RESPONSE OF GROWTH, YIELD AND ROOT CHARACTERISTICS OF A DETERMINATE COWPEA VARIETY TO VARIABLE PHOSPHORUS FERTILISER AND LIME APPLICATION RATES

By

PATRINA NARE MAPHOTO

MINI-DISSERTATION
Submitted in partial fulfilment of the requirements of the degree of
MASTER OF SCIENCE IN AGRICULTURE (SOIL SCIENCE)

in the

FACULTY OF SCIENCE AND AGRICULTURE
(School of Agricultural and Environmental Sciences)

at the

UNIVERISITY OF LIMPOPO, SOUTH AFRICA

SUPERVISOR: Prof F.R. KUTU

2018

DECLARATION

I declare that this research project entitled ‘Response of growth, yield and root characteristics of a determinate cowpea variety to variable phosphorus fertiliser and lime application rates’ is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references and that this work has not been submitted before for any other degree at any other institution.

Maphoto P.N
____________________ ____________________
Student’s signature Date

____________________ ____________________

Supervisor’s signature Date

DEDICATION

This mini-dissertation is dedicated to my beloved son Amogelang Raesibe Maphoto for being a source of my inspiration for making me to strive hard and my mother Ms Rebecca Ramokone Maphoto who taught me not to give-up in life no matter the challenge in any situation.

ACKNOWLEDGEMENTS

First and foremost, let me take this opportunity to thank Almighty God for giving me strength and wisdom without which I could be nothing. His security, mercy and grace made me to keep on striving until the completion. Secondly, I sincerely express my gratitude to my supervisor Professor F.R. Kutu. His guidance and positive criticisms has ensured that this study was a success. Thank you for putting your time and commitment to this study even when you were kilometres away. I salute you thank you once more.

I also express my appreciation to my family for their love, support and guidance throughout my studies especially my beloved sisters Salmina and Evah Maphoto. Mostly I will like to express my gratitude to Tshepo John Ndlovu throughout this project for his words of motivation made me to keep on endeavouring until the completion of this arduous task. “Ke a leboga”. Furthermore, I also express my gratitude to the staff in the School of Agriculture and Environmental Sciences who gave me productive suggestions and ideas until the desired results were met; the staff at University of Limpopo Horticultural Research Skill Centre for technical support and also not forgetting my friends and colleagues who assisted me in one way or the other until the completion. To all of you, I say, thank you.

Lastly I will like to express my sincere appreciation to Mr William Deale from ARC-Grain Crops Institute, Potchefstroom for providing me with Vaalburg dolomitic lime that was used in this study. I am also indebted to Ms L.L Molapo (Ausi Lerato) of the Department of Rural Development and Land Reform (DRDLR) and Mr Tebogo (the extension officer at Bronkhorstspruit for providing me the link with the small-scale farmers of Sokhulumi from whose field the needed acid soil used for this study was collected. Finally, the financial assistance from the National Research Foundation (NRF) South Africa through the Innovation Master’s Scholarship (Grant UID: 83073) and Department of Agriculture, Forestry and Fisheries (DAFF) for a grant holder link bursary support through the Zero hunger project are greatly acknowledged.

ABSTRACT

Soil acidity is one of the abiotic stress factors that greatly limit the productivity of crops on farmers' fields. A greenhouse study was carried out over two summer growing seasons to evaluate the effect of lime and phosphorus (P) application rates on the growth, yield and root attributes of a determinate cowpea variety on acid soil. The experiment was laid out as a 4x5 factorial arrangement with 4 replications. Treatment factors comprised of variable rates of Vaalburg dolomitic lime (0, 2, 4 and 6 t ha^{-1}) and P (0, 15, 30, 45 and 60 kg ha^{-1}) using single super phosphate, 10.5% P. The two treatment factors were combined resulting in a total of 20 treatment combinations. Data collected included cowpea growth parameters, crop phenology, yield attributes and root characteristics. While cowpea plants with no P application consistently gave the least plant height, stem diameter, number and length of trifoliate leaves, the 6 t ha^{-1} lime rate appears to be completely disadvantaged for all measured parameters with generally lower values than in soil filled pots without lime application.

Results showed that soil pH was increased with 6 t ha^{-1} lime application while soil electrical conductivity (EC), percent of organic matter (OM) and total organic carbon (TOC) were all increased with increasing P and lime rates. All measured cowpea growth attributes such as plant height, stem diameter, number of trifoliate leaves, and leaf area were significantly increased ($p \leq 0.05$) with increasing P and lime rates. During the two planting seasons, P and lime application resulted in reduced ($p \leq 0.05$) duration to flowering, pod formation and physiological maturity. The 6 t ha^{-1} lime application produced higher number of pods (2.50) compared to the other rates. Application rates of 45 kg P ha^{-1} and 6 t ha^{-1} of lime produced superior number of seeds per pod with high values of (13.71) and (12.85), respectively. However, cowpea root attributes namely number of nodules per plant, the third branching root diameter, angle of adventitious root, tap root diameter at 5 and 10 cm, shallow and deep score were significantly increased at moderate P rate of 30 kg P ha^{-1}. Overall, findings of this study revealed that application of both P fertiliser and lime were able to ameliorate the negative effect of P deficiency from soil acidity on the evaluated cowpea variety and promoted increased yield.

Keywords: Acid soil, grain cowpea, P fertiliser, lime, growth, root characteristics, yield

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

Cowpea *(Vigna unguiculata* (L.) Walp) is still one of the crops that are highly valued in several African countries due to its use as a component of daily staple food (Weinberger and Msuya, 2004). It is a well-known grain legume crop that is mostly consumed by local people of South Africa. Cowpea is reported to be a good source of fodder for animals; being very rich in protein, carbohydrates as well as vitamins (Keller, 2004; Adeyemi et al., 2012). Several other studies (Msangi, 2014; Thomas, 2014; Dube and Fanadzo, 2013) have suggested that cowpea plays important roles in human life including its benefits or uses for medicinal and cultural purposes as well as for addressing nutritional deficiencies in humans. Hence, cowpea can be recommended as one of the grain legumes that can assist in the eradication of food insecurity due to its nutritional benefits. Meanwhile food insecurity is one of the main causes of malnutrition in many households in South Africa (Schönfeldt and Pretorius, 2011).

Seemingly, Bado et al. (2006) stressed that cowpea production must be increased in-order to advance human health and nutrition in Africa. In South Africa, cowpea is locally known by indigenous African people as *dinawa;* and mostly grown by smallholder farmers for its leaves as *morogo* under dryland farming conditions (DAFF, 2011). As a leguminous plant, it has nitrogen (N) fixing ability and also plays an important role in erosion control, particularly; the creeping types (Aikins and Afuakwa, 2010). Increased and sustainable cowpea production, like other field crops, depends largely on the soil fertility status and productivity indicators such as nutrient content, soil reaction, rooting depth, and the general physical conditions (Richard and Simpson, 2011). Phosphorus (P) is one of the major plant nutrients that play critical roles in cowpea production. It stimulates root and plant growth, and also influences nodule formation and energy transfer, particularly adenosine triphosphate (ATP) in nitrogenase activity (Richard and Simpson, 2011).

Most smallholder farmers generally experience low productivity due to decline in the nutrient status of the soil (Mills and Fey, 2004; Mandiringana et al., 2005) and their poor or inappropriate crop production practices (Kutu, 2012). Odhiambo (2011) reported that the low productivity on smallholding farmlands is attributed to such reasons as little or no fertiliser use. Soil acidity is also an important inherent factor that influences crop productivity; exerting strong negative impact on nutrient availability, particularly P. Such acid affected soils are reported to contain toxic level of Al^{3+} and Mn^{2+} ions, possess pH value of less than 5.9 and 4.9 when measured in water and potassium chloride solution, respectively, with acid saturation greater than 40% (FSSA, 2007). Available records reveal that soil acidity affects about 4 billion ha of global agricultural soils (von Uexküll and Mutert, 1995) while between 5 and 16 million ha of arable farmlands in eastern Mpumalanga, Western Cape, Eastern Cape, KwaZulu-Natal and Limpopo provinces are reportedly affected by soil acidity in South Africa (Venter et al., 2001). The management of soil acidity may either entail the planting of acid tolerant crops or the use of corrective measures such as liming materials. Application of liming material helps to neutralise soil acidity by reducing the activity of Al^{3+} through its precipitation as $Al(OH)_3$ (Ward et al., 2011).

1.2 Problem statement

Grain crops production in South Africa, including cowpea, has declined in recent years due to a number of reasons, one of which includes soil acidity problems that have impacted negatively on household and national food production and nutrition security. Acidity is a core factor that causes P limitation in soils through Al^{3+} and Mn^{2+} toxicity. This problem exerts negative impact on P availability through fixation; and the consequent negative effect of huge crop yield losses. Similarly, it is a major limiting factor for N fixation by legumes (Yakubu et al., 2010; Haruna and Usman, 2013). Furthermore, the planting of low quality seeds that are predominantly landraces and not tolerant to acid soil conditions as well as the poor management practices of resource-poor cowpea producers all contribute to low cowpea productivity (Shiringani and Shimelis, 2011). This continues to promote persistent food scarcity, hunger and poor nutrition in many rural poor households and communities.

1.3 Motivation of the study

Cowpea is a rich protein food source and thus important in addressing poor nutrition in resource-poor communities. Appropriate lime and P fertiliser application is important for guaranteeing increased cowpea production under acidic soil conditions. The production of high quality and nutrient-rich cowpea grains is crucial for improved nutrition and healthy living. Appropriate management strategy to deal with soil acidity is thus required to promote growth, P acquisition, and yields of cowpea under acidic soil conditions.

1.4 Aim and objectives of the study

1.4.1 Aim

The aim of the study was to provide preliminary recommendation on the optimum lime and P rates that will promote better growth and high productivity of a determinate cowpea variety under acidic soil conditions.

1.4.2 Objectives

The objectives of the study were to:

i. Evaluate the growth and yield of a grain cowpea variety under acidic soil conditions following P fertiliser and lime application

ii. Assess the impact of soil acidity on root characteristics and P acquisition of the grain cowpea variety

iii. Determine the optimum P and lime rate for the grain cowpea variety grown under acidic soil.

1.4.3 Hypotheses

Hypotheses of the study were:

i. Cowpea growth and grain yield grown under acidic soil conditions will be affected by P fertiliser and lime application.

ii. Soil acidity has no negative impact on cowpea root characteristics and P acquisition.

iii. The optimum P and lime rates for grain cowpea production under acidic soil are not known.

