value was found at Ventersdorp SCF at depth of 0 – 15 cm. Generally, variations in available P content in soils are related to the intensity of soil weathering, the degree of P- fixation with Fe and Ca and continuous application of mineral P fertiliser sources.

4.5.2 Exchangeable indicator of the soils

Tables 4.1 and 4.10 depict the concentrations of exchangeable K in the soils. According to the South African classification, <125 cmol/kg is deficient, 125 – 190 is sufficient, and >190 is excess (FERTASA, 2016). Comparing the mean values obtained in this study with the ratings above, the soils fall into the high to very high categories (Table 4.1 and 4.7). This suggests that the soils have sufficient K for crop growth. This could be attributed to the K bearing minerals (biotite and muscovite) observed in the study area. This result agrees with earlier study by Kutu and Diko (2011) who reported the presence of fairly high amount of mica, a K-bearing mineral suggesting that K pool in these fields can be naturally replenished. Optimum values for exchangeable Ca (cmol/kg) in soil should ideally range from 300 to 2000 for grain crops, while values of < 200 cmol/kg are too low for proper plant growth (Buys, 1986). In the soils studied, Ca levels are within optimum to high range for proper plant growth (Table 4.2 and 4.7). The soils had sufficiently high amount of calcium. The high amount of Ca in the study area could be from the parent materials from where the soils are formed concurs with Kutu and Diko (2011) who reported that the soils were within the optimum levels of Ca concentration. Buys (1986), reported exchangeable Mg contents for grain crops should be in the range of 80 -300 cmol/kg.

In soils of the study area, exchangeable Mg (Table 4.2 and 4.8) ranged from 331 to 1273 and can support optimum crop production. The result is in accordance with that of Roberts *et al.* (2003). The optimum level of Mg observed could be attributed to the presence of Mg-bearing minerals in

the soils (Bühmann *et al.*, 2006). The exchange complex was dominated by Ca followed by Mg and K, which could be considered as appropriate for plant growth. This result tallies with Mengiste *et al.* (2015) who reported that cations in productive agricultural soils are present in the order: Ca > Mg > K > Na and deviations from this order can create ion-imbalance problems for plants.

Exchangeable aluminum concentration is used as a guide to the possibility of aluminum toxicity in soils: critical levels of 0 - 15 as low, 15 - 50 as medium, 50 - 100 as high and > 100 cmol/kg very high (Cregan, 1980; Hayes *et al.*, 2015). However, aluminum levels greater than 15 cmol/kg could be a problem and above 50 cmol/kg is toxic (Cregan, 1980; Hayes *et al.*, 2015). With the results from this study (0.30 to 1.43 cmol/kg), the soils were free from aluminum problem and had acceptable limits. Srinivasarao *et al.* (2004) reported 10 cmol/kg (0.01 %) as critical threshold for S deficiency for most soils. Based on the threshold value, the sulphur obtained from the study (0.13 to 0.84%) therefore, was above the threshold level and was sufficient for crop production. The above results for sulphur are in accordance with that of Bühmann *et al.*, (2006). The exchangeable acidity (0.10 to 0.87 cmol/kg) values were low and can support plant growth (Jones Jr, 2002). The slightly acidic to neutral pH could be attributed to the high concentration of exchangeable bases in the soils and the parent materials from which the soils were formed. Secondly, from the semi-arid nature of the environment which is characterised by low rainfall with less leaching loss of basic cations has also contributed the results observed (Brady & Weil, 2013). However, the results of this study indicated that pH of the study area was above 5.5 and basic cations had occupied the site. The concentration of exchangeable Al^{+3} was very low and Al toxicity problem was not expected in the study area.

According to Landon (1991), the soils having CEC of < 5, 5 - 15, 15 - 25 and > 25 cmol/kg) are rated as very low, medium and high, respectively. Based on the above ratings, the measured CEC concentrations of 11.7 to 18.31 cmol/kg in the soils sampled qualified for low to medium status, respectively. The low to medium CEC contents might be due to the parent materials from where the soils are formed. It could also be due to low levels of clay and organic carbon. This result was in accord with Kutu & Diko, (2011). Foth (1990) and Tan (2009) reported that humus combined with clay resulted in increased CEC, the addition of plant residues with OC content of 40 - 50% increased soil's negative charge while low pH reduces CEC. However, Sanchez considered CEC values above 4 as capable of withstanding heavy leaching losses of nutrients in tropical soils

(Sanchez, 1976; Dickson & Kamalu, 2021). . The results from the study area have enough CEC to withstand leaching loss of nutrients.

4.5.3 Micronutrients of the soils (Cu, Fe, Mn and Zn)

The critical levels of micronutrients in soils are categorized as follows: Cu < 0 - 0.7 mg/kg is deficient, 0.75 -100 mg/kg sufficient, 100 - 150 mg/kg high, > 150 mg/kg toxic; Fe < 5 mg/kg as deficient, > 5 sufficient; Mn < 50 as low, between 50 – 1000 mg/kg sufficient, 1000 - 2000 mg/kg high, > 2000 toxic; Zn < 3 mg/kg low, 3 - 150 as sufficient, 150 - 140 mg/kg high, and > 400 as toxic (Landon, 1991). According to ratings by Landon (1991), soils in the study area (2.95 to 5.94 mg/kg) indicated that Cu was within sufficient range in all locations for crop production. Iron had a range higher than the (32.6 to 60.5mg/kg) sufficient level. The range of Mn was within the (111.0 to 137.1 mg/kg) sufficient level too when compared to critical values. Available Zn (5.02 to 17.23 mg/kg) was sufficient for the production of crops in all locations. The sufficient levels of available micronutrients in the study area could be attributed to the nature of the parent materials from which the soils are derived. This is in agreement earlier study by Mandiringana *et al.*(2005) who reported on the mineralogical and fertility status of selected soils of the Eastern Cape Province, South Africa. However, findings observed in current study contradict the work by Roberts *et al.* (2003) who reported lower Mn and Zn levels in two resource-poor farming communities of KwaZuluNatal, South Africa.

4.5.4 Soil Fertility Index and Soil Evaluation Factor under different locations, land use types at 0 – 15 cm depth

In this research, both SFI and SEF were used to evaluate the fertility status of the soils (Table 4.14). The soils recorded high values of SFI and SEF in all the farms studied. It was observed that SCF had higher values than both CCF and CGL. The higher values of SFI and SEF could be attributed to the higher calcium, potassium, and magnesium contents in the study area. All the soils from the study area had SEF values much higher than the critical value of 5 and by the standard of Lu et al. (2000), the soils are considered fertile.

4.6 Conclusion

The study revealed marked variation in soil chemical fertility indicators across the different locations, land use types and soil depths. Soil pH values obtained were slightly acidic to neutral

and suitable for most crops. The soils were free from the salinity problem and OC was rated medium to high. Available phosphorus was rated low to medium, total nitrogen was rated high. Generally, exchangeable K, Ca, Mg were in high amounts and can support proper plant growth. It was also verified that the soils were free from Al toxicity problem. Sulphur levels were above the critical level and sufficient for normal crop production activities. Micronutrients statuses were also high enough for crop production in the study area. According to the SFI and SEF values, all wetland soils studied were fertile for agricultural production. Generally, most of the soil chemical fertility indicators determined fell within the acceptable limits and therefore, recommended for agricultural production. In addition, the variability of the measured soil chemical indicators could help to explain eventual abnormalities of the results in future studies. According to the findings of this study, it is suggested that adequate fertilisation and good crop and/or soil management should be practiced based on the soil variability in the research area. This could help to improve the productivity and fertility of the soils within the research area for sustainable crop production.

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CHAPTER FIVE

MINERALOGICAL STUDY OF SELECTED SOILS IN NORTH WEST PROVINCE OF SOUTH AFRICA

5.1 Abstract

Soils from twelve different farms were studied to quantify the mineralogical composition and mineral diversity. Thirteen different mineral phases were identified comprising of quartz, magnesioferrite, kaolinite, calcite, biotite, dolomite, muscovite, portlandite, nacrite, rutile, albite, brucite and pyrochroite. Quartz was the dominant clay mineral (71.2 to 99.4%) in all soils, followed by kaolinite (0.5 to 16.3%). Muscovite (0.7-11.6%), albite (3.2-5.9%), Nacrite (0.11.8%), magnesioferrite (0.1-1.6%), portlandite (0.1-0.6%), calcite (0.3-1.2%), biotite (0.1-1.2), dolomite (0.1-1.1%), rutile (0.1-1.2%), brucite (0.5%) and pyrochroite (0.2 %). The obvious amounts of magnesioferrite, dolomite, muscovite and biotite observed in the mineral suite suggests the potential ability of the soils to weather and supply plant nutrients (Ca, Mg, K, Fe and Mn) to the soil environment.

Keywords: mineralogical compositions, XRD, mineral, quartz, kaolinite, dolomite

5.2 Introduction

Soil mineralogy is the study of the composition of solid inorganic phase that controls the physical and chemical processes in soils. It is one of the most important soil forming factors and therefore a key determinant of basic soil functional properties (Jenny, 1994; Scalenghe, 2006). Soil mineralogy has a profound influence on the dynamic behaviours of soil namely the gains, losses, transformation and translocation of organic and inorganic substances (Nyambura, 2013). Amongst the numerous attributes of soil, mineralogical composition impacts the physical and chemical properties that develop the soil (Dixon & Schulze, 2002). Composition, properties and mineralogical transformations in parent material can provide a meaningful understanding of the weathering and pedogenetic processes occurring in soils (Coelho & Vidal-Torrado, 2003; Kämpf & Curi, 2012).

Soil minerals consist of physical, chemical and crystalline properties and are grouped into primary and secondary; silicates and non-silicates, crystalline and non-crystalline minerals (Brady & Weil, 2013), with silicates dominating in most soils. Other soil mineral groups include sulphides, oxides and hydroxides, halides, sulphates, carbonates and phosphates (Esu, 2010). Mineral particles make

up about 50% of the volume of most soils and knowing the different minerals present in a soil and chemical composition of these minerals is important to the understanding, use and management of the soils (Brady & Weil, 2013).

Information on the mineralogical composition of soils can show the degree of rock weathering that has taken place in the formation of soil and helps in the interpretation of evolutionary dynamics of soil and its properties, with direct consequences for management practices (Santos *et al.*, 2017). Information on soil mineralogy is also important for assessing the soil physical and chemical properties, such as interactions with nutrients, quantity of nutrients and its availability (intensity of retention by soil), sorption of metals, organics and nutrients to mineral surfaces, fertiliser response, water storage, erosion susceptibility and provision of sites for microbial and faunal activities (Nyambura, 2013).

Secondary soil minerals account for the vast majority of important phenomena contributing to soil fertility management (Gupta *et al.*, 1984). Ajiboye & Ogunwale (2013) opined that the secondary minerals make an important contribution to soil physical attributes (texture, structure, consistency, permeability, expansion and contraction) and chemical properties (nutrient availability, CEC, pH and sorption of metals) while Santos *et al.* (2017) reported that soil chemical properties are mainly due to the small size of the particles, their high surface area and surface reactivity. Soil minerals play a major role in controlling the fitness of soil for various land uses. They make available physical support for plants, add to soil structure formation, and source of soil nutrients, (Brady & Weil, 2008; Mandiringana *et al.*, 2005) and act as sorbents of several pollutants. Therefore, knowledge of soil mineralogy contributes to understanding many areas of land use central to solving specific agricultural and environmental problems.

Generally, the identification and semi-quantification of minerals of the soil fraction are performed by XRD techniques. The common methods used for soil mineral characterization are X-ray diffraction, thermal elemental and optical analysis. These techniques have special features which help predict their impact on the overall soil behaviour. The X-ray diffraction (XRD) technique is generally used to determine mineralogy of soils. It is a rapid, non-destructive technique for qualitative and quantitative analysis of crystalline compounds. For mineral identification (silicate clays, carbonates, oxides and some organic components) phases as little as 1-3% sample weight can be identified independent of the crystal type (Moore & Reynolds Jr, 1997). Information on the

mineralogy of soils in the North West Province is scanty, especially soils from the selected farmland areas. Such information is, however, important for any strategy that seeks to improve the agricultural productivity of the selected areas of the province. Thus, the over-arching objective of this study was to provide an outline on the mineralogical composition of the selected soils in North West Province of South Africa.

5.3 Materials and Methods

Chapter three sections 3.2.1 to 3.2.6 offer a description of the study area, map of the study area (Figure 3.1), climate of the province, vegetation, geology/agricultural activities, and soil samples collection.

5.3.1 Samples preparation

The twelve (12) selected farms from the four districts i.e., one smallholder crop farm, one commercial crop and one communal grazing land soils from each district were used for this research. The soil samples collected randomly from five different points from each farm at 0-15 cm, 15-30 cm and 30-45 cm depths were bulked to three samples per farm. In all, thirty- six (36) soil samples were collected for the XRD analysis. The samples were air dried and crushed in a mortar and pestle, sieved to pass through a 2 mm sieve and bagged for analysis. Representative bulk samples were crushed again, milled and homogenised to fine powder at approximately 10-15 μm in size.

5.3.2 Mineralogical Analysis of Soil Samples

5.3.3 X-ray pattern acquisition, phase identification and quantification

Quantitative and semi qualitative mineralogical analysis was determined on sub-samples taken from the bulk samples using X-ray diffractometry (XRD) as described by Loubser & Verry, (2008). The mineralogical study on the ground sub-sample was carried out based on random powder analysis using X-Ray diffraction (Ekosse & Ngole, 2012; Loubser & Verry, 2008). The XRD analysis is a non-destructive analytical technique for the identification and quantification of different crystalline phases present in a sample. A PANalytical X'Pert Pro XRD instrument was used to make a broad range identification to characterise the crystal structures of the materials present in the samples. Sample analysis was done using a back-loading technique and the samples were loaded onto a spinner stage inside the XRD. The samples were scanned using X-rays generated by a Cu X-Ray

tube. As a result of the different crystalline structures detected in the sample, using an X'Celerator detector, a unique diffractogram for each sample was generated. The diffractogram shows the different phases (peak positions) and phase concentrations (peak heights) of all the crystalline materials present in each sample.

The position and relative intensity of a series of peaks were used to match experimental data from the diffractogram to the reference patterns in the database. The relative abundance of the mineral compositions of the bulk soil samples were determined semi-quantitatively by peak heights (I) and were calculated using the methods developed by Schultz (1964) and (Hillier, 2002).

The ratio of peak intensities (I) varies linearly as a function of weight fractions for any two phases in a mixture. This gives semi-quantitative results by extracting the reference intensity ratio (RIR) from the Powder Diffraction File (PDF) reference database to quantify the mineral phases.

5.3.4 Data analysis

Data analysis was performed using the Powder Diffraction File (PDF) database (containing over 300,000 diffraction patterns of crystalline phases) from the International Centre for Diffraction Data (ICDD).

5.4 Results

5.4.1 Distribution of clay minerals in the soils of the farms from study area

Table 5.1 showed the clay mineral composition of the ground sub-sample of the soils from the farms at the four districts. Thirteen different clay mineral phases were identified in the study area. They are quartz, magnesioferrite, kaolinite, calcite, biotite, dolomite, muscovite, portlandite, nacrite, rutile, albite, brucite and pyrochroite with their percentages depicted. Quartz (SiO_2) had a percentage range of 71.2 to 99.4%. The highest value was recorded at Itsoseng smallholder crop farm (ISCF) at 15-30 cm depth and lowest quartz was observed in Mathopestad smallholder crop farm (MSCF) at 30-45 cm depth. Kaolinite constituted about 0.5 to 16.3% of the minerals' assemblage in the soils. The highest value was obtained at MSCF while the least was at Ventersdorp smallholder crop farm (VSCF) at 0-15 cm depth. Muscovite (0.7-11.6%) was obtained in MSCF, MCCF, MCGL and VSCF samples. Albite (3.2-5.9%) was identified in Taung smallholder crop farm (TSCF), Taung commercial crop farm (TCCF) and Taung communal grazing land (TCGL). Nacrite (0.1-1.8%) was

recorded at Itsoseng commercial crop farm (ICCF) and Itsoseng communal grazing land (ICGL). Magnesioferrite (0.1-1.6%) was identified in all farms. Portlandite (0.1-0.6%) was found in VCGL, ISCF, ICGL and TCGL. Calcite (0.3-1.2%) was also identified in all the farms investigated. Biotite (0.1-1.2 %) was recorded in MSCF, MCCF and MCGL. Dolomite (0.1-1.1%) was observed in MSCF, MCCF, MCGL, VSCF and TCGL. Rutile (0.1-1.2%) was identified in TSCF, TCCF and TCGL. Brucite (0.5%) was at TSCF and pyrochroite with 0.2% was identified in TCGL.

In general, Quartz (SiO_2) and Calcite (CaCO_3) were found in soils from all twelve farms while Magnesioferrite (Fe_2MgO_4) was found in soils from eleven farms. Kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_2$) was identified in soils from four out of the twelve farms while biotite ($\text{KAl}(\text{Mg},\text{Fe})_3\text{Si}_3\text{O}_{10}(\text{OH})_2$) was found in soils from three out of the twelve farms. Dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$) was recorded in five farms. Muscovite ($\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH},\text{F})_2$) was identified in four out of the twelve farms. Portlandite ($\text{Ca}(\text{OH})_2$) was identified in five farms. Nacrite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) also was recorded in soils from two farms, while Rutile (TiO_2) and Albite ($\text{NaAlSi}_3\text{O}_8$) were identified in soils from three out of the twelve farms. Brucite ($\text{Mg}(\text{OH})_2$) and pyrochroite ($\text{Mn}(\text{OH})_2$) were identified in soils from one farm each in very small percentages (Table 5.1 and Figures 5.2- 5.37).

Thirteen different clay mineral types were identified with the specific groups to which these mineral assemblages belong. Silica group (silicate mineral) with quartz and albite. Kaolinite group - 1:1 clay mineral consisting of kaolinite and nacrite. Mica group - 2:1 clay minerals identified were biotite and muscovite. Carbonate group had calcite and dolomite. Oxide and hydroxide groups had magnesioferrite, portlandite, rutile, brucite and pyrochroite. The silica group - quartz (SiO_2) represents the most dominant clay mineral constituting 71.2 to 99.4%, albite (3.2-5.9%), followed by kaolinite group (kaolinite) with 0.5 to 16.3% and nacrite (0.1-1.8%) of the minerals. The mica group showed muscovite with 0.7-11.6%, and biotite (0.1-1.2 %). Carbonate group had calcite (0.3-1.2%) and dolomite (0.1-1.1%). Oxide and hydroxide groups - magnesioferrite (0.1-1.6%) was identified in all farms. Portlandite (0.1-0.6%), rutile (0.1-1.2%), brucite (0.5%) and pyrochroite (0.2%) were also identified, respectively. Figures 5.1 to 5.36 represent the X-ray diffraction patterns of soil samples from the different locations of the study area presented in page 111 to 128.