CHAPTER 2

LITERATURE REVIEW

2.1 Origin and description of cowpea

Cowpea is a member of the Phaseoleae tribe of the Leguminosae/ Fabaceae family. It originated from Africa and is widely grown in Africa, Latin America, South-east Asia and in the southern United States (Timko et al., 2007). It is a warm-season, annual, herbaceous legume that has a taproot system, which spreads. The taproot system assists in water and mineral absorption from the deepest soil making it a drought tolerant legume. Cowpea has three growth habits which are determinate, semi determinate and indeterminate. These three growth habits are divided in different growth patterns such as erect, trailing, climbing and bushy. The determinate types (erect) flower early and mature evenly while the indeterminate types flower over a long period and do not mature evenly (Omadi et al., 2001*)*.

Most of cowpea varieties/ landraces that are grown in South Africa by smallholder farmers have indeterminate growth habit. However, some of the newly developed early maturity varieties have a determinate growth phenotype (Timko and Singh, 2008). The first pair of leaves is basic and opposite of each other while the rest are arranged in an alternate pattern; and trifoliate. The leaves are usually dark green in colour and they are grown on a striate, smooth or slightly hairy with purple shade stem. Cowpea consists of variable flower colours depending on the variety; and it is a self-pollinating crop that has intermediate inflorescences borne on short pedicels (DAFF, 2011). The seeds are borne in pods, which vary in shape, colour and size.

2.2 Importance of cowpea and its production levels in South Africa

Cowpea is one of the important food legumes in the tropical and sub-tropical regions where drought is a major production constraint due to low and erratic rainfall. It plays a critical role in the lives of millions of people in Africa and other parts of the developing countries (Singh et al., 2011). Furthermore, it is a major source of dietary protein that nutritionally complements staple low-protein cereal and tuber crops (Kebe and Sembene, 2011), and is a valuable and dependable commodity that produces income for farmers and traders (Singh, 2002; Langyintuo et al., 2003). According to Singh et al. (2011), cowpea is a major source of protein, minerals and vitamins in daily human diets and is equally important as nutritious fodder for livestock. It is a major source of cheap plant protein to most underprivileged families and provides regular income to farmers through the sale of grain and fodder. It has more than 25% protein in seeds, in young leaves (dry weight basis) as well as immature pods (Sebetha et al., 2010; TJAI, 2010). In addition, cowpea is important for the sustainability of soil fertility and the control of erosion through the provision of ground cover (Asiwe, 2009a).

Cowpea plant is very useful in all its growth stages as a vegetable (Sheahan, 2012), while in many parts of Africa, young cowpea leaves are used as vegetables (Ibrahim et al., 2010). Harvested tender cowpea leaves are prepared as salad in a similar way to spinach (*Spinacia oleracea* L.), lettuce (*Lactuca sativa* L.), amaranthus (*Amaranthus* species) and cabbage (*Brassica oleracea var. capitata*) for direct consumption and it can also be eaten as relish along with other foods like potato and maize meals. Studies have revealed that cowpea leaves contain carbohydrate whose concentration is higher in older leaves with the protein content in such older leaves comparable to that in seeds (Sebetha et al., 2010).

In South Africa, the predominant cowpea growers are smallholder farmers under dryland farming conditions that mostly rely on rainfall in order to produce their crops (DAFF, 2011). There are four provinces where cowpea is mostly grown and these include Limpopo, Mpumalanga, North West and Kwa-Zulu Natal. Limpopo province is the major producer of cowpea in South Africa and it was found that all the six districts in Limpopo Province produce cowpea although there are scanty records with regard to the size of area under production and the quantities produced. Asiwe (2009b) reported that the average land area planted per farmer ranged between 0.25 and 2.0 ha under small-scale production while grain yield ranges between 0.25 and 2.0 t ha^{-1} with an average of 0.5 t ha^{-1}.

2.3 Abiotic and biotic factors that affect cowpea growth and yield

Cowpea is a summer crop which is usually sown from mid-October to early January. The optimum temperature required for a successful cowpea production is 20-35°C, but it does not tolerate temperatures below 15°C (Onuh and Donald, 2009). DAFF (2011) reported that cowpea germinates satisfactory at the minimum temperature of 20°C while DARDLA (2012) reported that extreme temperature above 35° results in early flowering and shedding of flowers that consequently lead to poor pod setting. Butterworth et al. (2009) reported that climate change has both positive and negative effects on crop growth and also impact on soil fertility, availability of soil water and the incidence of pathogens. Several studies showed that climate change can massively reduce crop production in most agricultural farmlands including cowpea fields (Gbetibouo and Hassan, 2005; Dinar et al., 2008). Ntombela (2012) reported that low temperature regime significantly decreases seed emergence, plant height, number of trifoliate leaves, and area of trifoliate leaves and chlorophyll content of cowpea. The study revealed that cowpea plants grown at the lower temperatures showed stunted growth since growth and development was always less due to chilling injury. Furthermore, Hatfield and Prueger (2015) stressed that the growth and development of a plant is highly dependent on the surrounding temperature of the plant since each species has a specific temperature range.

Several researchers such as Walker and Schulze (2008), Befekadu and Berhanu (2000) reported that rainfall is the key parameter which influences the growth characteristics of crops. South Africa is currently faced with a problem of uneven rainfall which has negative impact on cowpea growth and yield. Roberts et al. (2005) and Warburton and Schulze (2008) reported that shifting of rainfall seasons has been triggered by the change in the composition of the global atmosphere resulting in changes in the global climate. This has greatly affected agricultural production since most of summer rainfall is delayed and production is reduced due to water stress. However, Ndamani and Watanabe (2015) reported that cowpea flourishes well at optimum rainfall of 400 to 700 mm where summer rainfall predominates. Also, DAFF (2011) emphasised that cowpea tolerates an annual rainfall of 450 mm which could be applied in the form of rainfall or irrigation for cowpea growth and development. Nonetheless, cowpea fails to grow well under high moisture conditions since N fixation is inhibited but if grown during high rainfall periods it results in low yield (Rabie et al., 2005). Onuh and Donald (2009) also reported that decrease in soil water potential can adversely affect root hair and retard nodule growth and nitrogen fixation. Study by Abayomi and Adidoye (2009) reported that yield reduction under severe moisture stress ranged from 63% in IT99K-1060 and 98.4% for IT00K-901-5; and under moderate stress, yield reduction ranged from 42.6% in IT99K-1060 to 65.8% for

IT98K-491-4; while under mild stress, yield reduction ranged from 9.5% in IT97K-356-1 to 47.2% for IT98K-491-1.

According to DAFF (2008), cowpea is planted in soils that vary from sandy to clay with the pH ranging from 5.6 to 6.0. In South Africa, constraints affecting cowpea production include soil acidity and salinity and the consequent low soil fertility, which ultimately impact on crop growth and yield. Soil acidity is accentuated by the leaching of basic cations, mostly Ca^{2+} and Mg^{2+}; and is especially very pronounced in sandy soils (Crozier and Hardy, 2003). Soil salinity is a serious obstacle for the growth of most crops including cowpea (Silva et al., 2003). Study by Patel et al. (2010) showed that an increase in soil salinity from 2 to 10 dS m^{-1} significantly reduced the germination percentages from 84 to 15%, 10 to 8% and 64 to 6% for cowpea cultivar Akshay-102, Gomti vu-89 and Pusa Falguni, respectively. Study by Patel et al. (2010) supported an earlier study (Bernardo et al., 2006) that observed a reduction in seed germination, plant height and shoot dry weight with increase in salinity among cowpea cultivars.

Cowpea is widely grown under sole and intercropping systems. According to Campillo et al. (2008), solar radiation or shade can cause high yield losses in crops. Furthermore, Egli and Bruening (2006) reported that the reduction of number of flowers per cowpea plant and small pod abortion are observed in intercropping systems. However, the study by Tsubo et al. (2001) showed that intercropping achieves higher radiation interception than the sole maize followed by sole beans. Their results also showed a significant correlation between the logarithm of leaf area index and radiation transmission for sole maize, sole bean and intercropping with ($R^2 \geq 0.85$).

According to Emechebe and Lagoke (2002), the biotic factors that affect cowpea production include insect pests and diseases, nematodes and parasitic weeds. The activities of these biotic factors result in decrease in cowpea yields (Singh and Ajeigbe, 2002). Among the cowpea diseases, the bacterial blight induced by *Xanthomonas axonopodis pv. vignicola* (Burkholder) has been reported to be probably the most widespread having been reported from all regions of the world where cowpea is cultivated (Bouker and Fatokun, 2007).

Singh and Ajeigbe (2001) reported that symptoms of cowpea bacterial blight on leaves begin with small water soaked spots that remain small but gradually coalesce into large, irregular, brown and necrotic lesions when the adjacent tissues die. Furthermore, cowpea bacterial blight also invades the stem where it produces cracking with brown stripes, swelling (canker) and dark green water soaking on pods from where it enters the seeds and causes their discolouration. Additionally, DAFF (2011) reported that pod-sucking bugs (*Riptortus* species, *Nezara viridula* and *Avantomia* species), aphids (*Aphis fabae* and *Aphis craccivora*), blister beetle (*Mylabris* species) and pod borer (*Maruca vitrata*) are from the list of insect pests that affects cowpea growth and they can cause up to 100% grain yield loss (Saria, 2010).

2.4 Importance and sources of phosphorus in soil and plant

Phosphorus is the most essential plant nutrient for crop production since its deficiency in soil could result in reduced root development, leaf expansion and generally stunted plant growth (Ajiboye et al., 2007). It is well known for its role in capturing and converting the sun's energy into useful plant compounds (Cordell et al*.,* 2009) and thus improving photosynthetic capacity of the plant. Ali et al. (2004) reported that adequate application of P levels is required in order to enhance shoot and root growth and in promoting early flowering and maturity. Nwoke et al. (2008) showed that P application of 23 kg P ha^{-1} significantly increased the shoot dry matter yield of both soybean and cowpea while Singh et al. (2011) indicated that grain yield of cowpea was significantly increased with high P rate of 60 kg P ha^{-1} (1353 kg ha^{-1}) as compared to unfertilized control (1017 kg ha^{-1}), 20 kg P ha^{-1} (1067 kg ha^{-1}) and 40 kg P ha^{-1} (951 kg ha^{-1}). Furthermore, Asuming-Brempong et al (2013) reported that application of 90-120 kg P ha^{-1} is required in growing cowpea at the coastal savannah zone of Ghana. These studies show that P is important in cowpea production and that P application may vary in terms of locations due to nutrient status of the soil.

Naturally, soil P differs significantly from one location to another ranging from around 500-2500 kg P ha^{-1} and its variability is caused by climatic factors and colloidal particles (SAUK, 2010). In agricultural farmlands, P is usually obtained from the application of fertilisers (inorganic and organic fertiliser). Although inorganic fertilisers are readily available while the organic sources require microbial activity to decompose and their nutrient are released slowly. Organic fertilisers are found in the form of plant and animal remains such as livestock manure and rock phosphate since they consist of important plant P sources that could increases soil P level. Organic supplements have been reported to increase P availability since it forms chelates with P-fixing ions soils (Agbenin and Igbokwe, 2006; Gichangi and Mnkeni, 2009) and humic substances enhance the bioavailability of P fertilisers in acidic soils (Hua et al., 2008).

Inorganic fertilisers are usually applied in the form of mono ammonium phosphate which is in the granular form which are Tripple Super Phosphate (TSP) and Single Super Phosphate (SSP) and ammonium polyphosphate which is in the liquid form (Hedley and McLaughlin, 2005). According to FAO (2005), cowpea requires more P than N and that P must be applied in the form of single superphosphate. Also, FAO (2005) recommend that application of 30 kg P ha^{-1} of SSP is required to aid cowpea to nodulate well and fix its own nitrogen from the air.

2.5 Origin and sources of acidity in the soil

According to Bolan et al. (2003), soil acidity used to occur naturally in areas of high rainfall whereby water leaches all basic nutrients and results in formation of acidic protons. TSO (2010) also indicated that soil acidity is caused by the parent material from which the soil develops especially on acidic rocks such as granites. Soil microbial activities and root respiration process produce CO_2 in the soil that cause the formation of weak acid called carbonic acid (Mohd Aizat et al., 2014). Epstein and Bloom (2005) further revealed that acidity occurs naturally by decomposition of organic matter in organic rich siliceous or base cation poor parent material can also result in formation of organic acids.

Recently, soil acidity is propelled by the activities caused by mankind in the agricultural and industrial sectors. The common anthropogenic causes in agricultural practices include the use of nitrogenous fertiliser, the oxidation of organic residues under cultivation which is combined with incorrect management practices and removal of basic cations via crop harvesting and livestock rearing (Ayuke et al., 2007). Industrially, acidity is caused by combustion of fossil fuels which results in acid rain due to sulphuric and nitric acids produced during combustion. Similarly, mining activities also result in increased oxidation of sulphide minerals to sulphuric acid in soils (Epstein and Bloom, 2005). According to Sydenham (2015) and Kochian et al. (2004), over 50% of world arable lands are classified as acidic. Under such conditions there is also high level of

Al^{3+} and Mn^{2+} which cause soil toxicity which acts as the main limiting factor for plant growth (Epstein and Bloom 2005; Kochian et al., 2004). Dam-ampai et al (2007) showed that natural and anthropogenic activities result in the increase of H^+ in the soil which results in a decrease of soil pH.

2.6 Effects of soil acidity and lime on plant growth

Soil acidity is an economic and natural threat worldwide since it reduces plant growth and leads to low production rates (Samac and Tesfaye, 2003). Most South African soils are becoming nutrient deficient due to dominant acidic soil conditions and many farmers require alternatives to highly priced conventional methods of soil amelioration. Sydenham (2015) reported that soil acidity is a serious production constraint which can result in loss of yield of 10 to 15%. It is one of the factors that hinder cowpea production through its negative impact on N fixation (Appunu et al., 2009) as well as rhizobium survival and persistence in soils (Ibekwe et al., 1997). The failure of nodulation under acid soil conditions is common, especially in soils with a pH less than 5 (Appunu et al., 2009). Thus, acidity in soils causes P fixation through the formation of insoluble compounds with aluminium, iron and lead (Khan et al., 2009). Oyeyiola et al. (2014) reported low cowpea grain yield of 156 kg ha^{-1} with slightly acidic soil of pH 5.7 as compared to grain yield of 1419 kg^{-1} ha with pH of 7.0. Legesse et al. (2013) also found that soil acidity at pH of 4.39 significantly reduced number pods per plant, pod length, grain yield, hundred seed weight and harvest index among 25 common bean genotypes.

Soil acidity problem is addressed by applications of agricultural lime such as calcitic or dolomitic lime. Agricultural lime comes from naturally occurring limestone that is mined and crushed; and they are basic in nature. The application of commercially available alkaline materials such as limestone, slaked lime and dolomite is a common practice for amelioration of soil acidity problem (Fageria et al., 2004). Lime has a tremendous effect in reclaiming acidic soils since it helps to raise the soil pH, plant nodulation, growth, and yield and improves soil structure. Buni (2014) reported a significant increase of soil pH in plots that were applied with lime ($CaCO_3$) that those without lime on field planted to haricot bean. The study revealed that application of 0 kg ha^{-1} lime produced soil pH of 5.03 followed by 1250 kg ha^{-1} lime with soil pH of 5.64 then 2500 kg ha^{-1} lime with soil pH of 6.14 and 3750 kg ha^{-1} lime with soil pH of 6.72.

The results further showed that soil chemical properties such as Al, Mn, Fe and Cu were significantly decreased with increasing lime application.

Poschenrieder et al. (2008) also reported that lime application enhances availability of nutrients such as Ca, Mg, Mo and P which assist in crop growth and yield production whilst Mupangwa and Tagwira (2005) indicated that application of calcitic lime at 800 kg ha^{-1} gave significantly higher kernel yield of groundnut (*Arachis hypogea* L.) as compared to lower rates of 0, 200 and 400 kg ha^{-1}. Comparable results were also obtained by Kumar et al. (2014) who stated that lime application at 0.6 ton ha^{-1} produced the highest yield attributes of pods per plant, pod length, grains per plant, filled pods per plant, pod filling (%) and 1000-grain weight as compared to the control, 0.2 ton ha^{-1} and 0.4 ton ha^{-1} of rice bean (*Vigna umbellata*).

According to Fageria and Baligar (2008), liming is an effective practice of raising soil cation exchange capacity (CEC) and also improving clay mineral and organic matter content in the soil. The amount of lime applied on the soil depends on the type of soil, quality of the liming material and also the type of crop to be planted. Mupangwa and Tagwira (2005) indicated that application of lime has significant effects on soil buffering capacity as well as the exchangeable sites that held the toxic metals in the soil. Adjustment and maintenance of soil acidity via liming is a very important soil management strategy for crop production. Application of lime produces soil mineral nutrients to be more available for plants use. Bierman and Carl (2005) indicated that regular application of required amount of lime is essential because soil acidification is an on-going process. Therefore, lime recommendation tests supposed to be done in order to identify severity of H^+ content in the soil since the amount of lime required to increase soil pH varies. DAFF (2011) reported that cowpea grow well on soil pH between 5.6 and 6.0 meaning that soil pH less than 5.6 causes constraints on cowpea production. Research work is also needed to give lime recommendations for cowpea production on the soils which are having pH less than 5.6.

Yet, numerous research work suggested that organic residues (plant residues, animal manures and composts) may also be used as an alternative liming materials since they take long to be decomposed and their application increases plant growth as well as ameliorating Al toxicity (Mkhabela and Materechera and 2003; Mokolobate and Haynes 2002; Oyeyiola et al., 2015). Mkhabela and Materechera (2003) reported that application of lime, ash and manure increased soil pH by 18%, 5% and 2%, respectively. Furthermore, the results showed reduced acid saturation by 98%, 59% and 61% by lime, ash and manure respectively, while exchangeable acidity was reduced by 94%, 58% and 89% by the respective amendments. These outcomes might be caused by the reactivity of the amendment in the soil. Conversely, application of either one of these three amendments ameliorate acidity problem but lime is more effective since it react faster than ash and manure. Nonetheless, application of organic residues such as kraal manure, chicken manure and plants residues can be recommended for small-scale farmers who cannot afford to buy lime.

2.7 Development and importance of root system in cowpea

Root system is an underground imperative organ that plays a significant role in growth and development of plants. According to Schrick and Laux (2001), root develops through the process of embryogenesis where the hypocotyl of an embryo in the seed gives rise to the primary root. These primary roots grow vertically into the soil and give rise to the emergence of numerous lateral roots which spreads in the soil surface (Shishkova et al., 2008). Their development varies with the stage of plant growth and species (Hochholdinger and Zimmermann, 2008); root has indeterminate growth with a functional meristem throughout its life. However, Chapman et al. (2003) reported that dicotyledonous plants such as cotton have a determinate root length, but in most cases it may be dependent on the environment. Interestingly, root systems consist of two main types of roots which are namely the tap and adventitious root systems. Simpson (2010) reported that plants with a tap root system occur in dicotyledonous plants and they are deep rooted as compared to those with adventitious type developing from the monocots plant.

Root system performs many essentials adaptive functions which includes water and nutrients uptake, anchoring the plant as well as the establishment of biotic interactions at the rhizosphere (Nui et al., 2013). According to Lòpez-Bucio et al. (2003), changes in architecture of the root system can profoundly affect the capacity of plant to take up nutrients and water. Therefore, plant roots and root architecture are partly controlled by physical and agronomic factors (White et al., 2013; Andraski and Bundy, 2003) while the amount of water and mineral nutrients available for plant use depends on how much soil is occupied by the root system. According to Torres et al. (2014), roots improve the organic matter content of the soil, which is responsible for the improving the physical, chemical and biological properties of the soil, resulting in higher crop yield.

Besides, roots also have other secondary functions such as storage, production of growth regulators, propagation and dispersal (Waisel et al., 2002). Moreover, grain legumes such as cowpea, groundnut (*Arachis hypogaea* L.) soyabean (*Glycine max*) and bambara groundnut (*Vigna subterranea* L. *Verdc*.) have been shown contribute to amounts of symbiotic nitrogen availability to the cropping systems due to formation of nodules on the hosts roots (Sanginga et al., 2002; Giller, 2001). In support Dube et al. (2014), reported that intercropping of cowpea and maize with the same planting basin showed the highest root density of 1789 kg ha^{-1} maize yield and 1226 kg ha^{-1} when it is not intercropped.