Table 5.1: Sampling sites and percent distribution of clay minerals in the bulk soil from the study area

<u>SMST</u>	<u>DPT</u>	<u>Qtz</u>	<u>Mgf</u>	<u>Cal</u>	<u>Kao</u>	<u>Bio</u>	<u>Dol</u>	<u>Mus</u>	<u>Pld</u>	<u>Nac</u>	<u>Rut</u>	<u>Alb</u>	<u>Bru</u>	<u>Pyr</u>
MSCF	0-15	91.1	1.6	0.6	4.5	1.2	1.1	-	-	-	-	-	-	-
	15-30	85.2	0.8	0.7	3.9	0.6	0	8.8	-	-	-	-	-	-
	30-45	71.2	0.1	0.5	16.3	0.2	0	11.6	-	-	-	-	-	-
MCCF	0-15	91.4	0.4	0.5	2.9	0.5	0.4	3.9	-	-	-	-	-	-
	15-30	88.7	0.4	0.8	3.4	0.7	0.3	5.6	-	-	-	-	-	-
	30-45	88.9	0.5	0.7	3.9	0.8	0.3	4.9	-	-	-	-	-	-
MCGL	0-15	93.2	0.4	0.6	1.8	0.2	0.4	3.4	-	-	-	-	-	-
	15-30	95.3	0.4	0.3	1.2	0.3	0.3	2.3	-	-	-	-	-	-
	30-45	94.9	0.4	0.5	1.6	0.1	0.2	2.3	-	-	-	-	-	-
VSCF	0-15	97.9	0.1	0.6	0.5	-	0.2	0.7	-	-	-	-	-	-
	15-30	97.2	0.4	0.6	-	-	0.20	1.60	-	-	-	-	-	-
	30-45	98.8	0.5	0.7	-	-	-	-	-	-	-	-	-	-
VCCF	0-15	98.8	0.2	0.7	-	-	-	-	0.30	-	-	-	-	-
	15-30	98.3	0.5	0.6	-	-	-	-	0.60	-	-	-	-	-
	30-45	98.3	0.4	0.7	-	-	-	-	0.60	-	-	-	-	-
VCGL	0-15	98.6	0.3	0.8	-	-	-	-	0.30	-	-	-	-	-
	15-30	98.7	0.3	0.6	-	-	-	-	0.40	-	-	-	-	-
	30-45	99.4	-	0.6	-	-	-	-	-	-	-	-	-	-
ISCF	0-15	98.8	0.2	0.7	-	-	-	-	0.30	-	-	-	-	-
	15-30	99.4	0.2	0.3	-	-	-	-	0.10	-	-	-	-	-
	30-45	98.8	0.4	0.8	-	-	-	-	0.10	-	-	-	-	-
ICCF	0-15	98.6	0.3	0.7	-	-	-	-	0.40	-	-	-	-	-
	15-30	97.4	0.4	0.7	-	-	-	-	0.70	0.80	-	-	-	-
	30-45	98	0.2	0.7	-	-	-	-	0.40	0.70	-	-	-	-
ICGL	0-15	97.4	0.2	0.7	-	-	-	-	0.40	1.20	-	-	-	-
	15-30	97.5	0.4	0.5	-	-	-	-	0.40	1.20	-	-	-	-
	30-15	97.1	0.3	0.8	-	-	-	-	-	1.80	-	-	-	-
TSCF	0-15	98.3	0.5	1.2	-	-	-	-	-	-	-	-	-	-
	15-30	95.2	-	-	-	-	-	-	-	-	1.00	3.80	-	-
	30-45	95.5	-	-	-	-	-	-	-	-	0.80	3.20	0.50	-
TCCF	0-15	94.8	0.2	1	-	-	-	-	-	-	0.10	3.90	-	-
	15-30	95.1	0.2	0.8	-	-	-	-	-	-	0.20	3.60	-	-
	30-45	95.2	0.1	0.9	-	-	-	-	-	-	0.20	3.60	-	-
TCGL	0-15	92.8	-	1.2	-	-	0.80	-	-	-	1.20	4.00	-	-
	15-30	91.7	-	1.2	-	-	0.60	-	-	-	1.00	5.30	-	0.20
	30-45	92.4	-	1	-	-	-	-	0.40	-	0.40	5.90	-	-

SMST = Sampling site, DPT = depth (cm), Qtz= Quartz, Mgf= Magnesioferrite, Cal= calcite, Kao= Kaolinite, Bio= Biotite, Dol= Dolomite, Mus= Muscovite, Pld= Portlandite, Nac= Nacrite, Rut= Rutile, Alb= Albite, Bru= Brucite, Pyr= Pyrochroite, MSCF = Mathopetard smallholder crop fam, MCCF = Mathopetard commercial crop fam, MCGL = Mathopetard communal grazing land, VSCF = Ventersdorp smallholder crop farm, VCCF = Ventersdorp commercial crop farm, VCGL = Ventersdorp communal grazing land, ISCF = Itsoseng smallholder crop farm, ICCF = Itsoseng commercial crop farm, ICGL = Itsoseng communal grazing land, TSCF = Taung smallholder crop farm, TCCF = Taung commercial crop farm and TCGL=Taung communa lgrazingland.

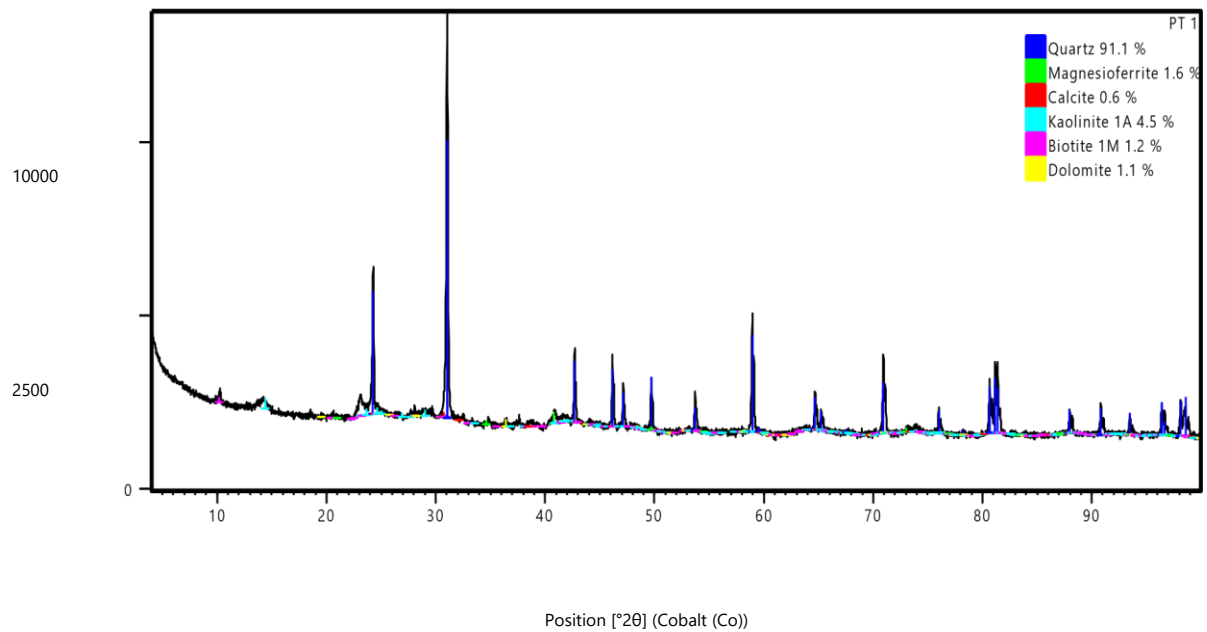


Figure 5.1: X-ray diffraction pattern of soil sample from 0 - 15 cm depth of small holder farm at Mathopestad

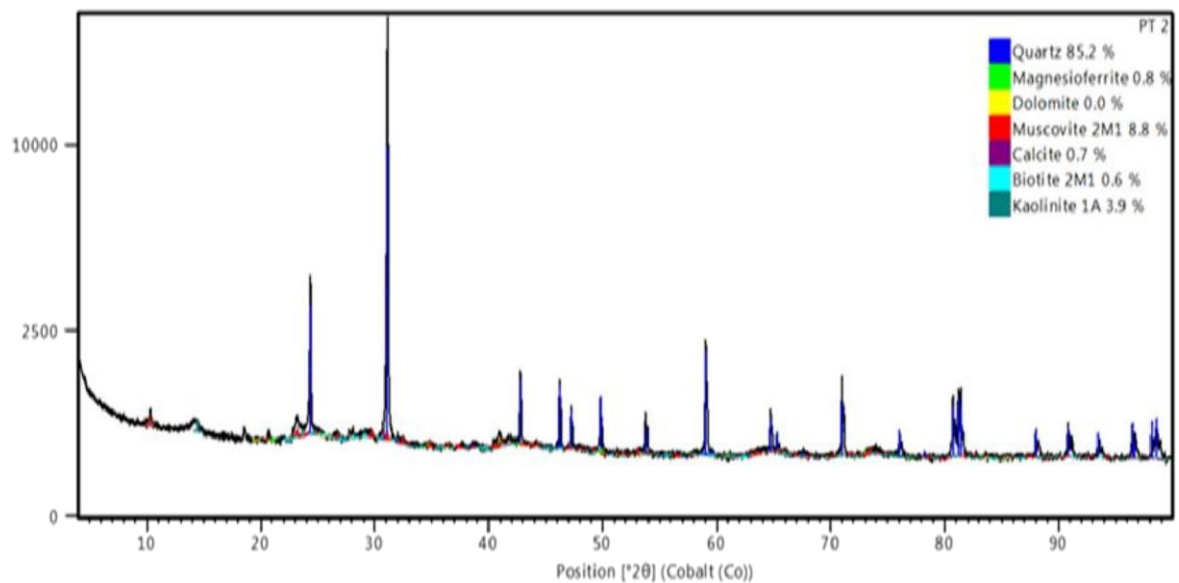


Figure 5.2: X-ray diffraction pattern of soil sample from 15 - 30 cm depth of smallholder crop farm Mathopestad

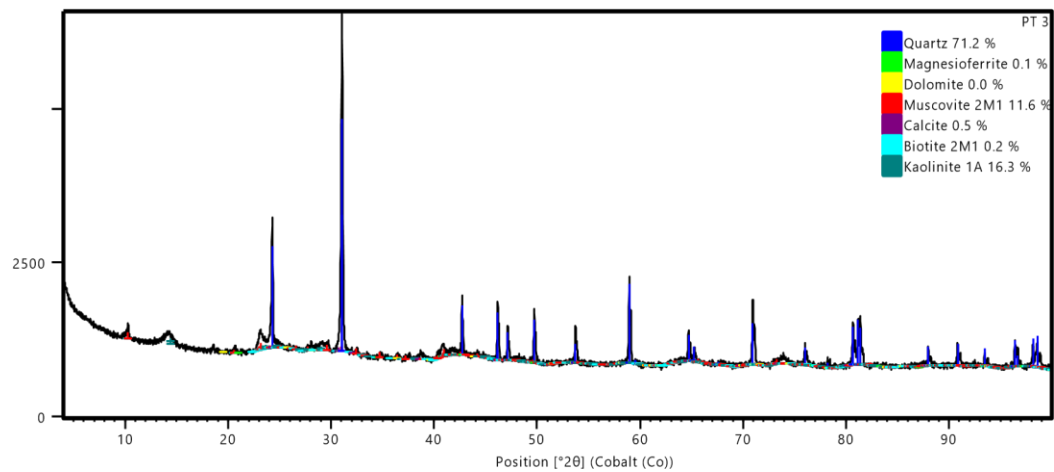


Figure 5.3: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of smallholder crop farm Mathopestad

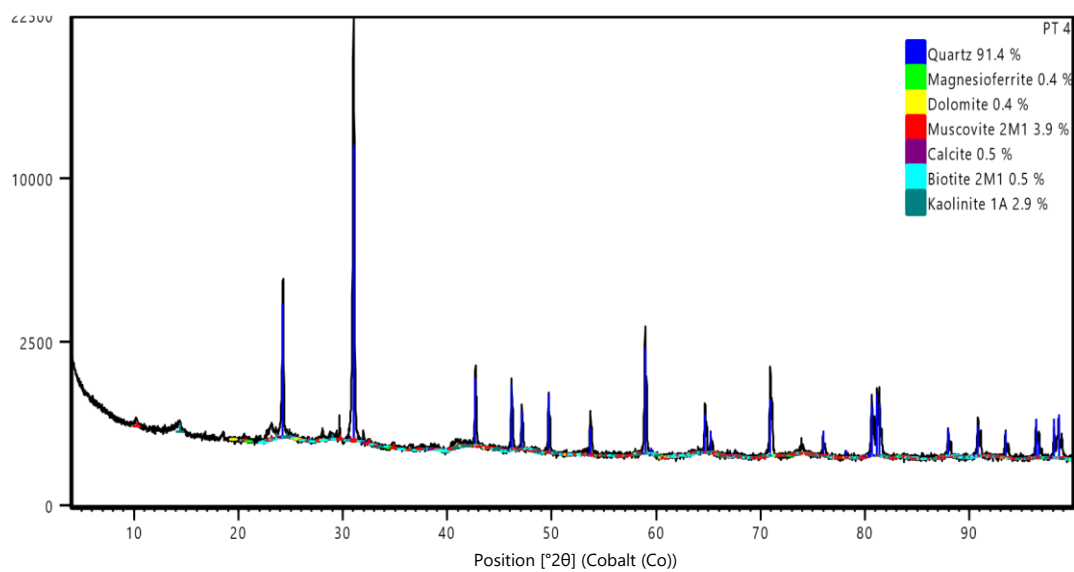


Figure 5.4: X-ray diffraction pattern of soil sample from 0 - 15 cm depth of commercial crop farm Mathopestad

Counts

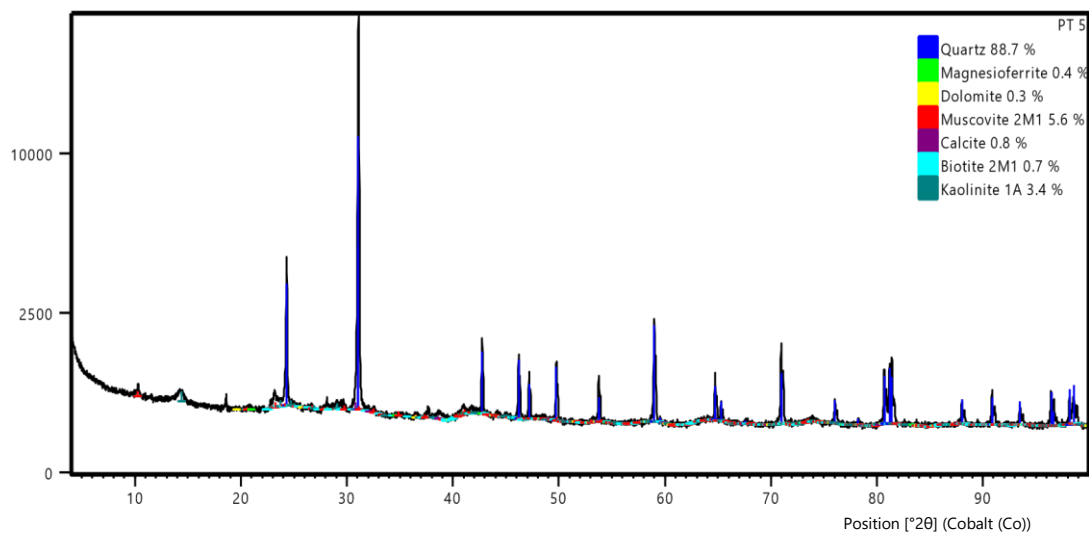


Figure 5.5: X-ray diffraction pattern of soil sample from 15 - 30 cm depth of commercial crop farm Mathopestad

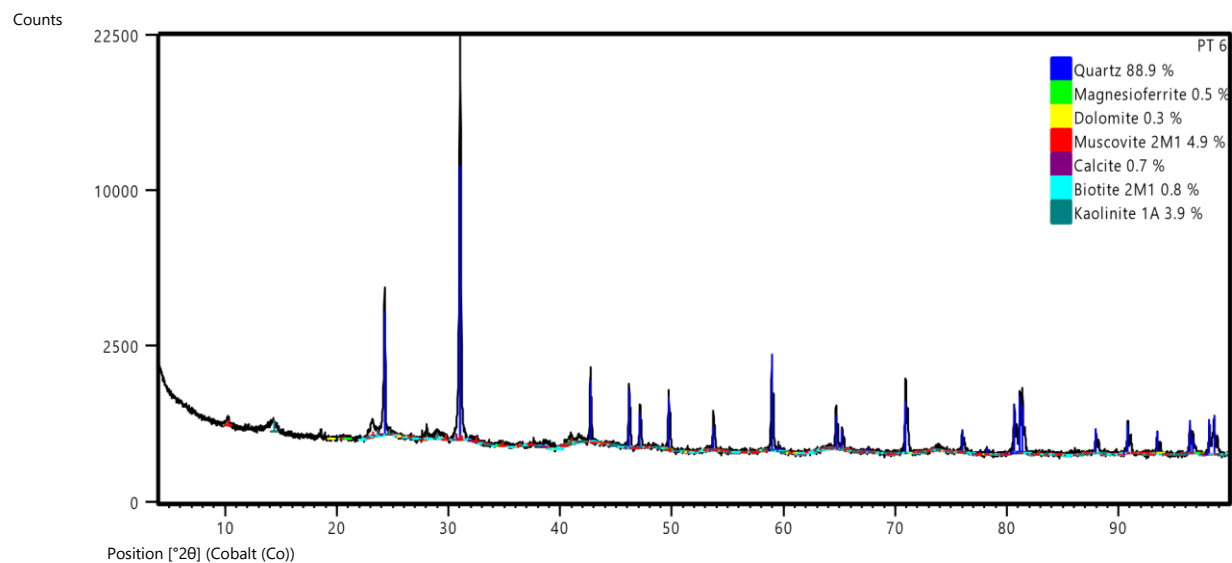


Figure 5.6: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of commercial crop farm Mathopestad