2.8 Effect of low soil pH on root distribution

Development, distribution and root growth through the soil profile are adversely affected by soil chemical constraints such as low soil fertility and Al^{3+} toxicity (Iqbal, 2012). According to Horst et al. (2007), soil with pH values of 5 or below results in formation of toxic forms of Al which disrupts functions of root growth since it inhibits cell elongation and division. Sanchez et al. (2003) reported that Al toxicity occur in the soil which have more than 60% Al saturation and it affects 1493 million hectares of tropical agriculture. This Al toxicity results in blockage of the cell division mechanism, leading to inhibition of root growth (Matsumoto, 2002). Consequently, roots become thin and brittle, root hair development is poor, and root tips are damaged and thickened, ultimately resulting in severe damage to the root system and leading to poor uptake of nutrients and water (Panda et al., 2009).

Root damage can reduce the nutrient uptake and eventually induce of mineral deficiencies, causing a reduction in dry mass. The results of a study by Ribeiro et al. (2013) showed that Al content decreases the level of N, P, K, calcium (Ca), and magnesium (Mg) in all plant organs of cacao geotypes. The results further showed decrease in N content of roots by 9% and 11%, stems by 48% and 29% and leaves by 77% and 41% for the variety Catongo and Theobahia hybrid, respectively. Also, Al content decreased the P contents growth by 38% and 38% in roots, 80% and 78% in stems, 94% and 75% in leaves for the variety Catongo and Theobahia hybrid, respectively. Jemo et al. (2007) also reported that *Vigna unguiculata* has negative response toward Al availability, since it significantly reduced P accumulation. Soil with low pH significant affects the survival and abundance rhizobia growth, and also their effectiveness in nodulation (Ferguson et al., 2010). In support White and Lin et al. (2012), reported that legume species differ in their nodulation and a growth response to acidic soil since nodule formation is more sensitive to low pH than other aspect of plant growth. The study showed that nodule formation has been reduced by more than 90% and nodule dry weight greater than 50% in species such as soybean, pea, cowpea, *Medicago savita* and lucerne for both determinate and indeterminate nodule forming species. Furthermore, Liao et al. (2001) reported that in low P conditions the roots of common bean (*Phaseolus vulgaris*) have less sensitivity to gravitropism resulting in a shallower root system than other genotypes.

Root morphology changes in response to P deficiency are characterized by more rapid development, higher root/shoot ratios, and finer and longer roots as well as more root hairs (Allousch, 2003). Paradoxically, Araújo et al. (2005) indicated that low soil P have high phenotypic and genotypic correlations between shoot mass and root mass in backcross bean families. Their (Araújo et al., 2005) results also showed significant correlation of shoot mass with root mass at early pod filling produced with R^2 of 0.734** at low P and 0.518* at high P while R^2-value of 0.420* and 0.427* at low and high P, respectively were reported at pod setting.

2.9 Factors affecting P acquisition by roots

Effectiveness and acquisition of soil P by plant roots largely depends on the plant ability to use insoluble P (Olaleye et al., 2012; Vance et al., 2003). During nutritional stress such as phosphorus deficiency, Al toxicity and low Fe plants have been reported to go through several morphological and physiological changes to efficiently use available soil P and to mobilize P from less available soil P fractions (Trindade and Araújo, 2014; Olaleye et al., 2012). One of the changes developed by plants in response to P availability is the modification of their root system or architecture. Krasilnikoff et al. (2003) reported increased root hairs and length of cowpea varieties in order to adapt to low P soil conditions by accumulating larger volume of the soil. Several studies showed that common bean (*Phaseolus vulgaris*) genotypes tend to form larger and branched root system with numerous basal roots and also change the gravitropic response of basal roots, resulting in a shallower root system to increase P uptake from the topsoil (Ge et al., 2000; Araújo and Teixeira, 2008). Under such conditions arbuscular mycorrhizae (AMF) fungi infection may also increase, since they are known to absorb phosphorus at lower solution concentrations than plant roots using their external hyphae (Smith and Read, 2008). Nwoke et al. (2008) found that increased rate of AMF infection on roots of numerous legumes and cereal was significantly higher at low phosphorus application than at high P supply.

Root exudates are also reported to play an important role in the mobilization of soil mineral nutrients from sparingly soluble phosphate (Zhou et al., 2012). Organic acids in particular are most important factor affecting P acquisition by plant roots. Nwoke et al. (2008) reported secretion of citric acid in pigeon pea (4.06 µmol g^{-1} soil), cowpea (10.85 µmol g^{-1} soil) and soybean (17.48 µmol g^{-1} soil) respectively, under relative low P soils in Nigeria ranging from 1.47 to 2.49 mg kg^{-1} P. Gahoonia et al. (2000) attributed high P acquisition by winter barley to its ability to obtain P from strongly adsorbed soil P by secreting more organic acids, in particular citric acid whilst Gerke et al. (2000) showed that acquisition of inorganic P was significantly increased by root exudates of *piscidate* in pigeon pea. The process of enhancing P mobilisation by root exudates results from reduced number of binding sites for P fixation through chelation of Ca, Fe and Al and replacing with phosphate and P fixing minerals for adsorption in the soil (Gerke et al., 2000; Ryan et al., 2001).

Another physiological response by plant roots in response to P acquisition in low P soil conditions is the secretion of phosphatase enzyme to mineralize organic P into inorganic form (Machado and Furlani, 2004). Li et al. (1997) found that increased acid phosphatase activity in the rhizosphere of phosphorus-deficient white lupin caused an appreciable depletion of organic P in the soil. Moreover, George et al. (2006) reported positive correlation between the activity of acid phosphatase and the depletion of organic P in the rhizosphere of clover. The ability of plants to secrete acid phosphatases differs greatly among species (Wang, 2009) and the direct contribution of phosphatase activity to organic P is well reported (Miller et al., 2001; Baldwin et al., 2001). Other studies showed that proton release by plant roots to modify the pH of rhizosphere maintains the electron neutrality inside the plant and thus increases P acquisition under low soil P conditions (Hinsinger et al., 2003; Bogayoko et al., 2000).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Description of the study site

This study was conducted under greenhouse conditions at the Horticultural Research Skill Centre of University of Limpopo (23° 53′ 10″ S, 29° 44′ 15″ E), Turfloop campus. The trial was initially planted during April to July 2014 but was affected by frost prior to flowering resulting in cold damage and termination. It was later repeated during November 2014 to March 2015.

Figure 1: Loss of vigour and reduced growth on cowpea plants due to frost and cold damage from the first trial.

3.2 Soil sampling and pre-planting soil analysis

The soil used for the experiment was collected from the surface 0-20 cm at an open crop field at Sokhulumi near Bronkhorstspruit (Mpumalanga Province) during March 2014 for the 1st study and November 2014 for the repeated study. The selection of the site for soil sample collection for this study was based on the knowledge of the soils in the area whose laboratory analysis revealed acidity problems. The results of the previous analysis revealed a pH value of 3.82 and acid saturation of 56%. A repeat of a representative sample of the soil sample collected for this study prior to planting of the experiments was subjected to detailed chemical analyses following standard procedures.

3.3 Experimental design, treatments and trial layout

The experiment was laid out as a 4x5 factorial experiment arranged in a completely randomised design (CRD) having four replications. Treatment factors consisted of four lime rates (0, 2, 4 & 6 t ha^{-1}) and five P rates (0, 15, 30, 45 & 60 kg P ha^{-1}) which resulted in a total of 20 treatment combinations. The P fertiliser was applied using single superphosphate (10.5% P) while lime was applied as Vaalbrug dolomitic lime obtained from ARC- Grain Crops Institute, Potchefstroom. The trial was planted in 30 cm diameter planting pots with each having 7 kg of soil and the soil was thoroughly mixed with each treatment in each pot. The soil filled pots were irrigated with 850 ml tap water and allowed to equilibrate for 24 hours prior to seed sowing. Five cowpea seeds were sown per pot and later were thinned to 3 plants per pot at one week after crop emergence. Thereafter, the pots were regularly irrigated at 60% field capacity as required by the plants at monitored temperature of 25-30°C. The plants were irrigated twice per week from planting date to maturity with 500 ml of tap water. The irrigation time was determined by visible sign of moisture stress by cowpea plants.

3.4 Data collection

3.4.1 Measurement of growth parameters

Phenological data such as duration to seedling emergence, initial flowering and pod formation, and 100% flowering and pod formation were all monitored and recorded. Growth parameters that were measured on the three (3) plants per pots included plant height (PL), stem diameter (SD), number of trifoliate leaves for each plant (NT), length of trifoliate leaves (LT), and the width of trifoliate leaves (WT). The trifoliate leaf (AT) area for each cowpea plant was measured using a ruler. The process entails the measurement of the linear dimensions of LT and WT of selected leaves followed by simple leaf area calculation using the equation trifoliate leaf area, $AT= (LT \times WT)*2.325$ according to Osei-Yeboah et al (1983). These parameters were all measured at 3, 6, 9 and 10 weeks after emergence (WAE) Plant height was measured using a ruler while the electronic calliper was used to measure the stem diameter at approximately 3-5 cm above the soil level. Number of trifoliate leaves were counted per plant and recorded whereas length, and width of each trifoliate was measured using a ruler. Subsequently, trifoliate area was calculated using measured length and width. Leaf chlorophyll content was measured using CCM-200 plus chlorophyll content meter on fully developed top and middle leaves during flowering to early pod formation.

3.4.2 Yield data collection

Yield data for this study was determined during harvest and included the number of pods per plant, pod weight, number of seeds per plant and seed weight was determined for each pot. Pods were detached from the plants in each pot, counted for each plant and recorded. Pods were weighed using an electronic balance to obtain the weight of the pods, which were thereafter, threshed manually and the number of seeds contained therein counted. All seeds obtained per plant was also weighed to determine the seed weight. Only fully developed seeds were counted and weighed. Subsequently, plants were cut using a scissor to divide roots and above ground plants biomass described as fodder. The fresh plants and roots biomass were weighed using an electronic weighing balance. Root biomass was collected from each harvested pot by washing of soil containing roots on 1.0 mm sieve under running tap water to remove soil particles; and the collected roots weighed fresh and also after oven drying at 65°C. The above ground plant and roots biomass were then oven dried at 65°C for 24 hours for dry biomass weight determination.

3.4.3 Measurement of cowpea roots characteristics

Cowpea plants were carefully removed at crop maturity from the pots and soil attached to the roots loosened from each plant by washing under tap water for the purpose of phenotyping. Thereafter, shovelomic technique was used to measure selected root traits as described by Trachsel et al (2010). They included the whorl angles for adventitious and basal roots, the tap root diameter at 5, 10, 15 and 20 cm soil depths, shallow and deep scores. The whorl angles were measured by displaying roots on a 180° protractor sketch board where the stem is at zero degree (0°) and the angle on both sides were measured and their average determines whorl angles (Figure 2). The number of basal roots was counted from each plant whilst the nodules present were carefully removed from the roots, counted and recorded. The third (3rd) root branching density and 1.5 mm root branching density at 5 and 10 cm soil depths as well as the plant stem diameter were measured at approximately 3 cm above the crown using electronic Vernier calliper.

Figure 2: Shovelomics board used to measure cowpea root characteristics data.

3.5 Postharvest soil sampling and analysis

3.5.1 Soil pH

Eighty treatment~~s~~ samples were sieved using a 2 mm sieve, thereafter 10 g of each sieved soil sample was weighed using electronic weighing balance and transferred inside 50 ml glass beakers and those samples were replicated. The pH (H_2O and KCl) was measured using pH meter calibrated in a buffer solution of pH 4.7 and 9.2. After calibration, 25 ml of distilled water was added in each glass beaker and stirred with a stirring rod for 5 seconds and it was let to be mixed for 50 minutes. After 50 minutes, the soil was stirred again for few seconds and pH meter was used to read the pH of soils and before moving the pH electrode to the next treatment sample it was thoroughly washed with distilled water in order to avoid contamination. Same procedure was also used in pH determination of KCl.

3.5.2 Bray-1 procedure for available P determination

Availability of P was determined using Bray-1 extraction procedure described by Bray and Kurtz (1945). Soil sieved through a 2 mm sieve was weighed to 6.67g and placed in a 250 ml plastic bottle. Prior to weighing the 80 soil samples, Bray-P1 solution was prepared by mixing 30 ml of NH_4F solution (37 g of NH_4F dissolved in 1 L distilled water) with 50 ml of HCl and then it was filled to the mark using deionised water in a 1000ml volumetric flask. The weighed soil was then transferred to a 250 ml plastic bottle and then mixed with 50 ml of Bray-P1 solution. The mixture was shaken using a mechanical shaker for 60 seconds after which extracts were filtered through 42 mm

Whatman filter paper. The extraction and analysis of P determination was done in duplicate with the first sample to represent a replication.

3.5.2.1 Preparation of standard solutions, colour development and P determination in extract

Preparation of standard P stock solution

Standard P stock solution was prepared by weighing 0.549 g KH_2PO_4 and dissolving it in 500 ml volumetric flask using distilled water; and filled to the mark. Thereafter, P stock solution was prepared by pipetting varying concentrations (0, 1, 2, 5, 10, 20 & 25 µg P g^{-1}) into 500 ml Erlenmeyer flask then 100 ml Bray-P1 and brought to volume of 500 ml with distilled water.

Preparation of reagents A and B

Reagent A was prepared under a fume cupboard by dissolving 12 g of ammonium molybdate in 250 ml of distilled water in a 250 ml Erlenmeyer flask. Also, 0.291 g of antimony potassium tartrate was weighed and dissolved by 100 ml distilled water. One hundred and forty eight millilitres of H_2SO_4 was poured into 1 L volumetric flask containing 500 ml of distilled water and the mixture was gently swirled so as to obtain a thoroughly mixed solution, which was filled to the mark with distilled water. The prepared 1000 ml dilute H_2SO_4 solution was transferred into 2000 ml volumetric flask, mixed with both ammonium molybdate and antimony potassium tartrate solutions that were previously prepared, and the mixture was properly swirled and then filled to mark with distilled water. The reagent B was prepared by dissolving 1.056 g of ascorbic acid into 200 ml of reagent A inside a 250 ml volumetric flask. This was added to the soil extract and used for colour development. Fresh reagent A was prepared daily for use during P determination.

Colour development and reading of absorbance

After the preparation of reagents A and B, six P standards were prepared using 0, 1, 2, 5, 10, 20 and 25 ml of prepared stock solution. Thereafter, 0 ml standard was prepared by pipetting 5ml of stock solution inside a test tube labelled 0 ml then 3 ml of Bray P-1 solution was added followed by 2 ml of reagent B. The mixture was shaken or swirled for 3 minutes and left for 25 minutes for colour change. Each of the seven standard stock solutions were pipetted in a test tube and same procedure as preparation of 0 ml stock solution was followed. The standards were blue in colour and the colour decreased gradually from 25 ml to 0 ml. Thereafter, 0, 1, 2, 5, 10, 20 and 25 ml standards were poured inside the cuvette for further P-analysis. The P-analysis was done by spectrometer which was used to measure the P-absorbance of the standards. The same procedure which was used for standards preparation was also used for 80 replicated soil samples.

3.5.3 Walkely Black method for organic carbon determination

The organic carbon content was determined following the method described by Walkely and Black (1934). An amount of 49.04 g potassium dichromate was weighed using a digital weighing balanced and it was added into 1 L volumetric flask were it was dissolved with distilled water which was filled to the mark to make 0.167M. Then, 0.5 M ferrous sulphate was prepared (196.1 g of ferrous sulphate and 148 ml of concentrated sulphuric acid) as well as diphenylamine indicator (3.71 g of o-phenanthroline and 1.74 g of $FeSO_4.7H_2O$ was slowly dissolved into 250 ml). Then, 1g of soil was weighed into 500ml Erlenmeyer flask and 10 ml of potassium dichromate was added in the samples and blank flasks. Later, 20 ml of concentrated H_2SO4 was carefully added using measuring cylinder and it was swirled for 10 seconds and allowed to stand for 30 minutes in a fume cupboard. Distilled water of 250 ml was added in the each flask followed by 10 ml concentrated ortho-phosphoric acid. Colour development was achieved by adding 3 drops of diphenylamine indicator then titrated with ferrous sulphate solution. Each sample was duplicated making it to be replicated.

3.5.4 Estimation of percentage soil organic matter (SOM) content

The SOM content was obtained by multiplying the organic carbon value by a correlation factor of 1.72 in order to convert it to percentage of organic carbon as described by Landon (1991).

3.5.5 Mineral nitrogen determination

Mineral N in the sample was determined using Kjeldahl procedure (Anderson and Ingram, 1996) and 0.5 M K_2SO_4 extraction methods (Bremner, 1960). Calorimetric determination of ammonium was done whereby 2 mm sieved soils were weighed to 10 g and put into 250 ml plastic bottle. Prior to weighing the 80 soil samples, 0.5 M K_2SO_4 solutions were prepared. The weighed soil was then transferred in a 250 ml plastic bottle and then mixed with 100 ml of K_2SO_4 solution. The mixture was shaken using a mechanical shaker for 1 hour, after which extracts were filtered through 42 mm Whatman filter paper. The extraction and analysis of NH_4^+ determination was done in duplicate representing replication.

3.5.5.1 Preparation of reagent solutions, colour development and determination of NH_4^+ in extract

Preparation of reagents N1 and N2

Reagent N1 and N2 were prepared 24 hours before use. Reagent N1 was prepared by weighing 34 g of salicylate, 25 g of sodium citrate and 25 g of sodium tartrate respectively and dissolving them together using 750 ml distilled water inside 1000 ml volumetric flask. Then 0.12 g of sodium nitroprusside ($Na_2 [Fe (CN)_5 NO)$ was also added into the solution and it was filled to the mark by distilled water. Reagent N2 was prepared by dissolving 30 g of sodium hydroxide into a 750 ml volumetric flask where the solution was allowed to cool down. Later on 10 ml of hypochlorite was mixed with the solution and it was filled to the mark with distilled water.

Preparation of standard NH_4^+ *stock solution*

Standard NH_4^+ stock solution was prepared by weighing 4.714 g $(NH_4)_2SO_4$ and dissolving it in 1000 ml volumetric flask using distilled water; and filled to the mark. Thereafter, NH_4^+ stock solutions was prepared by pipetting varying concentrations (0, 5, 10, 15, 20 & 25 µg NH_4^+ g^{-1}) into 100 ml volumetric flask then filled to the mark using K_2SO_4.

Colour development and reading of absorbance

Six NH_4^+ standards were prepared using 0, 5, 10, 15, 20 and 25 ml of prepared stock solution. Thereafter, 0 ml standard was prepared by micro-pipetting 0.2 ml of stock solution inside a test tube labelled 0 ml then 5.0 ml of reagent N1 solution was added and it was let-up for 15 minutes followed by addition of 5.0 ml of reagent N2. The mixture was shaken or swirled for 15 seconds and allowed to stand for 60 minutes for colour change. Each of the six standard stock solutions were pipetted in a test tube and same procedure as preparation of 0 ml stock solution was followed. The standards were green in colour and the colour decrease gradually from 25 ml to 0 ml. Thereafter, 0, 5, 10, 15, 20 and 25 ml standards were poured inside the cuvette for further NH_4^+-analysis on a UV spectrophotometer at a wavelength of 655 nm.

3.5.6 Electrical conductivity measurement

Electrical conductivity was measured in water (1: 2.5 soil: water ratio) using a conductivity meter as described by Okalebo et al. (2002). Prior to EC determination of soil samples, the EC meter was calibrated using buffer solution of 12.88 µg ms^{-1}. Distilled water was used during EC determination of 80 sieved soil samples using 10 g of each soil sample. The weighed soil samples were transferred inside 50ml glass beaker then 25ml of distilled water was added in each glass beaker containing soils. The mixture was stirred using a stirring rod for 5 seconds and it was left to be mixed for 50 minutes. After 50 minutes the soil was stirred for few seconds and EC meter was used to read the EC of the soils. Soil treatment were duplicated to make replicates during this determination.

3.6 Data analysis

Growth, phenological and yield as well as root data generated were subjected to analysis of variance (ANOVA) using STATISTIX 9.0 and the difference between treatments mean were tested at $P \leq 0.05$ using Duncan's Multiple Range Test (Gomez and Gomez, 1984). Plant growth and yield responses to the various P and lime rates were modelled using the quadratic polynomial equation ($Y= a+b_1X+b_2X^2$) where, Y represents the yield parameters obtained; 'a' is the intercept; 'b' is the coefficients of the quadratic equation, 'X' is the optimum P or lime rate. The line of best fit for the quadratic model was obtained using Microsoft excel® 2010 while the value of X was optimised at $-b_1/2b_2$.