Counts

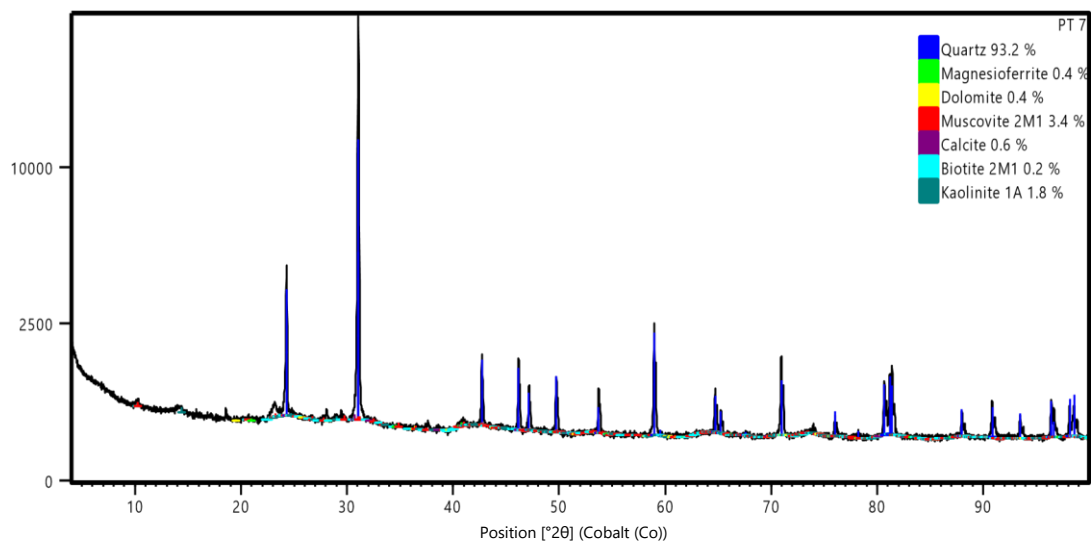


Figure 5.7: X-ray diffraction pattern of soil sample from 0 - 15 cm depth of communal grazing land at Mathopetard

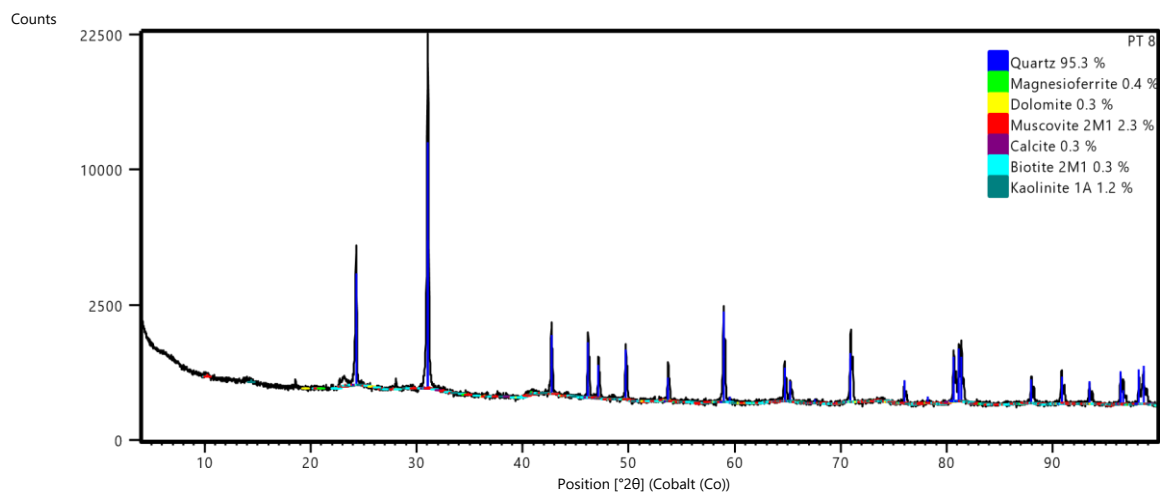


Figure 5.8: X-ray diffraction pattern of soil sample from 15 - 30 cm depth of communal grazing land at Mathopetard

Counts

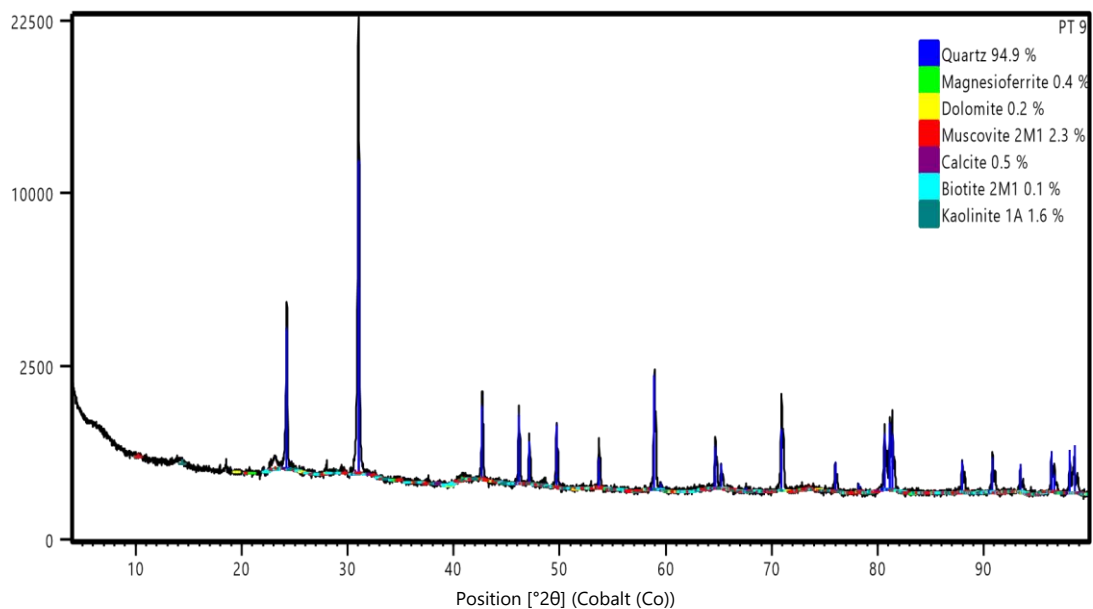


Figure 5.9: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of communal grazing land at Mathopestad

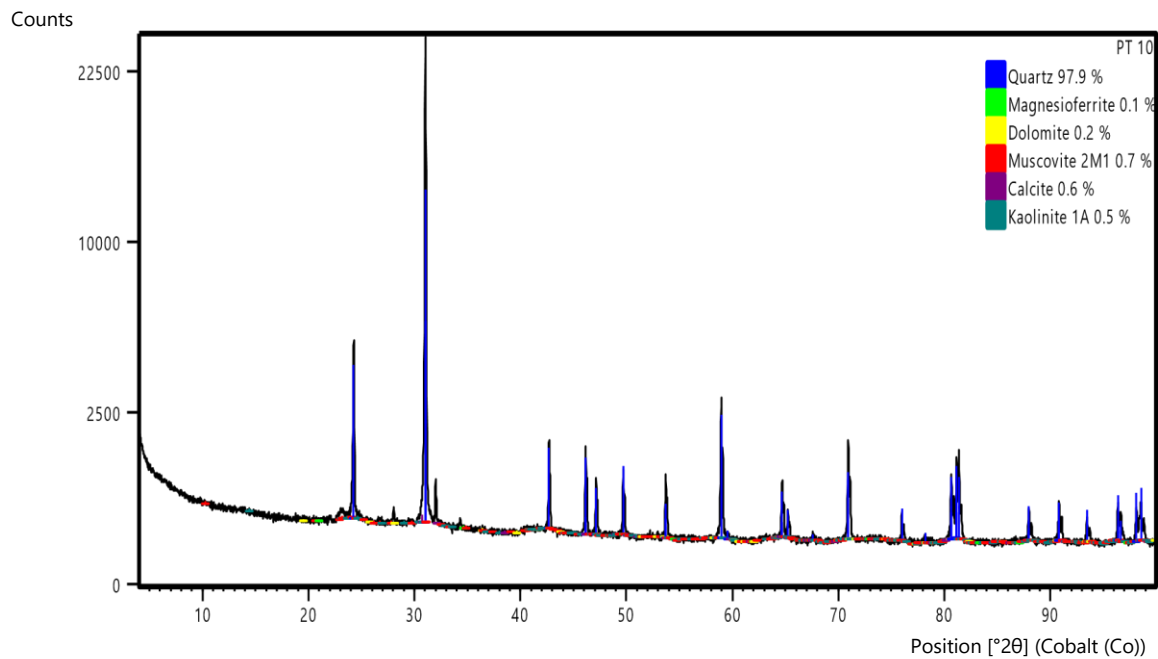


Figure 5.10: X-ray diffraction pattern of soil sample from 0-15 cm depth of smallholder crop farm at Ventersdorp

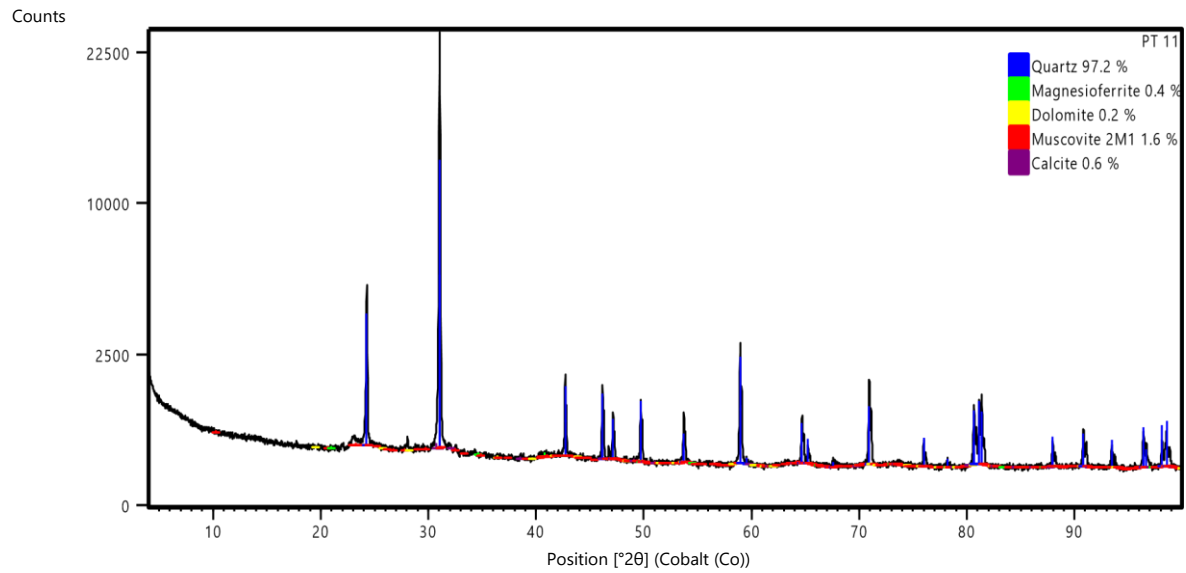


Figure 5.11: X-ray diffraction pattern of soil sample from 15-30 cm depth of smallholder crop farm at Ventersdorp

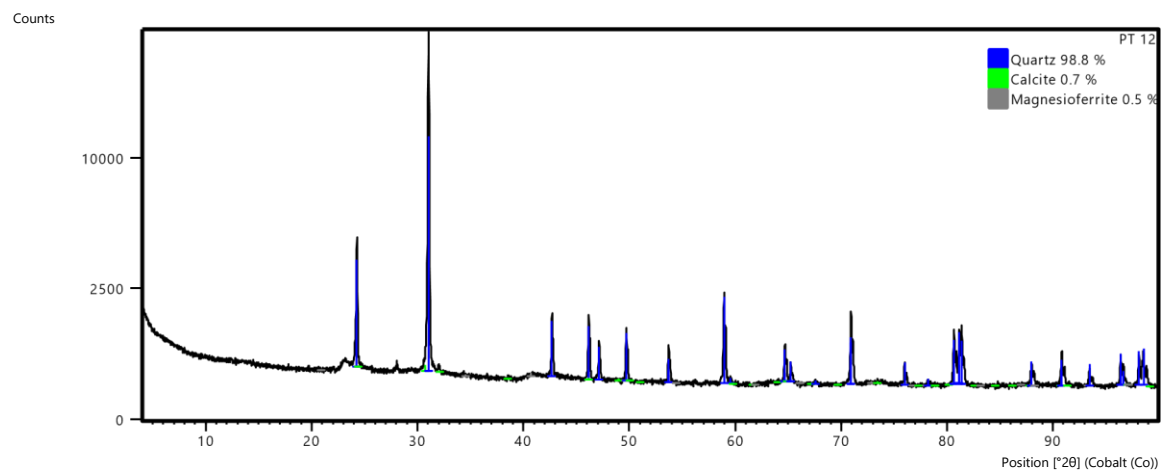


Figure 5.12: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of smallholder crop farm at Ventersdorp

Counts

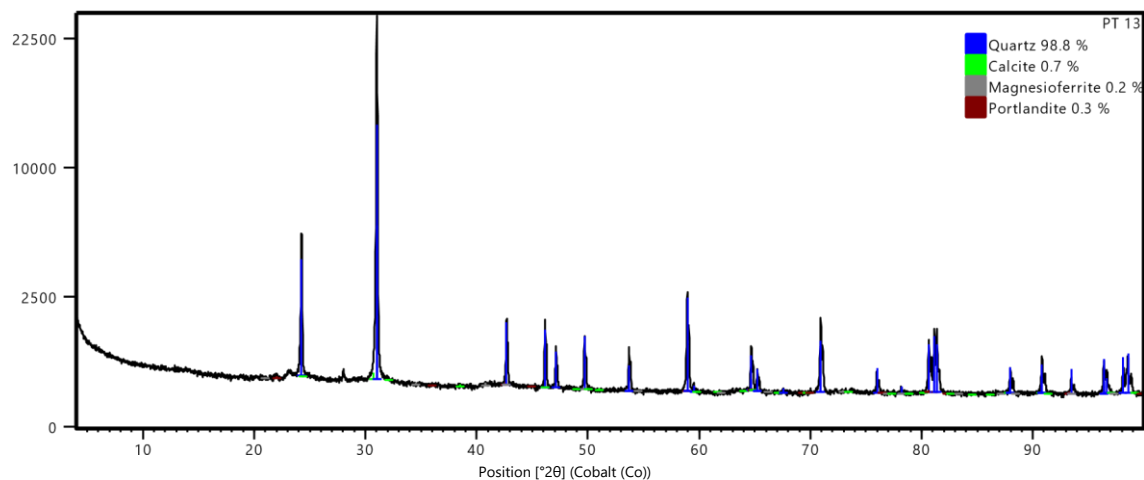


Figure 5.13: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of commercial crop farm at Ventersdorp

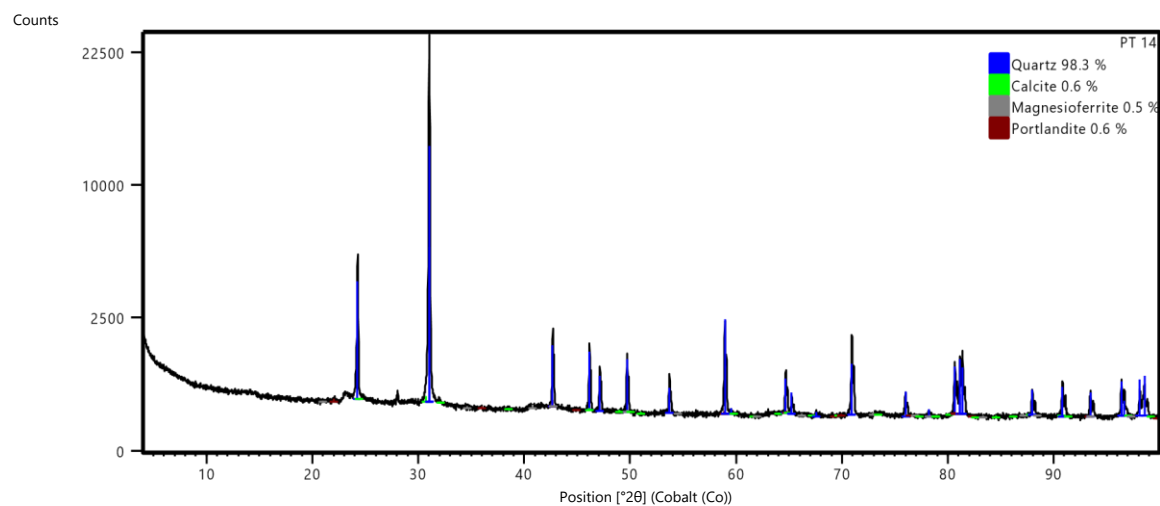


Figure 5.14: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of commercial crop farm in Ventersdorp

Counts

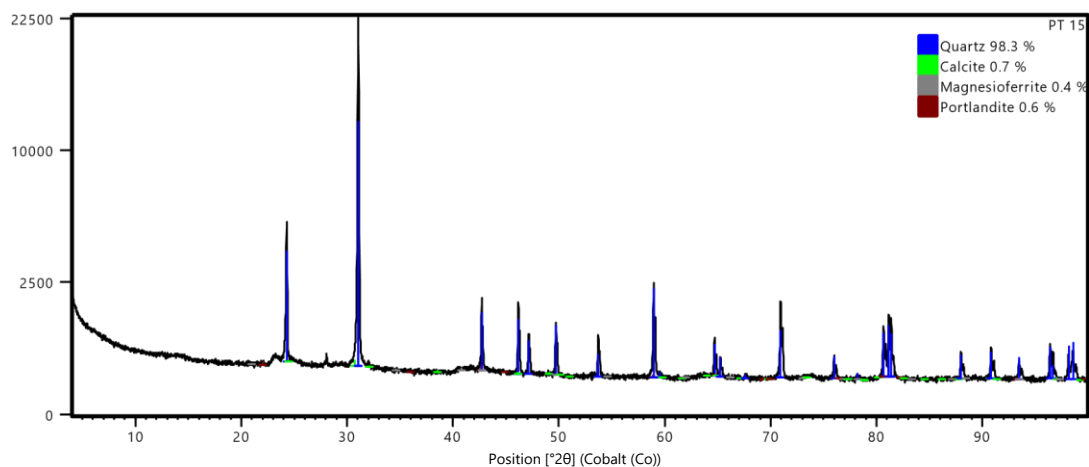


Figure 5.15: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of commercial crop farm at Ventersdorp

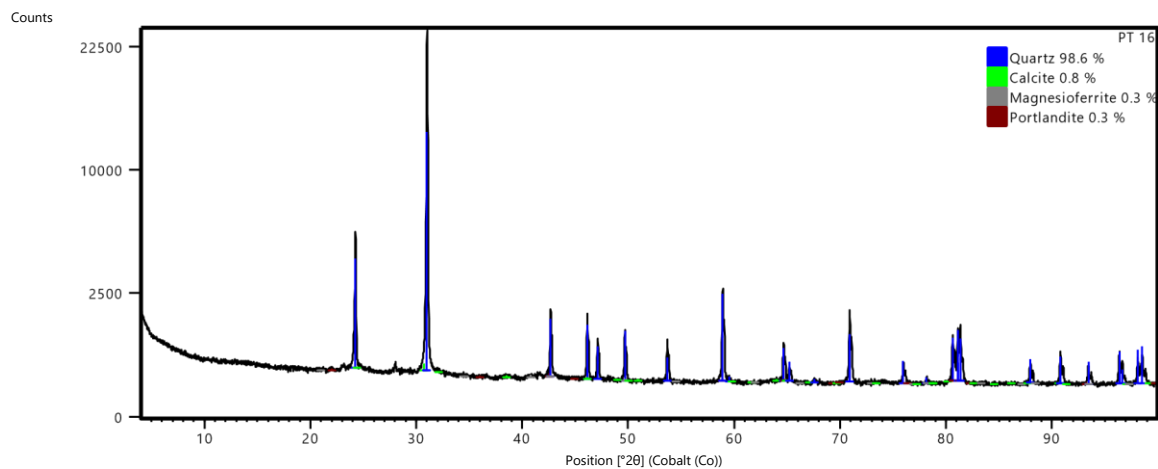


Figure 5.16: X-ray diffraction pattern of soil sample from 0 - 15 cm depth of communal grazing land at Ventersdorp