CHAPTER 4

RESULTS

4.1 Results of pre-planting soil analysis

The results of pre-planting analysis of sample of the soil used for this study are presented in Table 1. The pH of the soil was very strongly acidic while the contents of available P, exchangeable potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn) were low. The observed values of P, Ca and Zn were below the threshold levels of 8-15 mg kg^{-1}, 200 mg kg^{-1} and 2 mg kg^{-1} reported by FSSA (2007) for maize. The soil however, contained moderate content of exchangeable of sodium. The acid saturation of the soil as indicated by the percent aluminium content is very high and beyond the threshold level of 20% reported by Beukus (1995). The textural characteristic of the soil is sandy loam.

Table 1: Selected physico-chemical and physical soil properties of the soil used in the greenhouse study

Soil property	Value	Rating
pH (1:2.5 KCl)	3.82	Very strongly acidic
Bray-P1(mg/kg)	5	Low
Exchangeable cations (mg/kg)		
K	46	Low
Ca	89	Low
Mg	32.5	Low
Na	4	Medium
Al%	47.4	Very high
Zn	0.60	Very low
Particle size (%)		
Sand	80.5	Sandy loam
Clay	16.5	
Silt	3	

4.2 Effect of variable P and lime rates on seedling emergence

The results of duration to seedling emergence for the 2013/14 and 2014/15 are shown in Figure 3. Statistically, the variation in P and lime application rates did not exert significant (p>0.05) effects on the duration to seedling emergence within and across the two planting seasons (Figure 3).

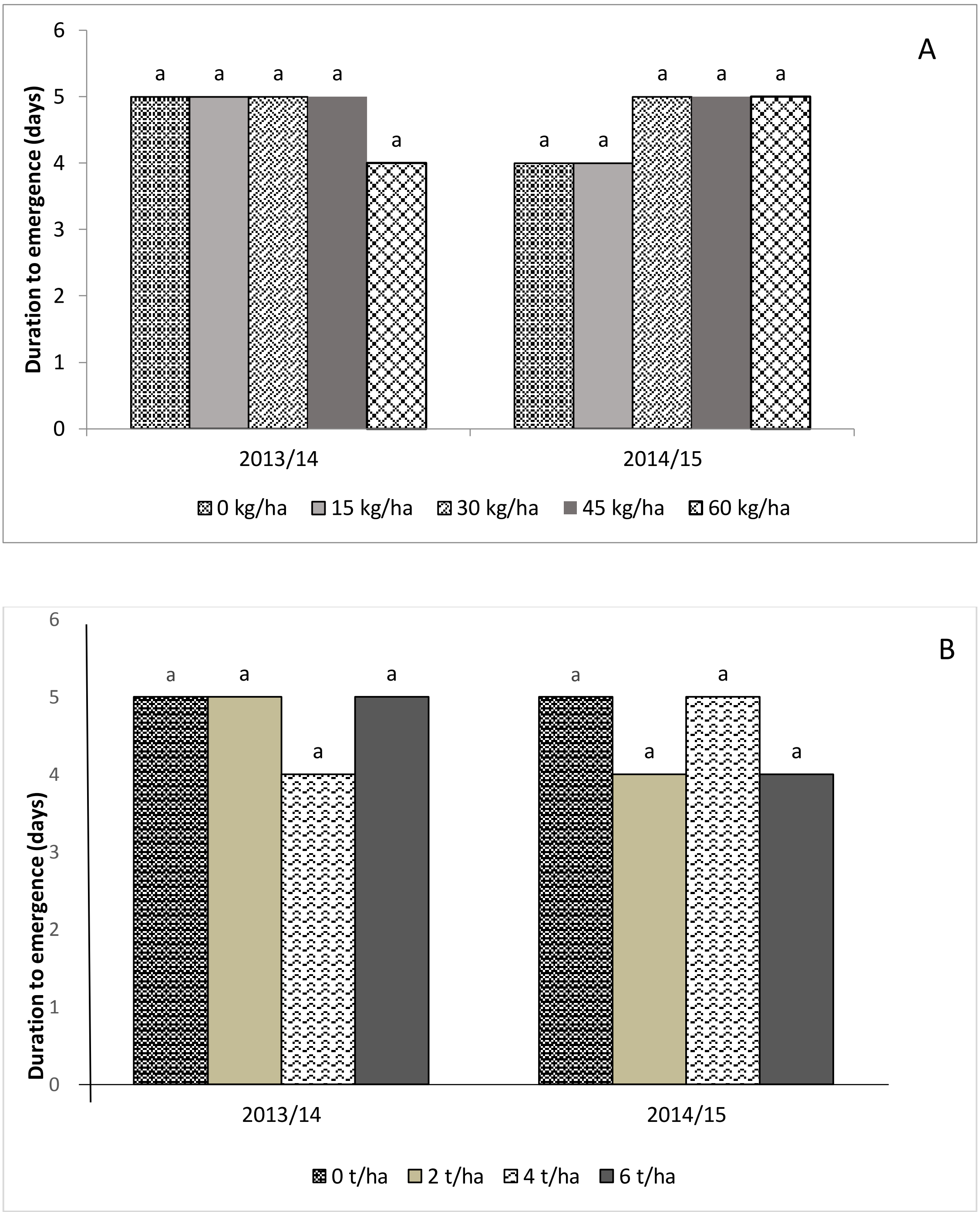


Figure 3: Effect of P (top) and lime rates (bottom) on seedling emergence duration. *Bars followed by the same letter are not significantly different at p≤0.05.*

4.3 Effect of variable P and lime rates on cowpea growth parameters during 2013/14 planting

4.3.1 Plant height

Cowpea plant height measured was significantly ($p \leq 0.01$) affected by P application at 6, 9 and 10 WAE (Figure 4a). Data obtained in 2013/14 revealed that the application 45 kg P ha^{-1} gave the tallest plants at 6, 9 and 10 WAE. Plant height measured from pots with 15, 30 and 60 kg P ha^{-1} application rates at 3, 6 and 9 WAE did not show any significant difference. The various lime rates exerted a significant ($p \leq 0.001$) effect on plant height measured during the four sampling dates (Figure 4b). Cowpea plant height was increased with the application of 2 and 4 t ha^{-1} during the different sampling dates; with statistically comparable values. The highest plant height of 19.41 cm was obtained in pots with no lime application at 6 WAE.

4.3.2 Stem diameter

There was no significant difference in the measured plant stem diameter following variable P rates application (Figure 5a). However, the measured plant stem diameter showed significant response to variable lime application rates (Figures 5b). Application of lime at 6 t ha^{-1} gave the highest diameter of 2.50 mm at 3 WAE but gave the least stem diameter of 2.60 mm at 10 WAE. The measured stem diameter at 6 t ha^{-1} was statistically comparable to the measured value at 2 and 4 t ha^{-1} at 3 WAE while soil without lime application had the least stem diameter of 2.19 mm. Stem diameter for 6 and 9 WAE did not differ significantly with lime application of 0, 2 and 6 ton lime ha^{-1}. Overall, application of lime at 4 t ha^{-1} produced the highest stem diameter throughout the sampling dates.