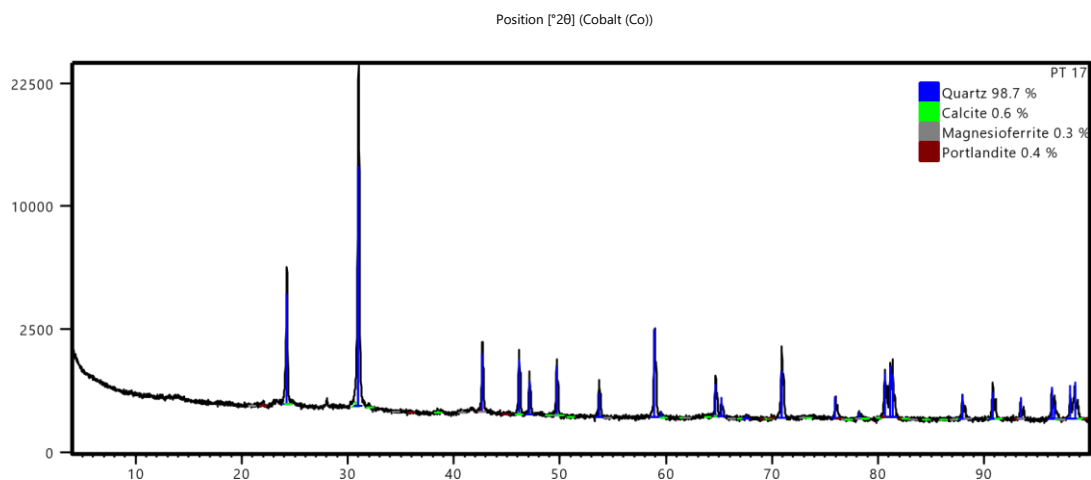


Figure 5.17: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of communal grazing land in Ventersdorp

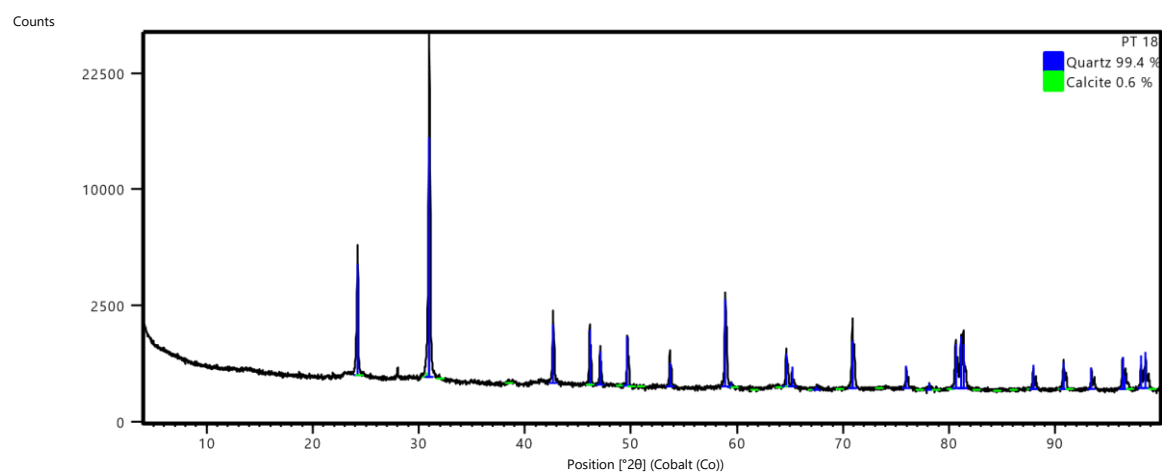


Figure 5.18: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of communal grazing land at Ventersdorp

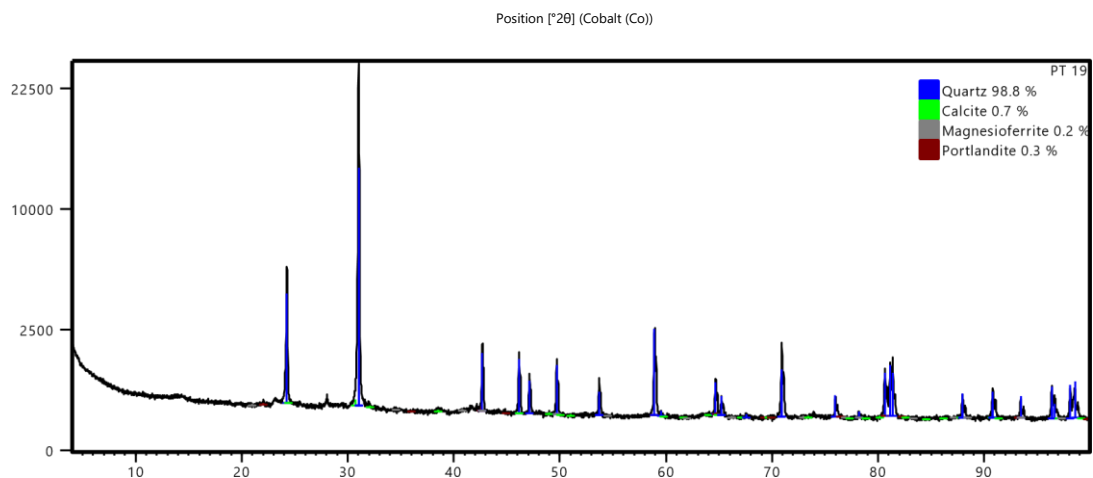


Figure 5.19: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of smallholder crop farm at Itsoseng

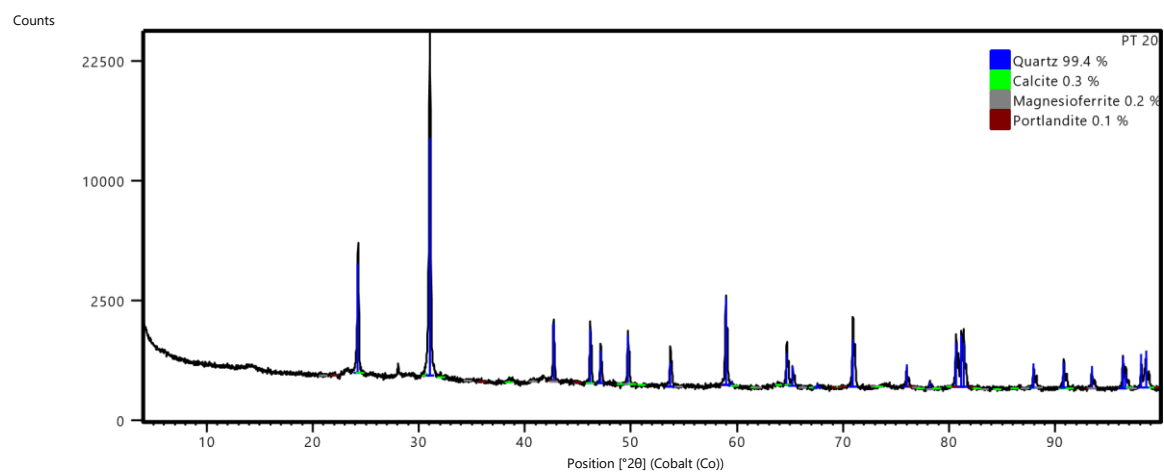


Figure 5.20: X-ray diffraction pattern of soil sample from 15 - 30 cm depth of smallholder crop farm at Itsoseng

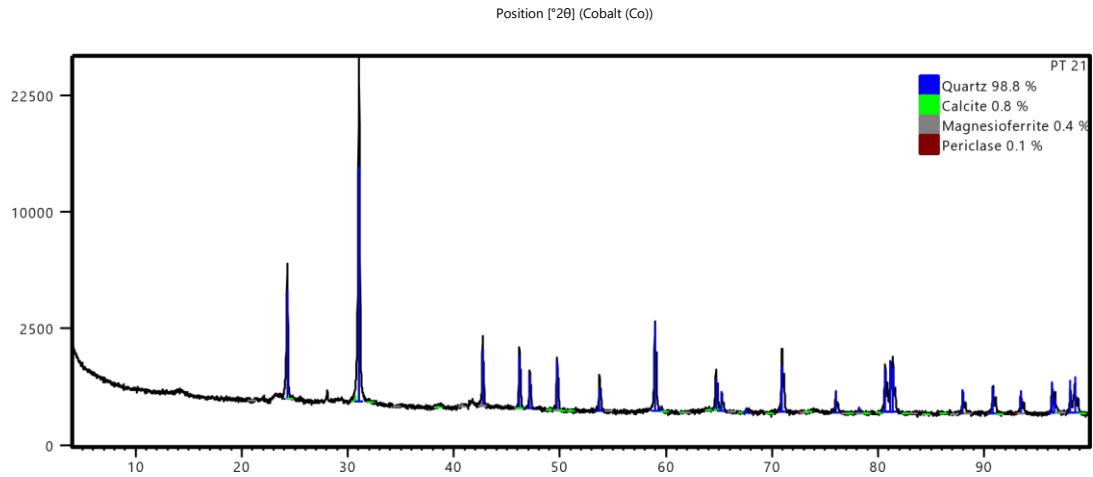


Figure 5.21: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of smallholder crop farm at Itsoseng

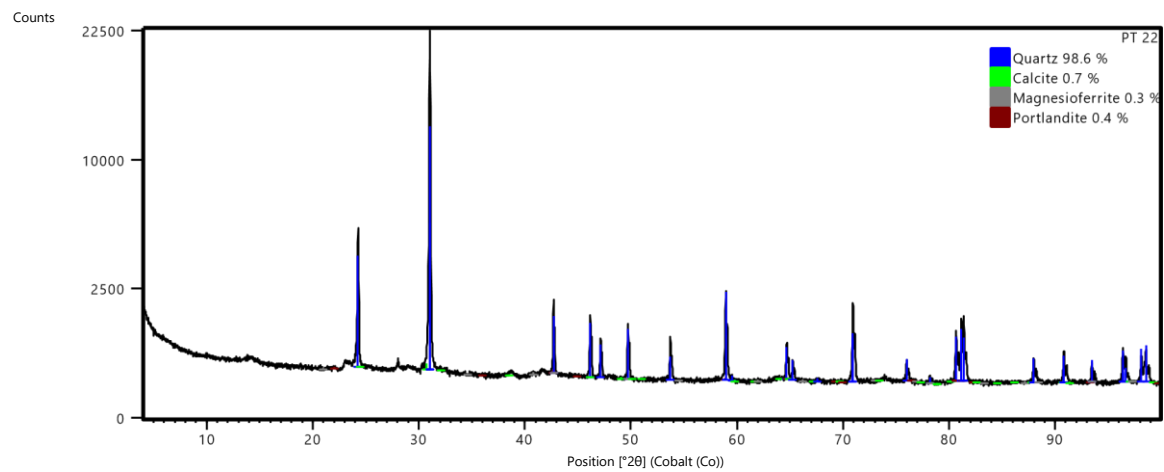


Figure 5.22: X-ray diffraction pattern of soil sample from 0 - 15 cm depth of commercial crop at Itsoseng

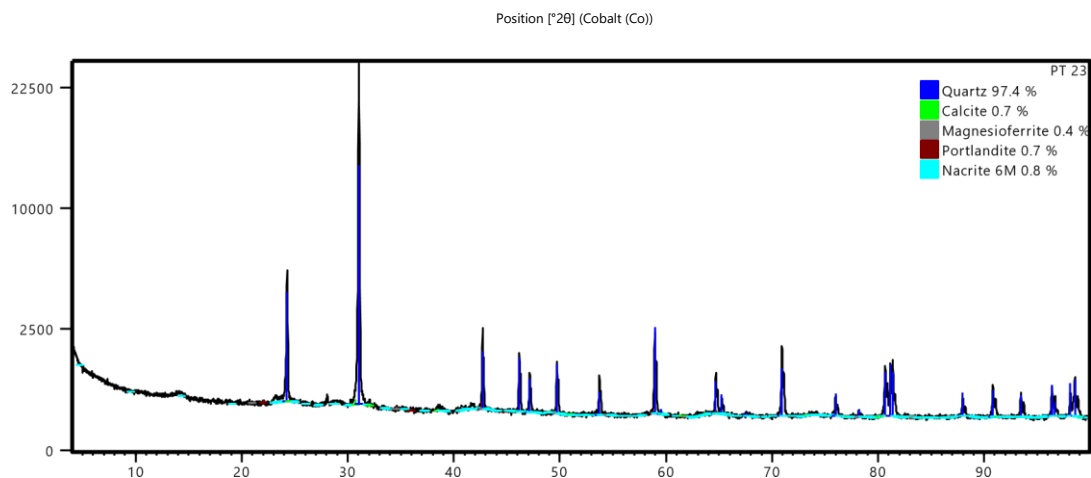


Figure 5.23: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of commercial crop farm at Itsoseng

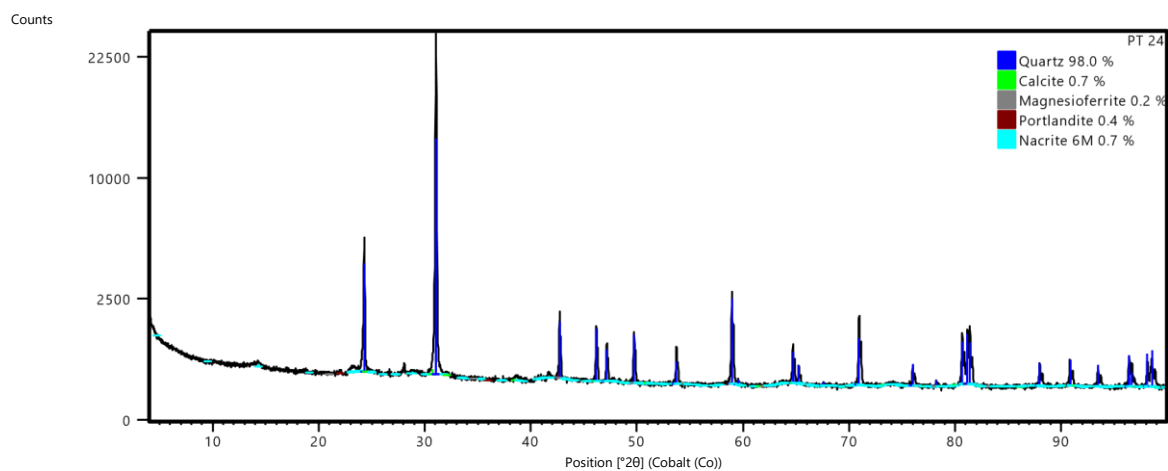


Figure 5.24: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of Itsoseng commercial crop farm

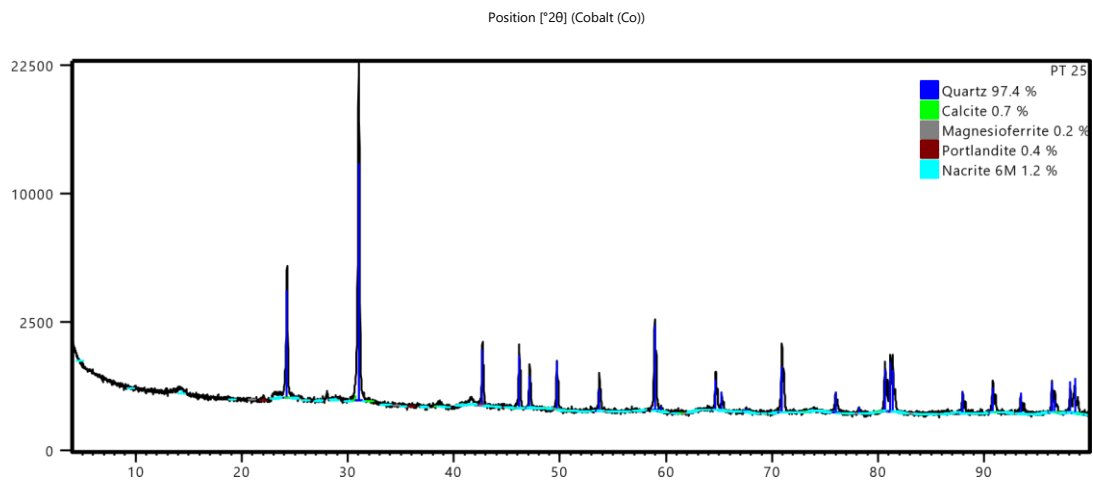


Figure 5.25: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of communal grazing land at Itsoseng

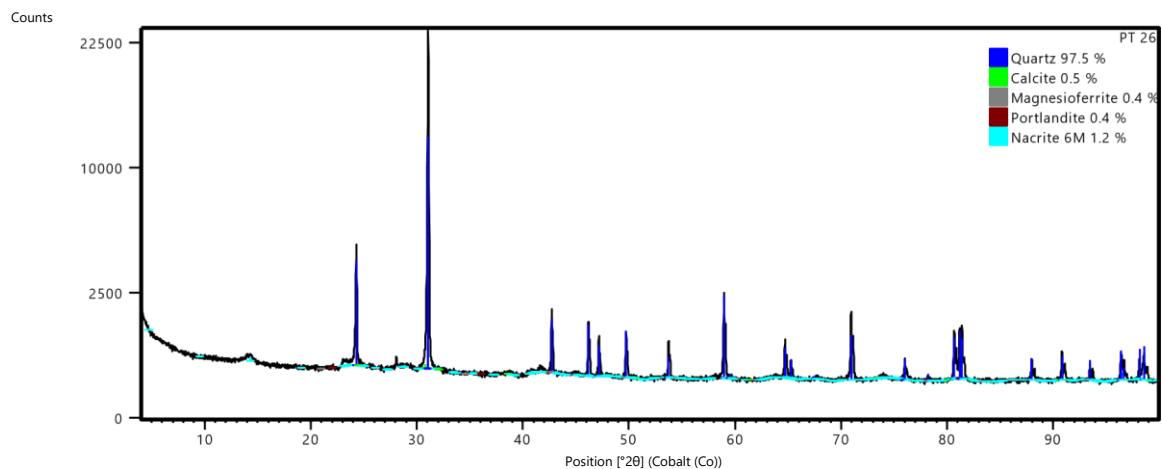


Figure 5.26: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of communal grazing land at Itsoseng

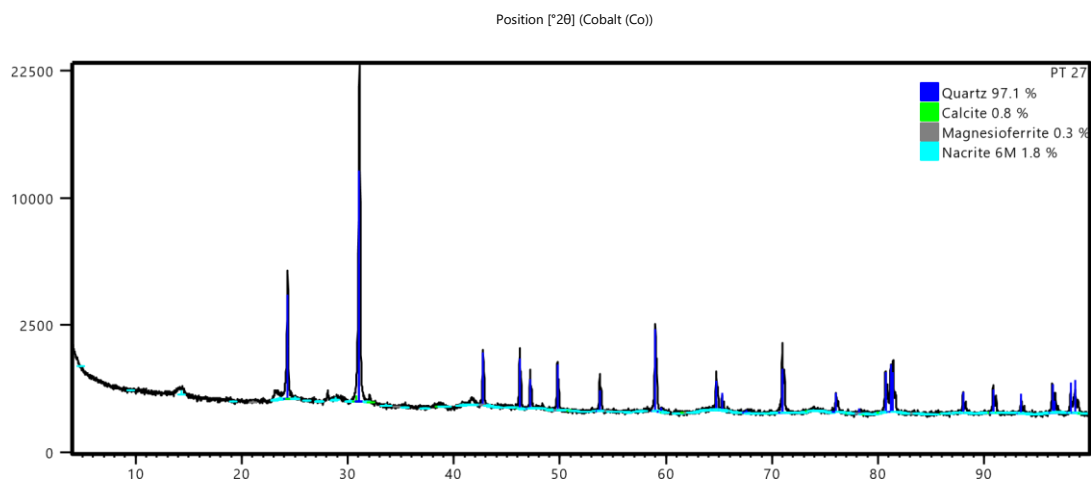


Figure 5.27: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of communal grazing land at Itsoseng

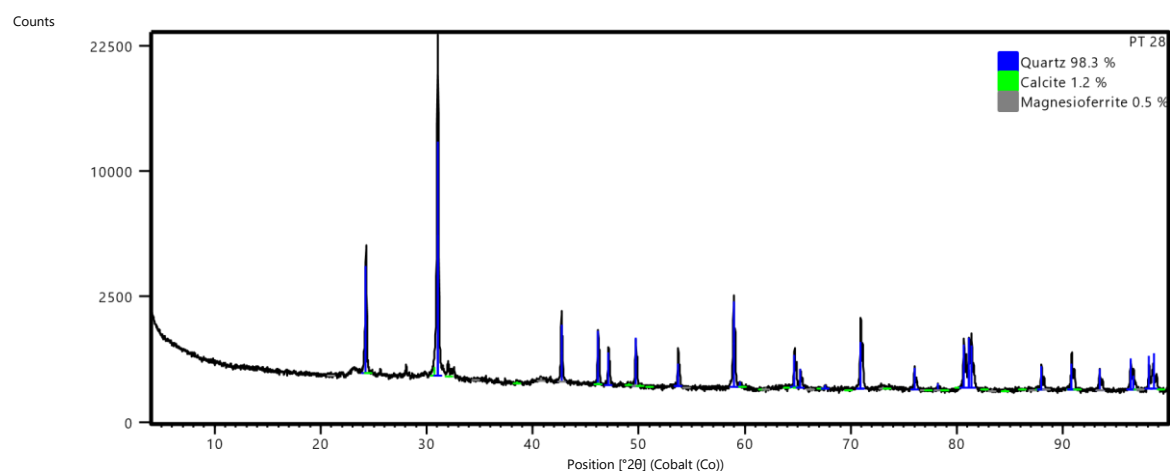


Figure 5.28: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of smallholder crop farm at Taung

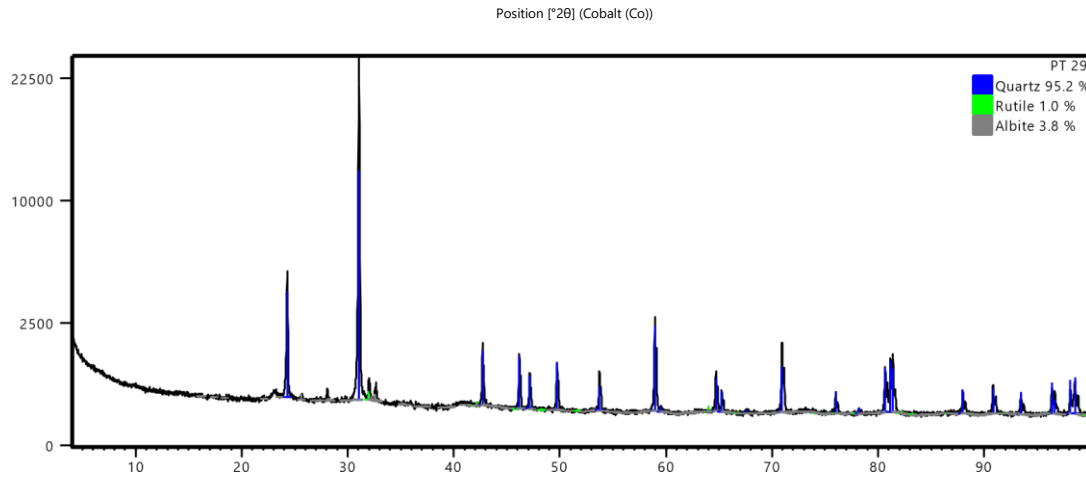


Figure 5.29: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of smallholder crop farm ant Taung

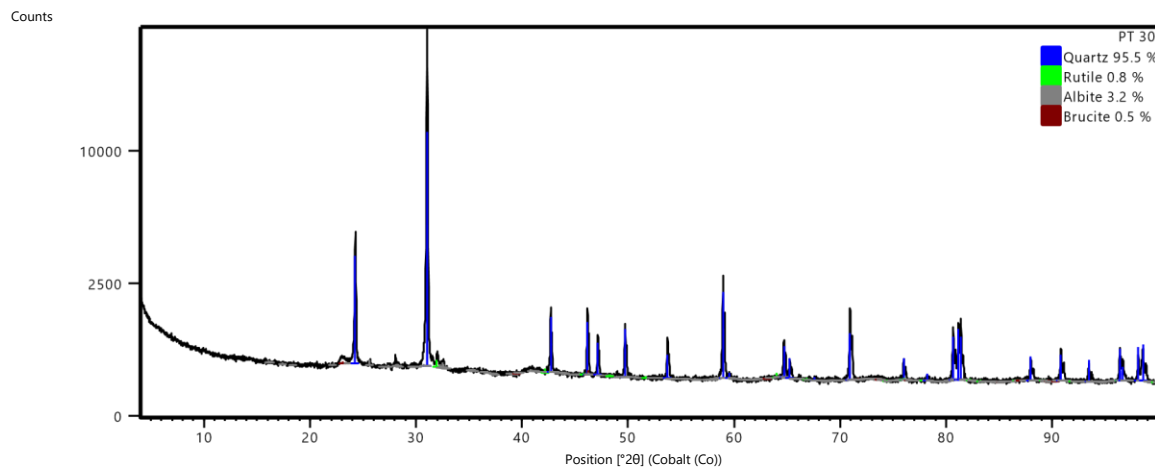


Figure 5.30: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of smallholder crop farm at Taung

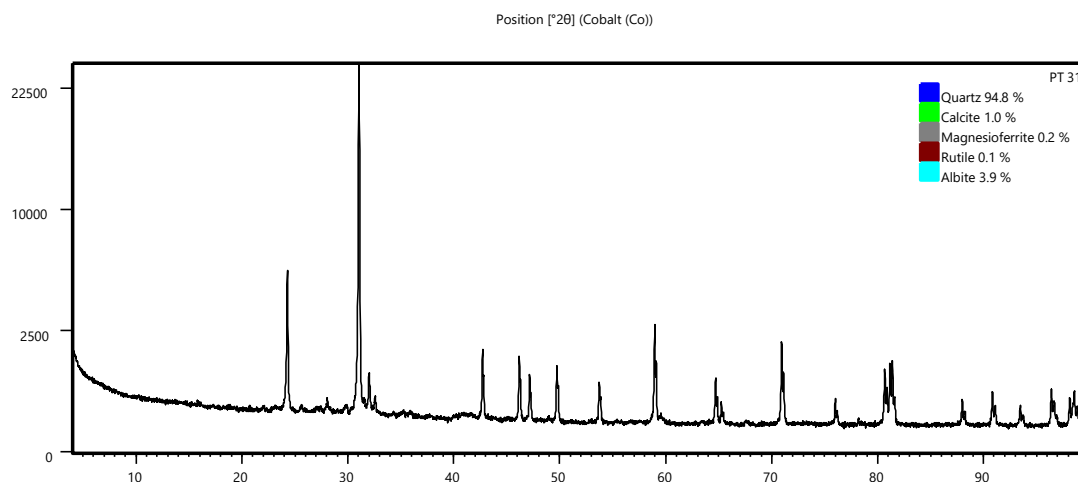


Figure 5.31: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of commercial crop farm at Taung

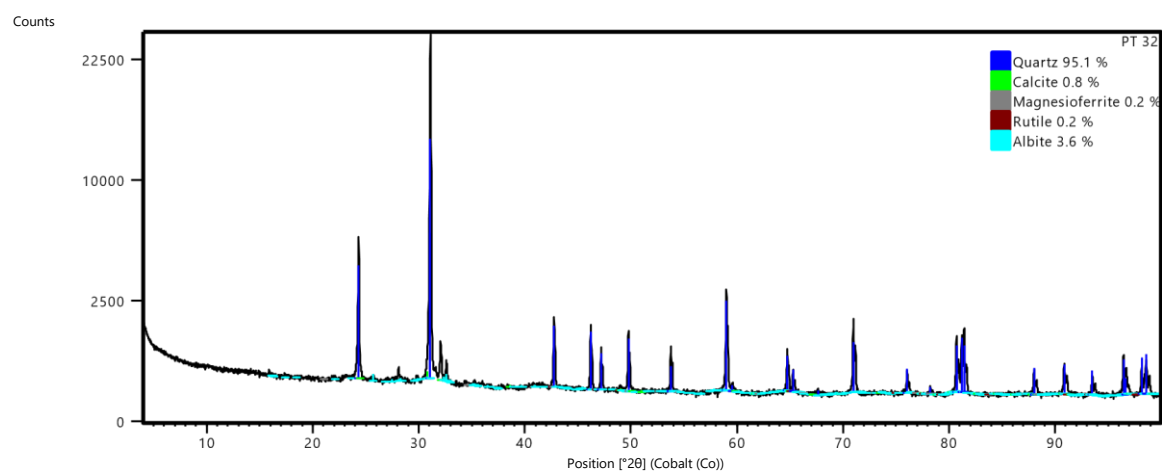


Figure 5.32: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of commercial crop farm at Taung

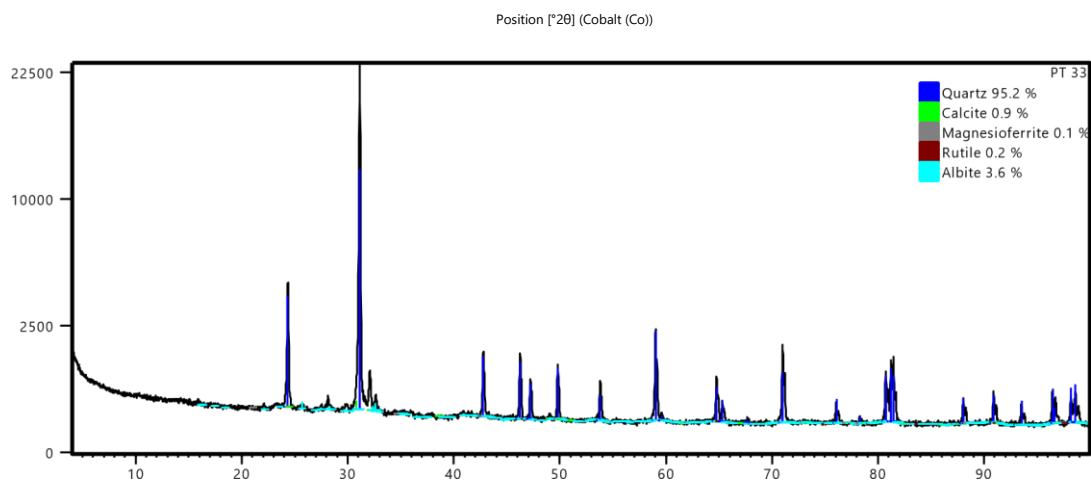


Figure 5.33: X-ray diffraction pattern of soil sample from 30 - 45 cm depth of commercial crop farm at Taung

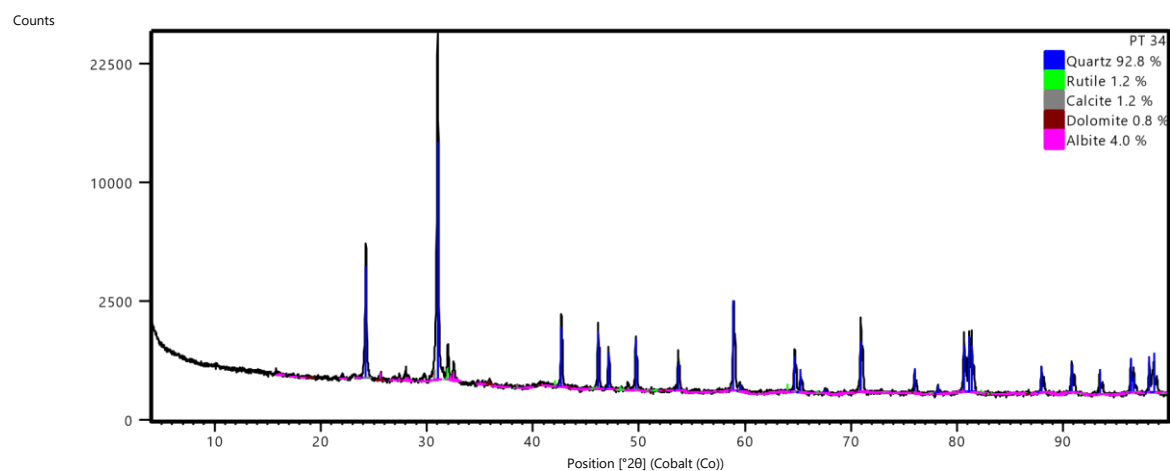


Figure 5.34: X-ray diffraction pattern of soil sample from 0 – 15 cm depth of communal grazing land Taung

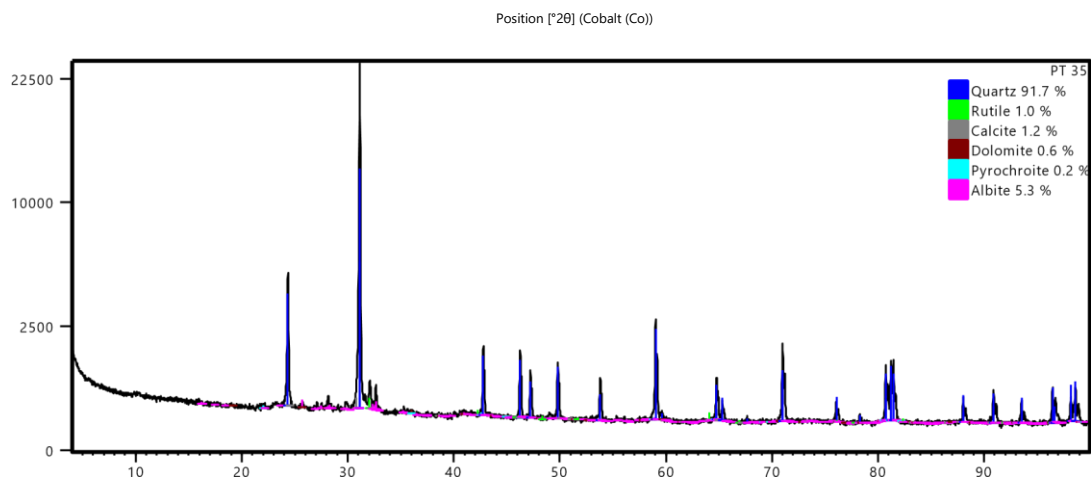


Figure 5.35: X-ray diffraction pattern of soil sample from 15 – 30 cm depth of communal grazing land Taung

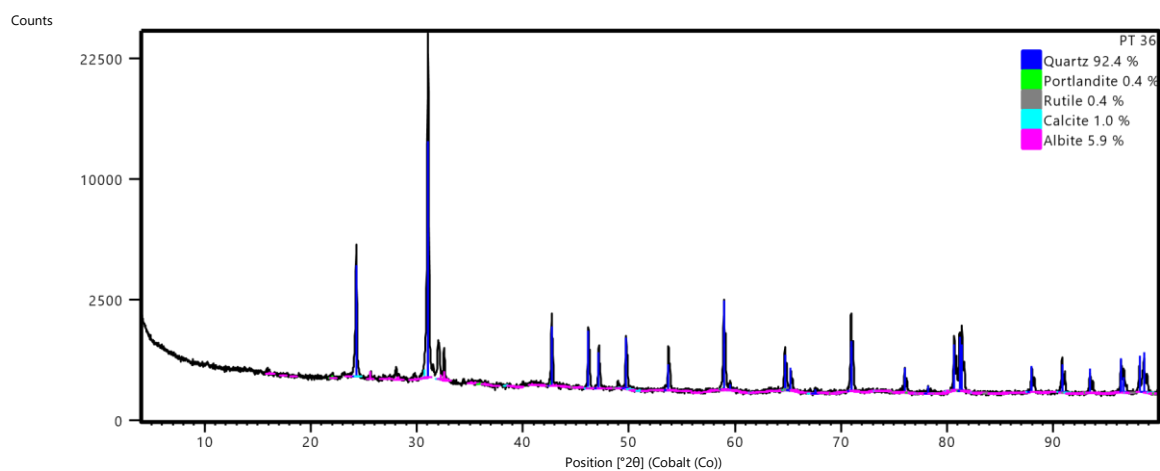


Figure 5.36: X-ray diffraction pattern of soil sample from 30 – 45 cm depth of communal grazing land at Taung

5.5 Discussion

Soils from the four locations had mixed mineralogical composition typical of most natural samples. The mineralogical composition of the soils studied based on XRD analysis from the four locations varied as reflected in the X-ray diffractions (Table 5.1 and Figure 5.1 - 5.36). The heterogeneous nature of the clay mineral collection reflects the intensity of weathering at the different locations. Mineral phase identification using Powder Diffraction File (PDF) Database established the contents of each of the randomly oriented bulk samples across the locations and composed mainly of quartz with other accessory minerals that were easily detectable. Quartz as the most dominant detrital mineral species fraction found could be attributed to its ubiquitous nature and its resistance to weathering (Brady & Weil, 2013). This result agrees with earlier findings by Ngole-Jeme & Ekosse (2015) who reported that mineral assemblages of soils from South Africa and Swaziland were dominated by high amounts of quartz. This study also corroborates that of Mandiringana *et al.* (2005) whose results show that most of the soils in Eastern Cape, South Africa, were dominated by quartz, mica and kaolinite in the clay fraction.