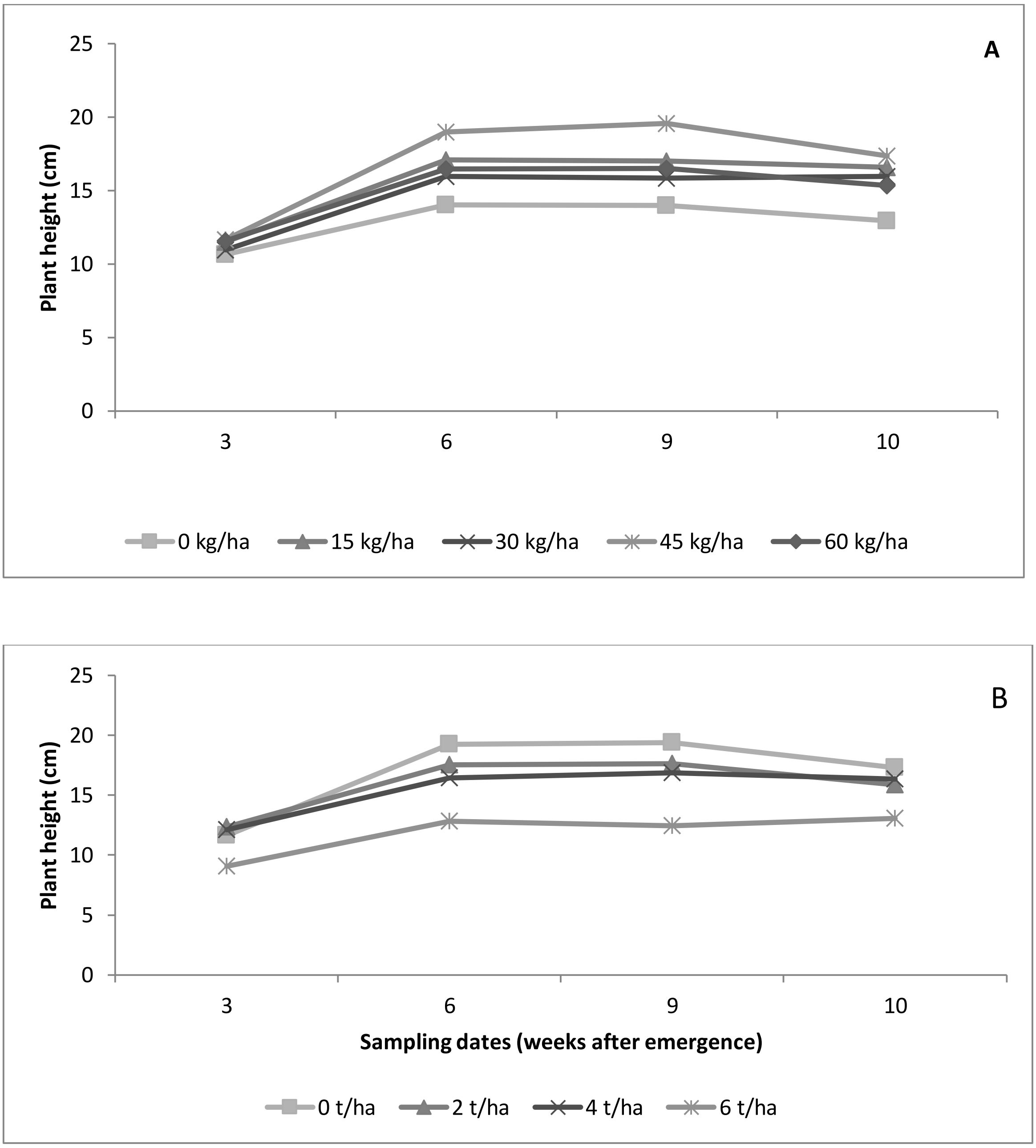
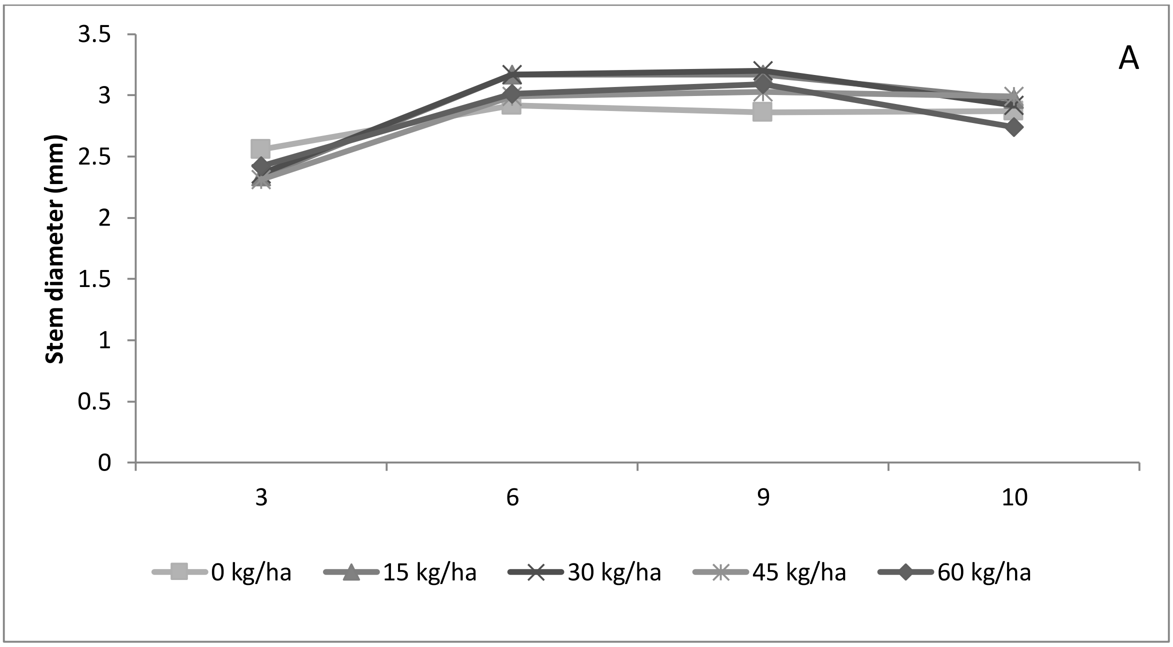


Figure 4: Effect of P rates (top) and lime rates (bottom) on plant height during different sampling dates.



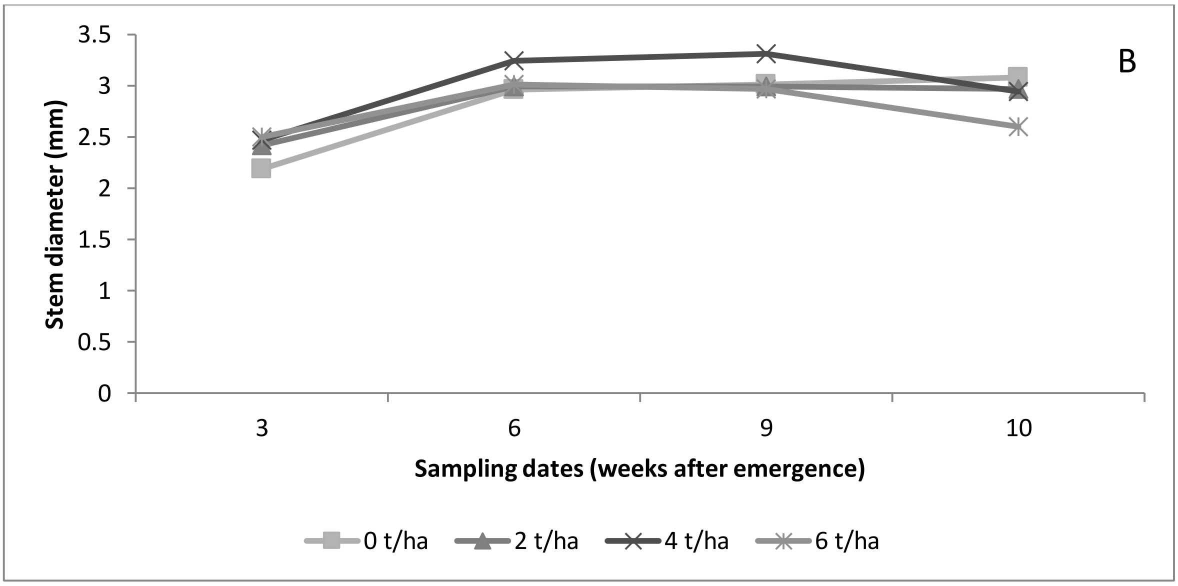


Figure 5: Effect of P rates (top) and lime rates (bottom) on stem diameter during different sampling dates.

4.3.3 Number of trifoliate leaves

Application of different P rates significantly ($p \leq 0.001$) affected the number of trifoliate leaves at 6, 9 and 10 WAE (Figure 6a). Application of 45 kg P ha^{-1} gave the highest number of trifoliate leaves, which was however, statistically comparable to the number of trifoliate leaves at P application of 15, 30 and 60 kg ha^{-1} during 3, 6 and 9 WAE. The lowest number of trifoliate leaves (1.23) recorded was at 3 WAE without P application. Similarly, the number of trifoliate leaves was significantly ($p \leq 0.001$) influenced by lime application (Figure 6b). The 0, 2 and 4 t ha^{-1} lime rates produced statistically comparable number of trifoliate leaves at 3 and 10 WAE while the 4 t ha^{-1} produced highest number of leaves (1.65) at 6 WAE than 2 and 6 t ha^{-1} lime rates.

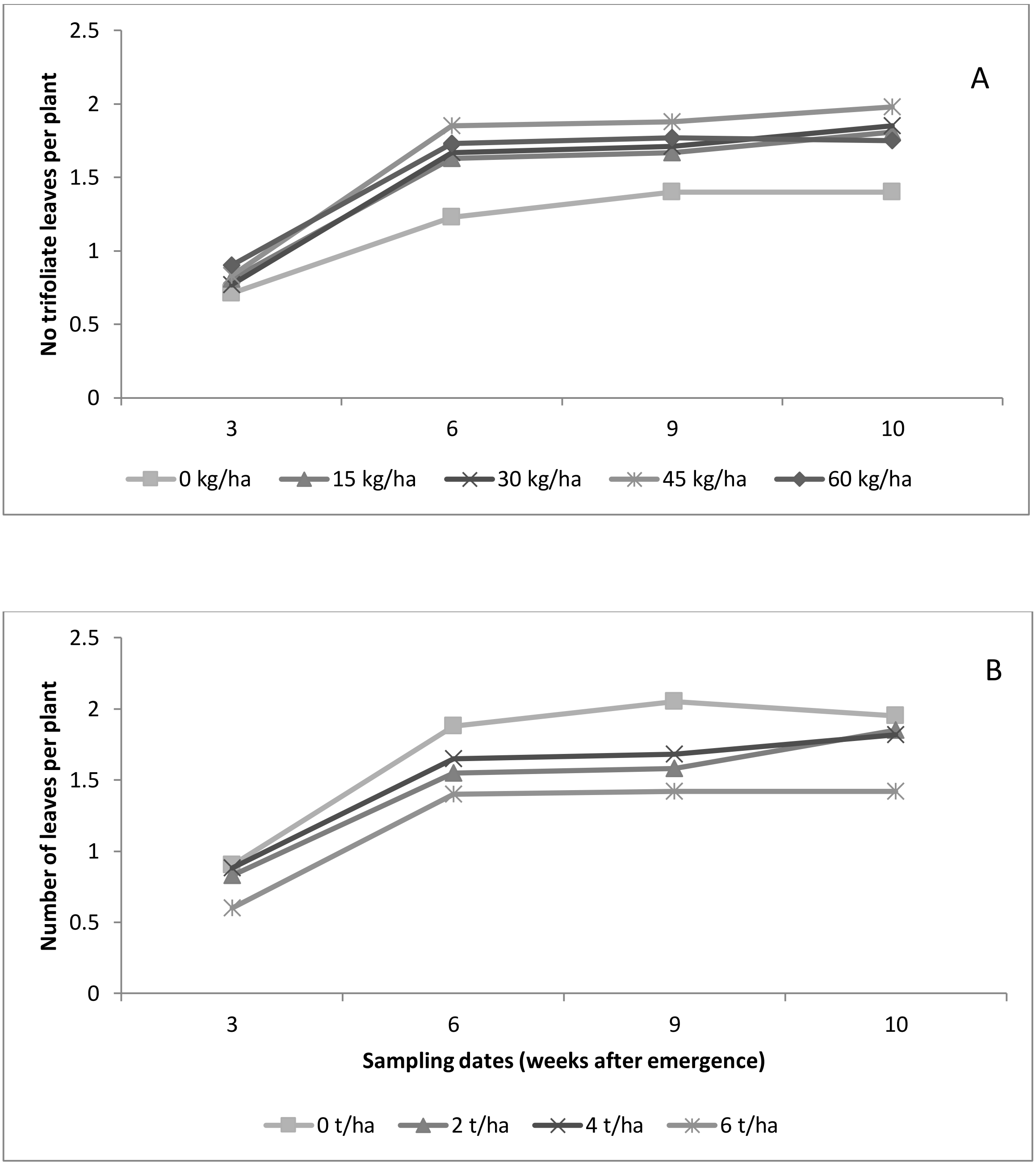


Figure 6: Effect of P rates (top) and lime rates (bottom) on the number of leaves during different sampling dates.