This study also verified that the mineral compositions within a soil sampling site was relatively uniform, but there were noticeable differences across the different sites (Table 5.1). However, there was commonality in the dominance of quartz across the different locations and all the sampling sites. The abundance of quartz as a mineral suggests that it is resistant to weathering and might have undergone moderate weathering. The mineralogical trends reflected different minerals but proposed that most of the soils mineral suite was dependent on weathering, a soil forming process that can influence soil mineralogy at all scales (Nyambura, 2013).

The presence of micas (biotite and muscovite) minerals in soils from the study area implies that the weathering of these minerals would add K to the soil for better plant nutrition (Manning, 2010). The presence of dolomite in soils of the study area helps to increase the soil pH and provides good source of calcium for plants (Vrinceanu *et al.*, 2019). The presence of brucite exert effect on exchangeable properties of soil probably due to increasing of soil surface area in association with a decreasing in the CEC (Al-Wotaify & Ali, 2013). The large quantity of quartz in soils may contribute to poor chemical and physical properties (Brady & Weil, 2013). Other clay mineral complements were calcite, magnesioferrite, kaolinite, biotite, dolomite, muscovite, portlandite, nacrite, rutile, albite, brucite and pyrochroite. The dominance of quartz and lesser amounts of 1:1, 2:1 clay minerals and oxides could exhibit low capacity for absorbing cations, low fertility

characteristics and need to be managed carefully. Beside quartz, the presence of rutile with low abundance of ferromagnesian minerals and kaolinite suggested advance weathering while the soluble minerals are more available at the incipient stage of weathering (Ofem, *et al.*, 2023). Quartz and rutile are resistant minerals that become most abundant at an advance stage of weathering (Morton & Hallsworth, 2007) while the soluble minerals are more available at the incipient stage of weathering. Hence, the presence of noticeable quantities of some weatherable minerals could contribute to the natural fertility of these soils (Kutu & Diko, 2011).

5.6 Conclusion

Mineralogical study of the selected soils in the North West Province of South Africa showed mix mineral composition with quartz dominating the mineralogical fractions. Limited amounts of other clay minerals such as magnesioferrite, calcite, kaolinite, biotite, dolomite, muscovite, portlandite, nacrite, rutile, albite, brucite and pyrochroite were identified.

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CHAPTER SIX

PHOSPHORUS SORPTION CHARACTERISTICS OF SELECTED SEMI-ARID AGRICULTURAL SOILS OF NORTH WEST PROVINCE, SOUTH AFRICA

6.1 Abstract

Phosphorus (P) sorption characteristics of soils from three farms with variable clay contents and textural characteristics (< 10%, 20% and > 30%) in a South African semi-arid area were evaluated. These soils were texturally described as loamy sand (RG), sandy loam (LC) and sandy clay (RC). Samples of each soil were equilibrated in 50 ml aliquot of 0.01M CaCl₂ solution containing 0, 10, 20, 40 and 80 mg P kg⁻¹ of P as KH₂PO₄. The samples were incubated at 25°C in an incubator over a period of 91 days. Available P was extracted using Bray 1 method and P not extracted was considered as P sorbed. Selected soil properties as well as P sorption characteristics were studied in the samples. The adsorption isotherms of the samples showed different curves verifying that P adsorption rate increased with increasing P concentrations, which became almost constant at 70 mg/L at day seven and had no more capacity to adsorb P. The LC (20%) soil had highest S_{max} of 5769 mg/kg, followed by RC (30%) with highest S_{max} of 1578 mg/kg and RG (10%) with highest S_{max} of 302 mg/kg. Phosphorus adsorption capacity decreased in the order of LC > RC > RG suggesting that LC soil with 20% clay content requires more P fertilisation than the other soil samples for plant growth.

Keywords: Phosphorus sorption, incubation study, clay contents, sorption capacity, soil P requirements.

6.2 Introduction

Phosphorus is one of the macro nutrient elements essential for plant growth and all other known life on earth (Brady & Weil, 2013), but the amount of plant available P in soil is often inadequate to meet plant requirements. An adequate supply of P is required in agricultural soils to meet the demands for growth in crops and the health of grazing animals (Daly *et al.*, 2015). Phosphorus is involved in most metabolic processes as it plays a major role in energy transfer as adenosine triphosphate (ATP). As phospholipids, P is part of cell membranes and as part of nucleotides, it is a major component in the formation of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA).

In addition, plants depend on P to generate energy in photosynthesis (Faucon *et al.*, 2015; Smil, 2000; Smit *et al.*, 2009).

The application of phosphorus has become an essential part of crop production systems. Phosphorous enhances the production of adequate food and fibre for human consumption. Maintaining an adequate P supply to crops has long been recognised as seminal for developed agriculture (Withers *et al.*, 2001). Availability of P in soils is influenced not only by parent material and land management but also by the sorption and desorption characteristics of the soil (Börling *et al.*, 2001). Therefore, an understanding of the interaction of phosphorus with those factors in soil is crucial for soil fertility management and sustaining phosphorus in soils. When P is applied to soil in the form of fertiliser, a series of reactions takes place, ranging from diffusion of P from the fertiliser granules into the soil solution, sorption of P into soil particles and with time, P precipitation (Hedley & McLaughlin, 2005).

The solubility of P in soil including the amount of P adsorbed and/or precipitated in the soil is controlled by several factors namely, the soil pH, clay mineralogy, organic matter content, types and amount of clay mineral formed during P precipitation and the concentration of Ca, Al, Fe and other cations in solution (Eriksson *et al.*, 2015; Gérard, 2016; Muindi *et al.*, 2015; Shigaki & Sharpley, 2011; Weng *et al.*, 2012). McLaughlin *et al.* (2011) reported that the amount of Ca, Al and Fe in soil solution controls P solubility and mobility from the inside of the fertilizer granule to the surrounding soil particles. In alkaline soils, P is primarily fixed to Ca; in weathered acidic soils, P is primarily sorbed to Al and Fe oxides, hydroxides, oxy-hydroxides and clay minerals, which makes it less available or effectively unavailable to plants (Chien *et al.*, 2014; Delgado & Torrent, 2000; Eriksson *et al.*, 2015). Therefore, the amount of P in the soil solution that is free to move with water through the soil profile (leaching) or horizontally (runoff) or taken up by plant roots is dependent on the sorption characteristics of a given soil and probably the Ca concentration in alkaline soils and Al/Fe concentration in acidic soils (Gama-Rodrigues *et al.*, 2014; Laboski & Lamb, 2004; Leytem & Westermann, 2003; Mihoub *et al.*, 2016).

Phosphorus sorption characteristics of four soil series in Pakistan were studied and reported that soils with higher amount of clay sorbed more P and needed P application than low clay content soils (Uddin *et al.*, 2014). Similar results have been reported in some selected soils of the Nigerian Guinea Savanna (Tsado *et al.*, 2012). In South Africa, P sorption studies on soils from KwaZulu-

Natal and Mpumalanga provinces have shown that highly weathered soils have high sorption capacities (Henry & Smith, 2002). Similar results of P sorption trends for soils in Lusikisiki area were reported (Gichangi *et al.*, 2008). Such information is necessary to guide P fertiliser recommendations to ensure that crop yields are not compromised due to under-application or overapplication of the soils. Still, little is known on the extent of P sorption traits of soils in North West Province of South Africa. In view of the potential low level of P in NWP and the role it plays in plant system, this study was designed to assess the phosphorus sorption characteristics of selected farms with varied clay levels in NWP. The objective of this study was to assess P sorption characteristics of selected soils in NWP of South Africa with a view to provide a proper management recommendation for the soils to optimize P use and crop production. The hypothesis for the study was that there will be no difference in P sorption characteristics of the selected soils.

6.3 Materials and Methods

6.3.1 Location of the Study

Refer to chapter three sections 3.2.1 to 3.2.6 on description of the study area, climate of the province, vegetation, geology/agricultural activities, soil samples collection and map of the study area (Figure 3.1).

6.3.2 Field studies and Laboratory Procedures

Soil samples used for this study were selected based on particle size analysis of the initial samples collected from the different sampling sites/points that had less than 10%, about 20%, and more than 30% clay at 0 - 15 cm depth from chapter three. About 1.5 kg of soil sample each was collected from soil with clay content less than 10% at Mathopstad communal grazing land (RG), about 20% at Itsoseng commercial crop farm (LC) and greater than 30% at Mathopstad communal crop farm (RC) at 0 - 20 cm depth. The soils are texturally described as loamy sand at RG, sandy loam LC and sandy clay RC. Collected samples were transported to the laboratory, air dried, crushed with mortar/pestle and sieved to pass through 2 mm diameter mesh. About 1 kg each of the different soil samples were used for P sorption study to establish their sorption characteristics while the remainder of it was used for the determination of some physical and chemical characteristics of the soils.

6.3.3 Determination of physical and chemical indicators of the soils

Refer to chapter three section 3.3.1 to 3.3.4 on determination of the physical indicators and chapter four section 4.2.1 on the determination of the chemical indicators of the soils.

6.3.4 Phosphorus sorption study

Phosphorus sorption study was made by Batch sorption method as described by Zhou *et al.* (2004). One (1) kg of air-dried soil sample each that had passed through 2 mm sieve was weighed into 15 polyethylene bags (16 cm by 27 cm) using three different clay levels of < 10%, about 20% and > 30% and labelled. The different soil samples were equilibrated in 0.01M CaCl₂ containing various rates of Phosphorus (KH₂PO₄) stock solution. Hence, the different treatments were soils with 3 clay levels (< 10%, about 20% and > 30%) and the 5 phosphorus levels (0, 10, 20, 40 and 80 P mg/kg soil. The different P rates represented the application rates of approximately 0, 10, 20, 40 and 80 mg/kg soil respectively; and exposed to variable incubation periods namely 1, 7, 21, 35, 49, 63, 77 and over 91days of incubation (i.e., DOI). Ten drops of toluene were added to each soil containing bag to prevent the growth of microbes during the equilibration period. Ten millilitres of distilled water was moderately added to each incubated soil at two weeks interval, thoroughly mixed to moisten the soil throughout the experimental period. The polyethylene bags were incubated at 25°C in CNW ETI-9052 Electro-thermostatic incubator in the laboratory with the tops open. At two weeks interval during incubation, soil samples were well mixed and approximately 100 g of soil was scooped, air-dried, ground to pass through 2 mm sieve and stored in plastic bags for determination of available P content.

Five (5) grams of air-dried sieved (2-mm) soil samples collected from the different study sites was weighed into a 100 ml centrifuge tube and 50 ml of extracting solution (0.03 N NH₄F and 0.025 N HCl) was added in a ratio of 1:10. The tube was closed with a rubber stopper and shaken for 30 minutes on a shaker at 200 - 300 rpm and centrifuged at 10,000 rpm for 15 minutes and the supernatant was filtered through Whatman No. 42 filter paper. Ten ml of clear filtrate was pipetted into 50 ml volumetric flask and 10 ml of distilled water added, 4 ml of reagent B (1.056 g of ascorbic acid dissolved in 200 ml reagent A) and made up to mark with distilled water and the colour development was done by blue method (Murphy and Riley (1962). It was replicated three times. A set of standard P solutions of 50 ml containing 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 mg/kg

(diluting 1, 2, 3, 4, 6, and 8 ml of 5 mg/kg P stock to 50 ml) were prepared. Each of the standards contained 10 ml of the extracting solution and 4 ml of reagent B and the colour was allowed to develop and the absorbance of blank, standards and samples were read after 15 minutes of colour development at 882 nm wavelength with CT 60 spectrophotometer (Murphy & Riley, 1962). Phosphorus that disappeared from the solution was considered as sorbed; and the sorbed P was plotted against P concentration in solution to a P sorption isotherm. The equilibrium concentration data were generated and interpreted using below two Langmuir equations proposed by Dubus & Becquer (2001).

Langmuir equation

Langmuir adsorption equation is given by,

$$C/X_m = 1/kb + C/b$$

(1)

where, C is the equilibrium P concentration (mg L⁻¹), x_m is the P adsorbed (mg) per soil (kg), b is the absorption maximum (the adsorption capacity) and k is the constant related to the binding energy of the soil for P or affinity constant according to Fang *et al.* (2002).

$$X_m \text{ is calculated as } C_oV_o - C_fV_f / \text{mass of soil (kg)} \quad (2)$$

where C_o is the initial concentration, C_f is final concentration, V is volume of solution. The linear form of equation (1) was obtained by plotting the equilibrium concentration of phosphate (C) against the amount of phosphate adsorbed (X) while the slope of the graph equals to 1/X_m and intercept of the graph equals 1/(k.X_m). The value of k was easily determined by dividing the slope by intercept according to Zhang *et al.* (2005).

6.4 Results

6.4.1 Physical and chemical characteristics of the soils

Physical and chemical characteristics of the soils studied are shown in Table 6.1. Particle size distribution showed that texture of soils varied between loamy sand (RG), sandy loam (LC) and sandy clay (RC). Sand content in the soils ranged from 55.2 to 79.6%. Silt particles ranged from 7.9 to 15.8%, while clay ranged from 7.9 to 36.9%. Bulk density (BD) of the soils ranged from

1.16 to 1.56%. Porosity of the soils ranged from 55.47 to 65% while WHC ranged from 52.5 to 56.23%. The pH-H₂O of the soils ranged from 6.3 to 7.58, while pH-KCl ranged from 4.52 to 6.19.

Table 6.1: Physical and chemical characteristics of the soils

Soil properties	RG sample	LC sample	RC sample
Sand (%)	79.6	63.6	55.2
Silt (%)	12.5	15.8	7.9
Clay (%)	7.9	20.6	36.9
Texture	Loamy Sand	Sandy Loam	Sandy Clay
BD (g/cm ³)	1.18	1.56	1.16
Porosity (%)	55.47	62.5	65
WHC (%)	52.5	41.13	56.23
pH H ₂ O	6.54	7.58	6.3
pH KCl	4.52	6.19	4.76
EC dS/m	0.15	0.12	0.08
Org. C (%)	0.89	0.92	1.49
Tot. N (%)	1.14	0.82	0.47
Avail. P (mg/kg)	2.99	11.5	2.74
Exch. K (mg/kg)	200	429	260
Avail. S (%)	0.09	0.6	0.09
Exch. Al (cmol/kg)	0.16	0.32	0.32
Exch. Ca (mg/kg)	682	2560	1841
Exch. Mg (mg/kg)	131	438	254
Exch. Acid (cmol/kg)	0.6	0.13	0.18
CEC (cmol/kg)	5.59	17.6	12.12
Cu (mg/kg)	2.1	2.4	4.4
Zn (mg/kg)	6	11.7	9.4
Mn (mg/kg)	14.2	130.2	103.4
Fe (mg/kg)	131.8	32.4	20.8

RG = Mathopestad communal grazing land; LC= Itsoseng commercial crop farm; RC= Mathopestad commercial crop farm

The samples were slightly acid to neutral in pH-H₂O but strongly acid to moderately acid in pHKCl. The EC of soils in the research area were not saline and the values were less than 1 mS/m. The soils had organic carbon (OC) content that ranged from 0.89 to 1.49%. Total N content ranged from 0.47 to 1.14%, while available Bray 1 P content recorded ranged from 2.99 and 11.5 cmol/kg. Exchangeable K in the study area ranged from 200 to 429 cmol/kg. Available sulphur ranged from 0.09 to 0.6 %. The exchangeable aluminium ranged from 0.16 to 0.32 cmol/kg. Exchangeable Ca of the soils ranged from 682cmol/kg to 2560 cmol/kg, exchangeable Mg results ranged from 131

cmol/kg to 438 cmol/kg and exchangeable acidity ranged from 0.6 cmol/kg to 0.18 cmol/kg. The cation exchange capacity (CEC) ranged from 5.59 to 17.6 cmol/kg. Micronutrients: Cu ranged from 2.1mg/kg to 4.4 mg/kg, Zn ranged from 6 mg/kg to 11.7 mg/kg, Mn ranged from 14.2 mg/kg to 130.2 mg/kg and Fe had a range of 20.8 mg/kg to 131.8 mg/kg.

6.4.2 Phosphorus sorption isotherms of the soils

There was a good fit of the data to Langmuir equations and sorption behaviour of soils was adequately described by the linearised Langmuir sorption equation (Table 6.2). The sorption maxima of the soils ranged from 70 to 302 mg P kg⁻¹ and binding energy ranged from -28.854 to 3.1485 mg⁻¹. The coefficients of determination (R²) values of 0.573 to 0.999 observed in RG < 10% clay. The intercept and slope ranged from -22.5 to 10.832 and 3.311 to 13.653. The SPR (P_{0.2}) values of 2.7 to 104 mg/kg were also recorded (Table 6.2).

Sorption maxima of 1199 to 5769 mg/kg, intercepts of -2.031 to 28.474 and slope of 3.877 to 8.338, coefficients of determination (R²) values of 0.796 to 0.999 in LC about 20% clay. Binding energy of -7.928 to 3.840 mg⁻¹ and SPR (P_{0.2}) of 100.4 to 400 were observed (Table 6.2). In soils of RC with clay content greater than 30%, sorption maxima values of 529 to 1578 mg/kg, intercept of -2.031 to 28.474, slope values of 1.733 to 8.338, coefficients of determination (R²) of 0.711 to 0.997. Binding energy ranged from -0.444 to 1.2433 mg⁻¹ with SPR (P_{0.2}) of 2.5 to 124 mg/kg were recorded (Table 6.2).

Figure 6.1 presents the amount of phosphorus sorbed at different P concentrations in soils with <10%, about 20% and >30% clay contents at various incubation times. Soils with varied clay contents and their ability to sorb added phosphorus and sorption behaviour was influenced by clay and other inherent soil properties. The graphs showed increased soil P concentrations with increasing clay levels resulting in an increase in P sorption. Rapid Phosphorus sorption was observed at day one in < 10% and about 20% clay leading to the highest sorption (Figure 6.2 and 6.3). Soils with more than 30% clay had highest sorption at day seven (Figure 6.4). Phosphorus sorption also increases with an increase in incubation time up to a maximum. The highest concentration of P sorbed was recorded across all three soils with a plateau attained after day seven of incubation period, which stabilized till the ninety-first day. Soil surface exchange sites become saturated with sorbed P after day 7 (seven) on the average (Pinto *et al.*, 2013). The three different clay levels have almost similar P sorption patterns (Figure 6.1). The soil sample with about 20%

clay with highest concentration of P, sorbed more P than the < 10% clay and >30% clay and with their P concentrations. On the other hand, soils with 20% clay have higher P retention capacity than the one with < 10% and > 30% clay. A graphical representation of the amounts of phosphorus sorbed on the investigated soils was also plotted as a function of equilibrium concentration (Figure 6.2 to 6.4).

Table 6.2: Phosphorus sorption characteristics of the three groups of soils based on the Langmuir model

Days of incubation	S _{max} (mg/kg)	a	b	R ²	k	SPR (P _{0.2})
Soil from communal grazing land Mathopestad with < 10% clay						
1	302		3.3117	10.832	0.573	0.305
7	82		12.181	-22.564	0.965	-0.540
21	92		10.991	10.646	0.991	1.027
35	73		13.675	-15.284	0.994	-0.883
49	70		14.343	-5.495	0.999	-28.854
63	141		7.108	58.888	0.893	0.120
77	122		8.168	9.802	0.998	0.836
91	73		13.653	4.350	0.999	3.148
Soil from Itsoseng commercial crop farm with about 20 % clay						
1	5769		1.733	0	1	1.733
7	1291		7.745	2.016	0.998	3.840
21	1332		7.505	-1.971	0.999	-3.808
35	1574		6.351	3.378	0.999	1.880
49	1199		8.338	-2.031	0.999	-4.105
63	1475		6.779	9.822	0.985	0.690
77	2575		3.877	28.47	0.796	0.136
91	1371	7.295	-0.920		0.999	-7.928
Soil from commercial crop farm Mathopestad > 30 % c lay						
1	1427		7.008	58.977	0.792	0.017
7	1578		6.337	111.76	0.711	0.056
1	641		15.611	89.78	0.959	0.271
35	529		18.912	-51.435	0.987	-0.367
49	529		18.904	-49.365	0.987	-0.382
63	1225		8.165	6.566	0.997	1.243
77	531		18.829	-42.395	0.989	-0.444
91	531		18.829	-42.395	0.989	-0.444

S_{max}= sorption maximum (mg/kg), a = slope, b = intercept, k = binding energy, SPR (P_{0.2}) = standard phosphorus requirement

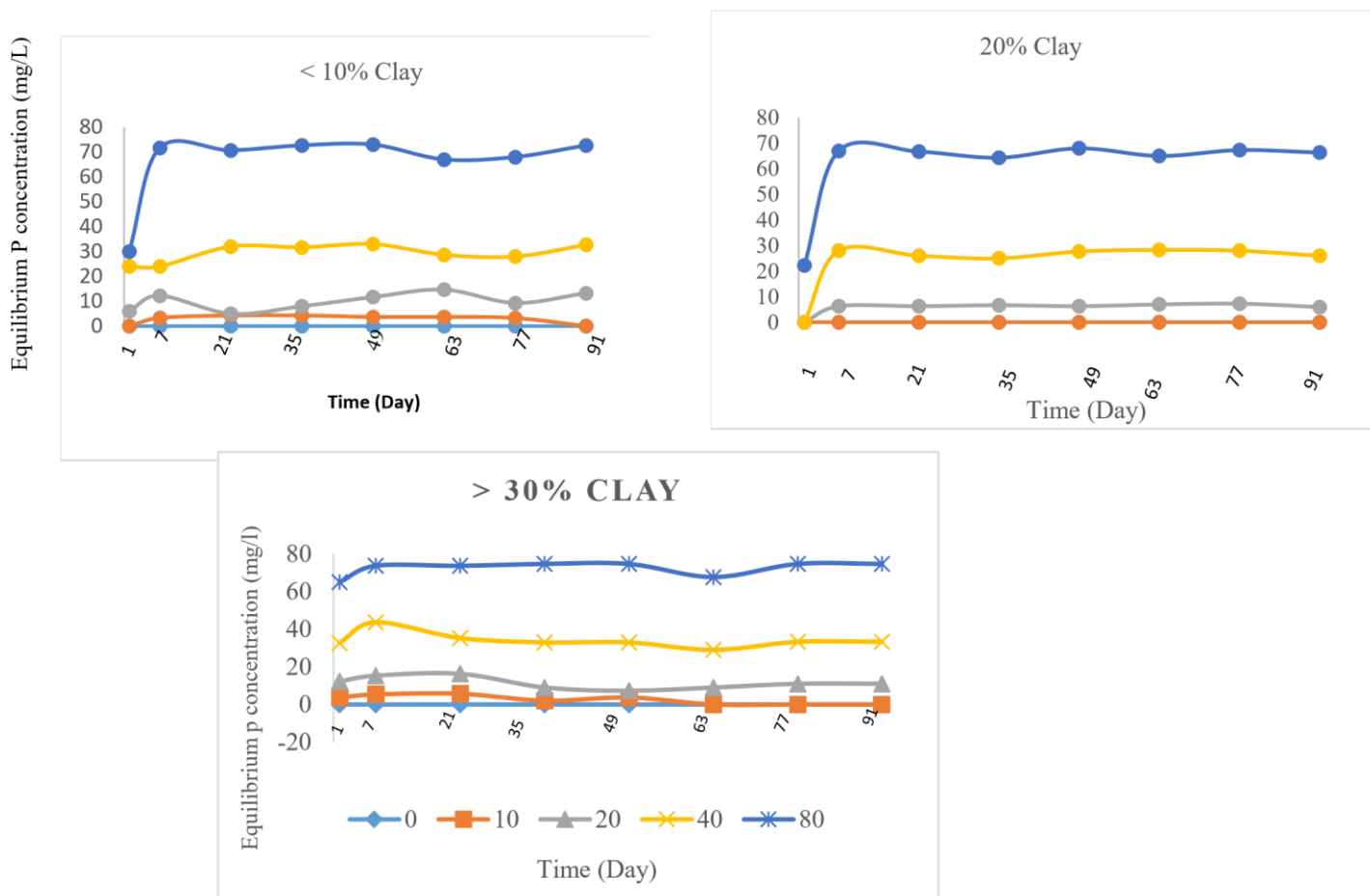


Figure 6.1 Phosphorus sorbed at equilibrium concentrations in < 10%, about 20% and > 30% clay at different incubation time (days) point

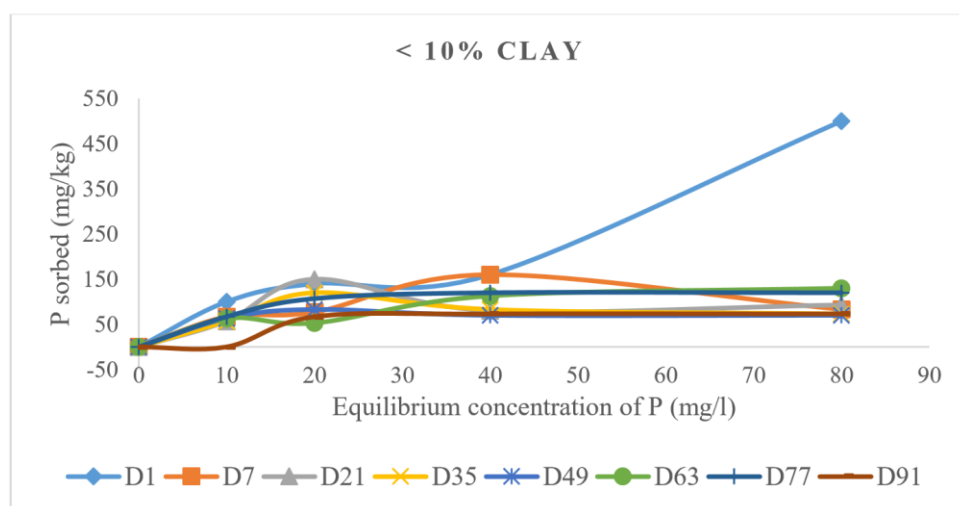


Figure 6.2 Phosphorus sorbed at different concentrations in soil with < 10% clay content

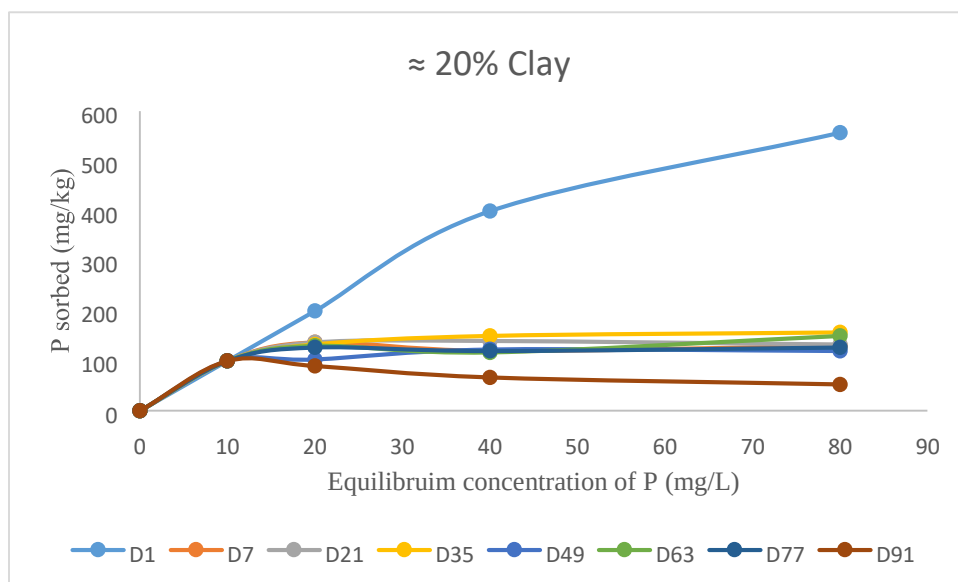


Figure 6.3 Phosphorus sorbed at different concentrations in soils with about 20% clay content

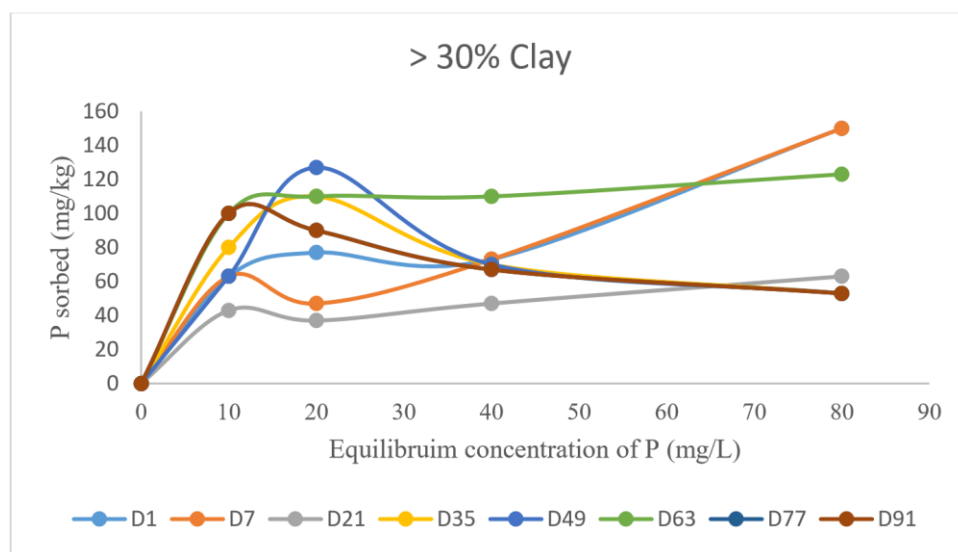


Figure 6.4 Phosphorus sorbed at different concentrations in >30% clay content

6.4.3 Pearson's correlation analysis of P sorption with soil physical and chemical indicators

The correlations of these relationships are presented in Table 6.3. Clay had positive correlation with sorption maxima ($r = 0.124$) but showed negative correlation with sorption affinity ($r = 0.757$). The pH-H₂O was positively correlated with sorption maxima ($r = 0.933$) and sorption affinity ($r = 0.820$). Organic carbon was negatively correlated with sorption maxima ($r = -0.279$) and sorption

affinity ($r = -0.954$). Available P had positive correlation with sorption maxima ($r = 0.976$) and sorption affinity ($r = 0.723$). Exchangeable K had positive correlation with sorption maxima ($r = 0.998$) and with sorption affinity ($r = 0.504$). Exchangeable Fe had negative correlation with sorption maxima ($r = -0.5847$) and positively correlated with sorption affinity ($r = 0.3511$). Exchangeable Al had positive correlation with sorption maxima ($r = 0.6592$) and negative relationship with sorption affinity ($r = -0.2605$). Exchangeable Ca was positively correlated with sorption maxima ($r = 0.895$) and sorption affinity ($r = 0.125$). Exchangeable Mg also had positive relationship with sorption maxima ($r = 0.977$) and sorption affinity ($r = 0.3656$). Exchangeable acidity had negative correlations with sorption maxima ($r = -0.7289$) and positive sorption affinity ($r = 0.1657$). Cation exchangeable capacity was positively correlated with sorption maxima ($r = 0.929$) and sorption affinity ($r = 0.2081$). Sorption maxima was also positively correlated with sorption affinity ($r = 0.554$).

Table 6.3: Pearson's correlation coefficients describing relationships of P sorption parameters with selected soil properties

	Clay	pH water	OC	Avail. P	Exc. K	Fe	Ext. Al	Exc. Ca	Exc. Mg	Exc. Acid	CEC	Smax	k
Clay	1												
pH water	-0.2463	1											
OC	0.918	-0.6104	1										
Avail. P	-0.0965	0.9884	-0.4832	1									
Exc. K	0.1828	0.9078	-0.2219	0.9609	1								
Fe	-0.8776	-0.2485	-0.6156	-0.3925	-0.6317	1							
Ext. Al	0.8281	0.3394	0.5379	0.4781	0.7026	-0.996	1						
Exc. Ca	0.5535	0.6709	0.1779	0.7756	0.92	-0.885	0.925	1					
Exc. Mg	0.3314	0.8328	-0.0698	0.9071	0.9882	-0.743	0.803	0.969	1				
Exc. Acid	-0.7699	-0.4289	-0.4538	-0.5609	-0.7682	0.982	-0.995	-0.958	-0.857	1			
CEC	0.4816	0.7308	0.0947	0.8258	0.9497	-0.843	0.890	0.997	0.987	-0.930	1		
Smax	0.1242	0.9311	-0.2794	0.9756	0.9982	-0.585	0.659	0.895	0.977	-0.729	0.929	1	
K	-0.757	0.8198	-0.954	0.7234	0.504	0.351	-0.261	0.125	0.366	0.166	0.208	0.554	1

6.5 Discussion

Particle size distribution showed that texture of the soil varied between loamy sand in RG, through sandy loam in LC to sandy clay (RC). Earlier studies from the study area revealed that the soils at the sites were derived from ancient geological heritage that are inherently rich in minerals and dominated by igneous rock formations (Moussa *et al.*, 2009; Venter *et al.*, 2012), which constitute the parent materials from which the soil textures are derived. Texture plays a dominant role in soils behaviour as it affects water and nutrient retention as well as the suitability as rooting medium ((Phogat *et al.*, 2015). The measured bulk density, porosity and water holding capacity values were within normal range for crop growth (Brady & Weil, 2013). Soil pH of the study fell within slightly acid to neutral pH-H₂O and strongly to slightly acid in pH-KCl. The pH values obtained were attributed to the presence of soluble bases particularly calcium, magnesium, and potassium (Hazelton & Murphy, 2016; Brady & Weil, 2013). Secondly, from the semi-arid nature of the environment which is characterized by low rainfall with less leaching loss of basic cations has contributed to the results recorded (Brady & Weil, 2013). The observed low to medium organic carbon and available phosphorus content of these South African soils were in agreement with earlier study in by Barnard & Du Preez (2004). The low to medium levels of organic carbon in South African soils were attributed to paucity of vegetation cover, rapid mineralisation of organic matter, inadequate return of crop residue, bush burning and short fallow periods (Mandiringana *et al.*, 2005). Organic matter can inhibit P sorption reactions to some extent (Leytem & Mikkelsen, 2005). Thus, organic matter may increase P availability through the production of organic acids or humic substances which compete with phosphates for binding the sorption sites in the soil and produce stronger complexes with calcium (Ca²⁺) that consequently increase P content in the soil solution. The soils of the study were rated as medium to high in total nitrogen contents.

The total N content could be attributed to high organic C contents, long-term cultivation coupled with frequent burning of crop residues which accelerated the rapid turnover rates of organic materials under cultivation since total N in the soil is closely associated with organic C (Jahn *et al.*, 2006; Jamaluddin *et al.*, 2013). The sufficiently high amounts of exchangeable bases could be because of the parent materials from where the soils are formed (Kutu and Diko, 2011; Naseem *et al.*, 2012). The exchangeable acidity values were low and below the critical level, which indicated slightly acid to neutral classes of soils (Jone Jr, 2002). From the results, the soils were free from aluminium problem as this was at acceptable limits, and sulphur obtained from the characterisation

was above the threshold level and linked to the parent materials of the soils. The CEC contents were between low and medium. The low to medium CEC contents might be due to the parent materials from where the soils are formed. It could also be because of low levels of clay and organic carbon. Micronutrients of the soils (Cu, Fe, Mn, and Zn) levels were sufficient for crop production, and it could be attributed to the parent materials from where the soils are formed (Mandirigana *et al.*, 2005; Landon, 1991).

Phosphorus sorption characteristics data were satisfactorily described by the Langmuir equation and the soils varied in their extent of P sorption as reflected by the ranges in sorption maxima (S_{max}) and other sorption characteristics (Table 6.2). Phosphorus sorption maxima of the soils showed that 66% of the samples are considered as having high sorption capacity, particularly if compared to values for soils from South Africa (Gichangi *et al.*, 2008; Henry & Smith, 2002). Wolde (2015) proposed a classification of soils with respect to their S_{max} , considering soils with very high sorption as the one that adsorb 1000 mg/kg of P, and those that adsorb between 500 and 1000 mg/kg of P as high. It could be seen from the present study, that soils from LC and RC apart from RG, are classified as very high sorbers.

Data from the sorption isotherm showed that the amount of P sorbed increase with increase in soil P solution concentration for all the soils studied i.e. 80 mg/L > 40 mg/L > 10 mg/L. Similar results have been reported by other workers (Fortin & Karam, 2001; Tsado, 2008; Eriksson *et al.*, 2015; Mundi *et al.*, 2015; Gerard, 2016). These authors observed that P sorption was found to be concentration dependent and change in the range of diffusion co-efficient, which increased with increasing amount of P added. For the three soils studied, the amount of phosphorus sorbed was greater in LC soil than in RC and RG soils. The differences in the observed sorption isotherm of the soils could be because of differences in clay and other physical and chemical characteristics of the soils. This result is accordance with Pinto *et al.* (2013) who reported that P sorption phenomena and P-availability depend on the interaction of soil attributes. However, other studies have also shown that soils with higher levels of clay sorbs more P than with lower clay contents (Tsado *et al.*, 2012; Uddin *et al.*, 2014; Abdulbari, 2014). It has also been reported that highly weathered soils such as the oxisols and ultisols contains large quantities of Al and Fe hydrous oxides that have the ability to sorb P unto their surfaces (Chien *et al.*, 2014; Eriksson *et al.*, 2015) thus rendering much of the added P fixed and not readily available for plant uptake (Mokolobate &

Haynes, 2003). These observations agree with the findings of Agbenin (2003) and Li *et al.*, (2000) who reported that key soil components influencing phosphorus sorption include nature and quantity of soil clay, soil pH, organic matter and the presence of amorphous Fe and Al oxides. The Langmuir equation described phosphorus sorption satisfactorily in these soils. The goodness-of-fit of Langmuir to sorption data may indicate that sorbed P by the soils and the concentration of added P are within the range of validity of the isotherm. It was observed that soil samples from LC soil containing about 20% clay sorbed more P than the rest of the other two soils suggesting that P sorption may be attributed to factors other than clay content (Pinto *et al.*, 2013). The higher P adsorption capacity observed in LC sample with about 20% clay could be attributable to the higher content of CEC, Ca, Na, Mg, and Mn in the soil. The RG sample with 30% clay sorbed less P than LC. It could be due to the samples having less CEC, Ca, K, Mg and Mn than the LC. Earlier study revealed that the presence of CEC, Ca, K, Mg, Mn significantly enhanced adsorption of P in soils (Pakarinen *et al.*, 2010). However, the observed positive or negative with non-significant correlation between S_{max} and the measured soil physical and chemical characteristics agrees with earlier studies (Rehman & Oayyum, 2020; Afsar *et al.*, 2012; Al-Salam, 2008; Gichangi, 2007). The non-significant correlation may also either suggests possible non-linear relationships between measured variables or limitations in the data generated.

6.6 Conclusion

This study revealed that P-sorption phenomenon depends on many important soil inherent attributes including the clay content. The use of only one soil indicator such as clay content or pH, as a criterion for recommendation of phosphorus fertilisation constitutes a limitation of the current study. Thus, adjustment to each particular soil condition by including other key soil parameters that contribute to P sorption such as the mineralogical characteristics of the clays, oxides, hydroxides and oxy-hydroxides of Ca, Fe and Al indicators is ultimately recommended. Mineralogy results of the soils revealed that the 1:1 and 2:1 clay, oxides, and hydroxides that could influence P sorption pattern. Findings from this study have implication on the fertiliser P management strategy including cost at the three different soils particularly the highly variable LC soils containing 20% clay content, which require more P fertiliser application (approximately 400 P kg/ha) to achieve optimum crop production.

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CHAPTER SEVEN

GENERAL SUMMARY, CONCLUSION AND RECOMMENDATION

7.1 General summary

The North West Province of South Africa is one of the country's leading grain producers. It contributes massively to the country's food production. The province is also noted for animal rearing and game reserves with numerous commercial and communal grazing lands. Therefore, this study was conducted to assess the fertility status, know the mineralogy and phosphorus characteristics of soils of selected crop and grazing lands in the province designed for developing management strategy to promote sustainable use the soils for agricultural purpose. Detailed soil assessment was conducted in four different locations within the province namely: Mathopetad, Itsoseng, Ventersdorp and Taung. In each location, one crop field each from smallholder, commercial farm and a communal grazing land were identified, selected and studied. The size of the fields ranged from 0.5 to 20 hectares. Soil samples were randomly collected from five points at each sampling site at 0 – 15 cm, 15 – 30 cm and 30 – 45 cm soil depths using a soil auger and hand trowel. A total of one hundred and eighty (180) soil samples were collected and used for this study.

The physical and chemical, mineralogical and phosphorus (P) sorption characteristics of the soil samples were assessed following standard procedures. The physical and chemical parameters examined include particle size distribution, water holding capacity, bulk density, total porosity, pH (H₂O and 1M KCl), electrical conductivity, total nitrogen, and organic carbon. Others include available phosphorus, exchangeable bases (Ca, Mg, and K), exchangeable acidity and Al, cation exchange capacity and extractable micronutrients (Cu, Fe, Mn and Zn). The mineralogical study carried out on the clay fraction was based on random powder analysis. The P sorption study was on soils categorised as containing less than 10% clay, about 20% clay and more than 30% clay sampled from the surface 20 cm depth. Soil fertility was assessed using Soil Fertility Index (SFI) and Soil Evaluation Factor (SEF). Some of the physical and chemical indicators were within critical limits while others were deficient hence, deficient nutrients should be supplied on these soils for increase and sustainable crop production. Pearson correlation analysis at $p \leq 0.05$ as well as analysis of variance (ANOVA) on the data generated from the physical and chemical parameters. Significant treatment means were separated using the Duncan multiple range test.

Results of soil physical indicators showed significant ($p \leq 0.05$) differences across the four locations, land use types and soil depths. Soil samples at Taung had the highest (73.16%) mean sand content while the soils at Ventersdorp had the lowest (57.90%) sand content. The mean sand content of soils at Itsoseng and Mathopestad were not significantly ($p \geq 0.05$) different. Soils obtained at Ventersdorp had significantly highest (24.96%) silt content. On the contrary, the Mathopestad soils had significantly higher clay content while the silt/clay ratio was highest (1.81) at Taung soils and differed significantly from values obtained at other locations. The highest mean WHC (57.49%) recorded was at Mathopestad soils, which differed significantly from the WHC obtained at other locations, Taung soils recording the least WHC content of 41.13%. The mean soil BD differed significantly at different locations with the highest recorded value of 1.41 g/cm^3 in soils at Taung, which was, however, not statistically different from samples collected at Ventersdorp. The Mathopestad soils had the least mean BD value of 1.13 g/cm^3 but highest total porosity (66.06%). The BD and total porosity values were ideal for crop growth when compared with the critical values. This lies within the desired limits for good water retention, movement and workability of the soils for crop production.

There was a significant ($p \leq 0.05$) variation in the three primary soil particles (sand, silt and clay) across the land use types with the highest mean sand content (67.35%) obtained on the communal grazing land (CGL) while the least value of 62.06% was on smallholder crop farm (SCF). On the contrary, the highest mean silt content of 19.14% was from SCF while the least silt content of 16.61% was from commercial crop field (CCF). Notwithstanding the significant variation in the mean clay content across the three land use types, the difference between CCF and SCF was not statistically significant while SCF had a marginally higher (18.89%) value. The highest recorded silt/clay ratio of 1.40 was from CGL implies that the soil has started undergoing ferralitic pedogenesis and could support plant growth within the acceptable threshold values. The SCF land use type gave the highest mean WHC of 57.49%. The variation in total porosity differed significantly ($p \leq 0.05$) across the three land use types. While there was no significant difference in the mean BD values obtained across the land use types, the CCF land use type yielded a quantitatively highest mean BD of 1.33 g/cm^3 .

Soil pH-H₂O, pH-KCl and ΔpH differed significantly ($p \leq 0.05$) across the four trial sites (Table 4.1) with the highest pH-H₂O (7.19), pH-KCl (6.14) and ΔpH (1.48) obtained at Mathopestad soils.

Variation in the EC and OC contents also differed significantly across soil sampling sites with the highest EC (0.13 d/Sm) and OC (1.82%) found in soils at Mathopestad and Taung respectively and were within the threshold level for crop production. Similarly, TN, available P and exchangeable K differed significantly across soil sampling locations with the highest values obtained in soils, respectively at Taung, Ventersdorp and Taung.

Soil pH-H₂O and pH-KCl were significantly influenced by differences in land use types with the highest pH-H₂O (7.03) and pH-KCl (6.08) value both observed in SCF. Similarly, change in soil pH (Δ pH) was significantly influenced by land use types with the highest recorded pH change (1.40) found in CGL. The contents of EC, OC, available P and exchangeable K differed significantly across the various land use types. The highest EC (0.15 dS/m) and OC (1.51%) were obtained from SCF and CGL respectively and are within the desirable threshold levels for crops growth. The OC in the study area was medium to high. The medium to high OC levels of the study area could be attributed to the agricultural residues added to the soil. While available P was rated low to medium, the availability of P under most soils of South Africa decline from the impact of fixation, abundant crop harvest and erosion. The exchangeable K (427 cmol/kg) content was obtained in SCF. Although there was no significant difference in the total N content across the land use types, the recorded highest content (1.41%) was in CGL. Soil pH-H₂O and exchangeable K content were significantly different across the various soil depths. The recorded highest pH-H₂O of 6.91 was at 15 - 30 cm to 30 - 45 cm soil depths respectively, while highest exchangeable K content of 370 cmol/kg was at 0 - 15 cm depth. There was no significant difference in the contents of total N and pH-KCl at various soil depths. The highest mean pH-KCl (5.73) was obtained at depth 30 - 45 cm. The mean Δ pH across various soil depths differed significantly with the highest value of 1.20 obtained at 15 - 30 cm depth. Electrical conductivity, OC, NT and AP had no significant difference across soil depth. The highest mean EC value of 0.13d/Sm and OC content of 1.44% were both recorded at 0 -15 cm soil depth. The observed highest mean total N (1.36%) and AP (7.42 cmol/kg) were at 30 - 45 cm and 0 - 15 cm depth, respectively.

Thirteen different clay mineral types were identified with the specific group to which these mineral assemblages belong. Silica group (silicate mineral) with quartz and albite. Kaolinite group - 1:1 clay mineral consisting of kaolinite and nacrite. Mica group - 2:1 clay minerals identified were

biotite and muscovite. Carbonate group – calcite and dolomite. Oxide and hydroxide groups had magnesioferrite, portlandite, rutile, brucite and pyrochroite.

The minerals identified are grouped into six main groups. The silica group - quartz (SiO_2) represents the most dominant clay mineral constituting 71.2 to 99.4%, albite (3.2-5.9%), followed by kaolinite group (kaolinite) with 0.5 to 16.3% and nacrite (0.1-1.8%) of the minerals assemblage in the soils. The mica group - muscovite with 0.7-11.6%, and biotite (0.1-1.2 %). Carbonate group - calcite (0.3-1.2%) and dolomite (0.1-1.1%) were recorded. Oxide and hydroxide groups - magnesioferrite (0.1-1.6%) was identified in all farms. Portlandite (0.1-0.6%), rutile (0.1-1.2%), brucite (0.5%) and pyrochroite (0.2%) were also identified, respectively.

The measured P sorption parameters in the three soil textural types varied greatly across land use types. In the RG soil with less than 10% clay, sorption maxima ranged from 70 to 302 mg P kg⁻¹, the binding energy between phosphate ions and the surface of soil particles varied between -8.8542 and 3.1485 mgL⁻¹ while the coefficient of determination (R^2) was 0.5734 to 0.9997. The intercept and slope ranged from -22.5 to 10.832 and 3.3117 to 13.653 respectively while the SPR ($P_{0.2}$) varied between 2.7 and 104 mg/kg. In the LC soil with 20% clay content, sorption maxima of 1199 to 5769 mg/kg, intercepts of -2.0314 to 28.474 and slope of 3.8772 to 8.3381, coefficients of determination of 0.7967 to 0.9999. Also, its binding energy -7.9289 to 3.8407 mgL⁻¹ and SPR ($P_{0.2}$) of 100.4 to 400 were observed. In the RC soil with clay content greater than 30%, sorption maxima and intercept ranged from 529 to 1578 mg/kg and -2.0314 to 28.474 while slope ranged from 1.7332 to 8.3381 and the coefficients of determination (R^2) varied between 0.7113 and 0.9973. Binding energy between phosphate ions and the surface of soil particles ranged from 0.4442 to 1.2433 mgL⁻¹ with SPR ($P_{0.2}$) of 2.5 to 124 mg/kg. Soils with 20% clay content from LC contained with the highest concentration of P, sorbed more P. In summary, LC had the highest P sorption (1199-5769 cmol/kg), followed by RC (529-1427 cmol/kg) and RG (73-302 cmol/kg). According to the critical P values for soil sorption interpretation, values of the range of 0-100, 100-400 and >400 mg/kg are regarded as low, moderate, and high, respectively. Therefore, the soils are classified as moderate to high P sorbers. Remarkable differences existed in the observed P sorption capacities among the LC, RC, and RG soils. The implications of the contrasting differences in the P sorption capacities of the soils suggested that the reliance on blanket phosphate

fertiliser recommendations to address crop production may not be a good strategy for the study area, which calls for review.

7.2 Findings from the main study

The main findings from the study are elaborated hereunder:

Soil texture of the study area belongs to three textural classes: loamy sand, sandy loam and sandy clay loam, bulk density, total porosity, water holding capacity were ideal for normal crop growth when compared with the critical values and the soil pH value fell within slightly acidic to neutral in pH-H₂O and strongly acid to slightly acid in pH-KCl. The soils were free from salinity and Al toxicity. Carbon was medium to high; available phosphorus was low to medium with medium to high P sorption capacity. Total nitrogen, exchangeable K, Ca, and Mg were high. Sulphur content and micronutrients status were above critical levels and can support crop production.

This study also provided quantitative information for monitoring changes in soil physical and chemical indicators and improving soil management practices thereby enhancing the fertility and productivity of the soils in the study area.

7.3 Conclusion and recommendations

The results of this study showed marked variation in the physical and chemical indicators across the different locations, land use types and soil depths. Data from the mineralogical study showed thirteen different mineral compositions, with quartz dominating the mineralogical fraction. The study also established that these soils are highly weathered due to the dominance of quartz and high silt/clay ratio, which is characteristics of many tropical soils that are highly fragile, possess poor nutrients and water retention ability and susceptible to erosion and degradation when poorly managed. This study also showed that P-sorption phenomenon depends on many soil attributes including clay content. Phosphorus sorption was highest during the early stage of P-incubation in Mathopstad soils (communal grazing land and commercial crop field) but highest towards the end of the incubation period in Itsoseng soils from commercial crop farm. Sorption maxima had strong and positive correlation with pH H₂O P ($r = 0.933$), available P ($r = 0.976$), exchangeable K ($r = 0.998$), CEC ($r = 0.929$), exchangeable Ca ($r = 0.895$), exchangeable Mg ($r = 0.977$) but moderate positive correlation with sorption affinity ($r = 0.554$). It has weak positive correlation with clay (r

= 0.124) and weak negative correlation with organic carbon ($r = -0.279$). These observations have strong implications on P fertilizer application and management for increase and sustainable crop production. The sole reliance on the use of only clay content and soil pH for P interpretation and recommendation in these soils may lead to misinterpretation in soil fertility management, especially in the semi-arid soils.

The main aim of this research was to assess the fertility status and phosphorus sorption characteristics of soils in selected areas in NWP of South Africa and proffer sustainable soil fertility management strategies, based on the findings of the study, the following recommendations were made.

1. Some of the soil physical and chemical fertility indicators were within critical limits while others were deficient hence, the deficient nutrient should be supplied on these soils for increase and sustainable crop production.
2. It is also recommended that adequate P fertilisation be made based on the variability of the sorption pattern of the soils. Soils from RC be applied with 104 kg P/ha, LC 400 P/ha and RG 124 kg P/ha.
3. Given the variability of measured soil physical and chemical fertility indicators, soil fertility research in the province be geared towards site specific fertiliser recommendations such as organic and inorganic fertiliser rates for sustainable soil management.
4. There is need to further investigate other phosphorus sorption characteristics like time, soil pH, soil organic matter, iron, and aluminium oxides of soils to clarify the other factors that contribute to P sorption rather than using only clay.

LIST OF APPENDIXES

APPENDIX 1

TABLE 3.2: P-VALUES OF ANOVA FOR THE MEASURED SOIL PHYSICAL FERTILITY PARAMETERS

Factor	Sand	Silt	Clay	Si/C ratio	TP	BD	WHC
Sites (S)	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Land use types (LUT)	<0.001***	0.017**	0.003**	0.257	0.291	0.29	<0.001***
Soil depth (SD)	0.004	0.224	<.001***	<0.001***	0.161	0.162	0.363
S*LUT	<0.001 ***	<0.001 ***	<0.001***	<0.001***			<0.001***
S*SD	0.358	0.207	0.833	0.003**			0.848
LUT*SD	0.929	0.266	0.230	0.635			0.195
S*LUT*SD	0.922	0.996	0.976	0.996			0.859

*= indicates significant effect of treatments at 5% **=indicates significant effect of treatments at 1% and ***= indicates significant effect of treatment at 0.1%

APPENDIX 2

TABLE 4.1: P-VALUES OF ANOVA FOR THE MEASURED SOIL CHEMICAL FERTILITY PARAMETERS

Factor	pH(H ₂ O)	pH(KCl)	Δ pH	EC	OC	TN	Avail P	Exc K
Sites (S)	<0.001***	<0.001***	<0.001***	0.004**	<0.001***	<0.001***	<0.001***	<0.001***
Land use types (LUT)	<0.001***	<0.001***	<0.001***	<0.001***	0.007**	0.193	<0.001***	<0.001***
Soil depth (SD)	0.053	0.734	0.231	0.033*	0.130	0.587	0.886	<0.001***
S*LUT	<0.001***	<0.001***	<0.001***	<0.001***	0.005**	<0.001***	<0.001***	<0.001***
S*SD	0.679	0.999	0.434	0.704	0.037*	0.889	0.116	0.989
LUT*SD	0.963	0.990	0.801	0.971	0.922	0.751	0.756	0.462
S*LUT*SD	0.997	0.998	1.000	1.000	0.972	0.900	0.868	0.891

*= indicates significant effect of treatments at 5% **=indicates significant effect of treatments at 1% and ***= indicates significant effect of treatment at 0.1%

APPENDIX 3

TABLE 4.2: P-VALUES OF ANOVA FOR THE MEASURED SOIL CHEMICAL FERTILITY PARAMETERS

Factor	Exc. Ca	Exc Mg	Exc. Al	Avail. S	Ext. acidity	CEC	Ext Cu	Ext Fe	Ext Mn	Ext Zn
Sites (S)	<0.001***	<0.001***	<0.001***	0.003**	0.018*	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Land use types (LUT)	<0.001***	0.027*	<0.001***	0.423	<0.001***	<0.001***	0.001***	0.003**	<0.001***	<0.001***
Soil depth (SD)	0.433	0.625	0.530	0.298	0.988	0.625	0.466	0.869	0.725	0.756
S*LUT	0.002**	<.001***	0.007**	0.371	0.128	<0.001***	0.052	<0.001***	0.002**	<0.001***
S*SD	0.925	0.964	0.930	0.635	0.973	0.987	0.477	0.986	0.863	0.953
LUT*SD	0.929	0.909	0.201	0.908	0.848	0.908	0.350	0.849	0.942	0.982
S*LUT*SD	0.877	0.941	0.405	0.351	1.000	0.864	0.624	1.000	0.969	0.995

*= indicates significant effect of treatments at 5% **=indicates significant effect of treatments at 1% and ***= indicates significant effect of treatment at 0.1%