4.3.4 Length of trifoliate leaves

Although the highest value of trifoliate leaf length (6.89 cm) was obtained at 15 kg P ha^{-1} at 10 WAE, values obtained at higher rates of 30, 45 and 60 kg P ha^{-1} did not differ significantly (Figure 7a). The length of trifoliate leaves in unfertilized control pot was shortest throughout the sampling dates. The various lime rates exerted a significant ($p \leq 0.001$) effect on cowpea trifoliate leaf length. However cowpea trifoliate leaf length measured at 3 and 9 WAE at lime application rates of 0, 2, and 4 t ha^{-1} did not differ significantly (Figure 7b). The 4 t ha^{-1} produced the longest length at 6 and 10 WAE.

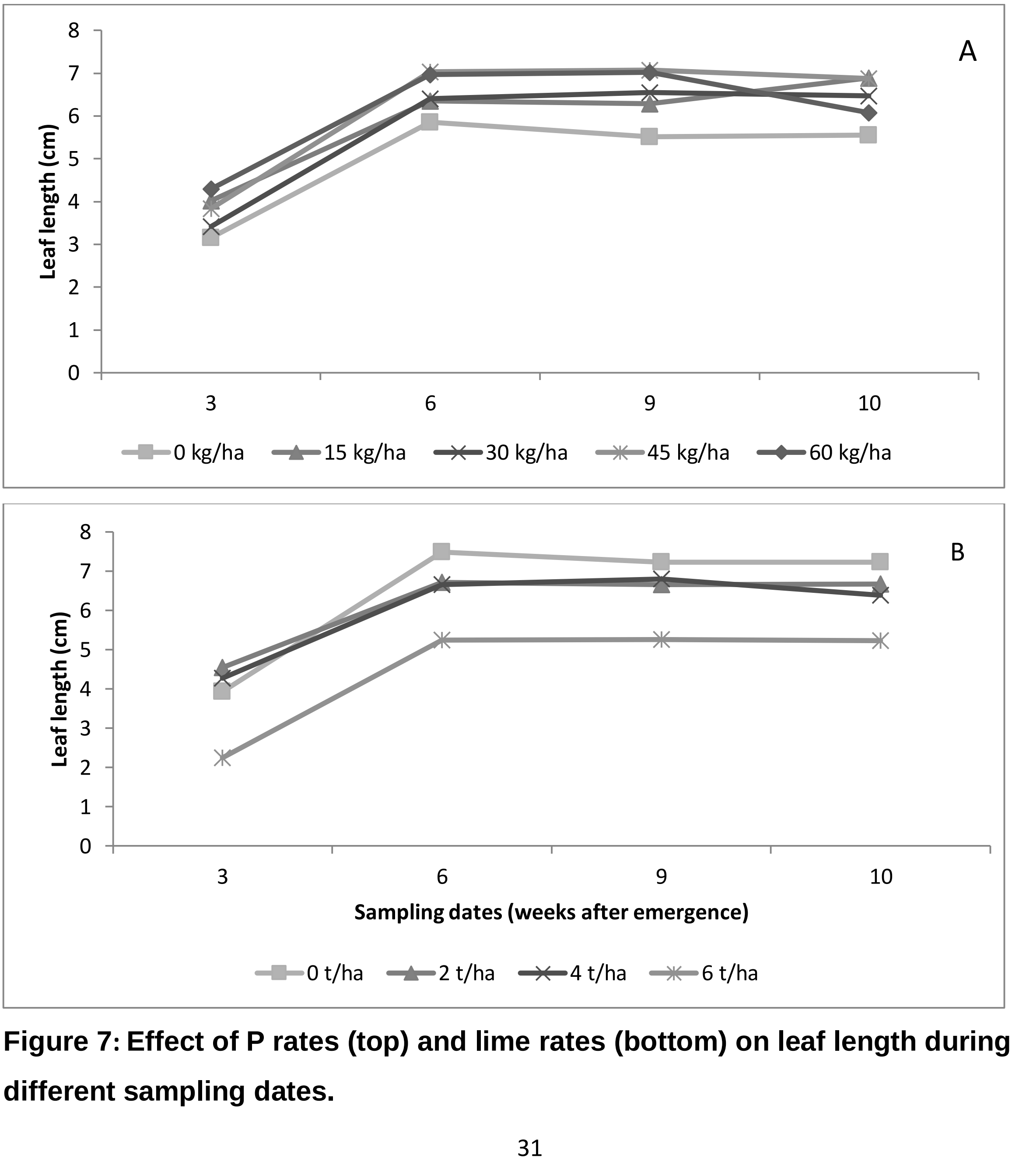


Figure 7: Effect of P rates (top) and lime rates (bottom) on leaf length during different sampling dates.

4.3.5 Width of trifoliate leaves

Statistical analysis indicated that P application significantly ($p \leq 0.01$) affected the width of cowpea trifoliate leaves only at 3 and 10 WAE, with the widest width (2.41 cm) produced at 60 kg P ha^{-1} (Figure 8a). The width of trifoliate leaves measured at 10 WAE was highest at 30 kg P ha^{-1} rate. However, the measured highest width of 3.52 cm was statistically similar to the value obtained at 15 and 45 kg P ha^{-1} rates. Application of variable lime rates significantly ($p \leq 0.001$) affected the width of trifoliate leaves during 3 and 6 WAE with the widest width of 2.51 cm measured at 3 WAE when lime was applied at 2 t ha^{-1} (Figure 8b). The widest width recorded at 2 t ha^{-1} was statistically similar to the 2.28 cm recorded at 4 t ha^{-1} lime rate.

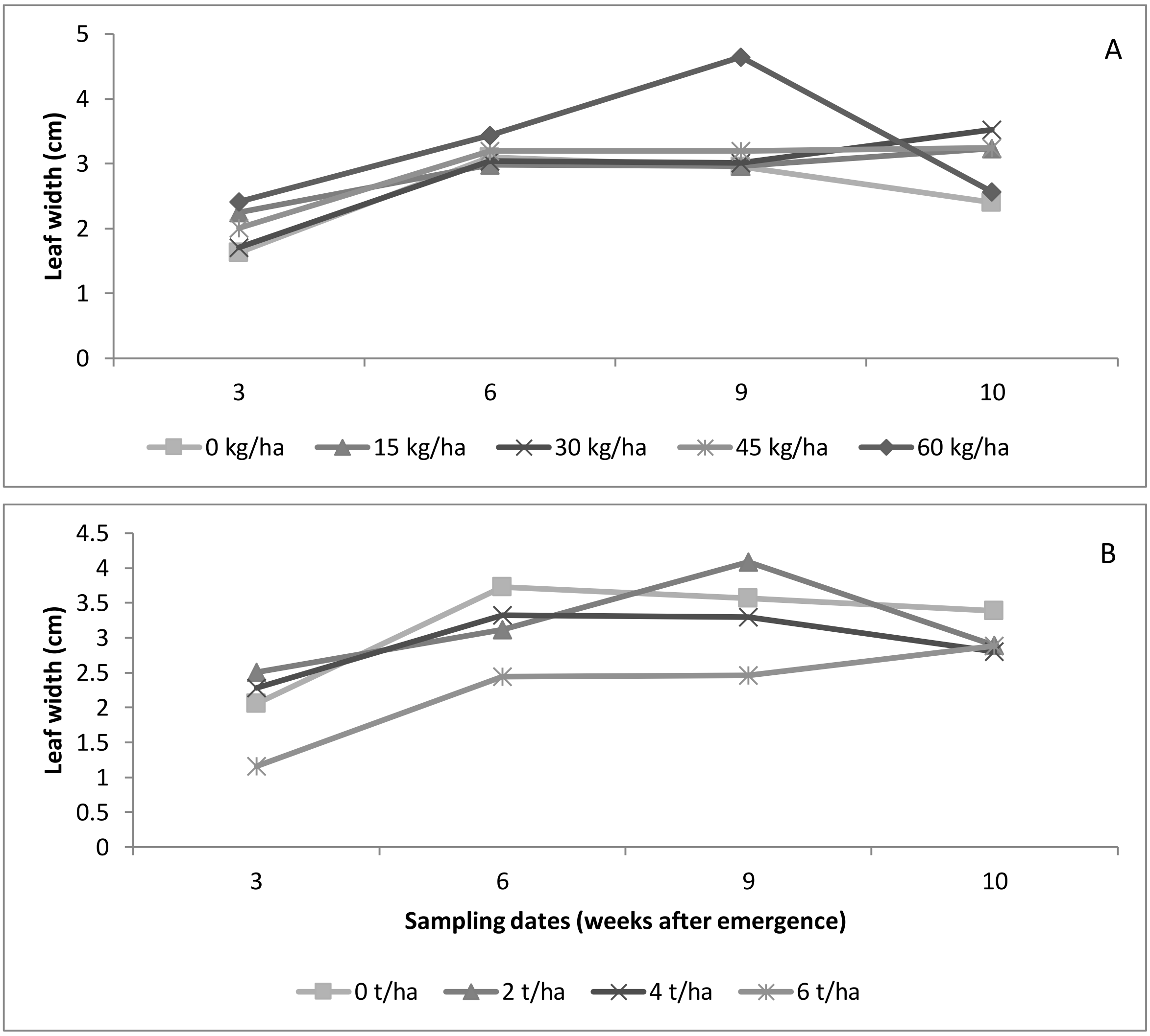


Figure 8: Effect of P rates (top) and lime rates (bottom) on leaf width during different sampling dates.

4.3.6 Area of trifoliate leaves

The area of trifoliate leaves measured at 3, 9 and 10 WAE per pot was significantly influenced by P application (Figure 9a). The 60 kg P ha^{-1} rate gave the highest value of 12.94 cm^{2}, which did not differ significantly from the measured values of 15 and 45 kg P ha $^{-1}$ fertiliser rates. Similarly, the area of trifoliate leaves measured at 9 and 10 WAE under P fertiliser rates of 30 and 45 kg ha^{-1} are statistically similar. Soils with no P application resulted in decreased area of trifoliate leaves across the different sampling dates. The various lime rates showed a significant ($p \leq 0.001$) effect on measured area of trifoliate leaves (Figure 9b). The results revealed that the application of 2 and 4 t ha^{-1} lime rates resulted in increased trifoliate leaf area measured at all sampling dates even though the values were statistically not different from that measured from un-limed pots.

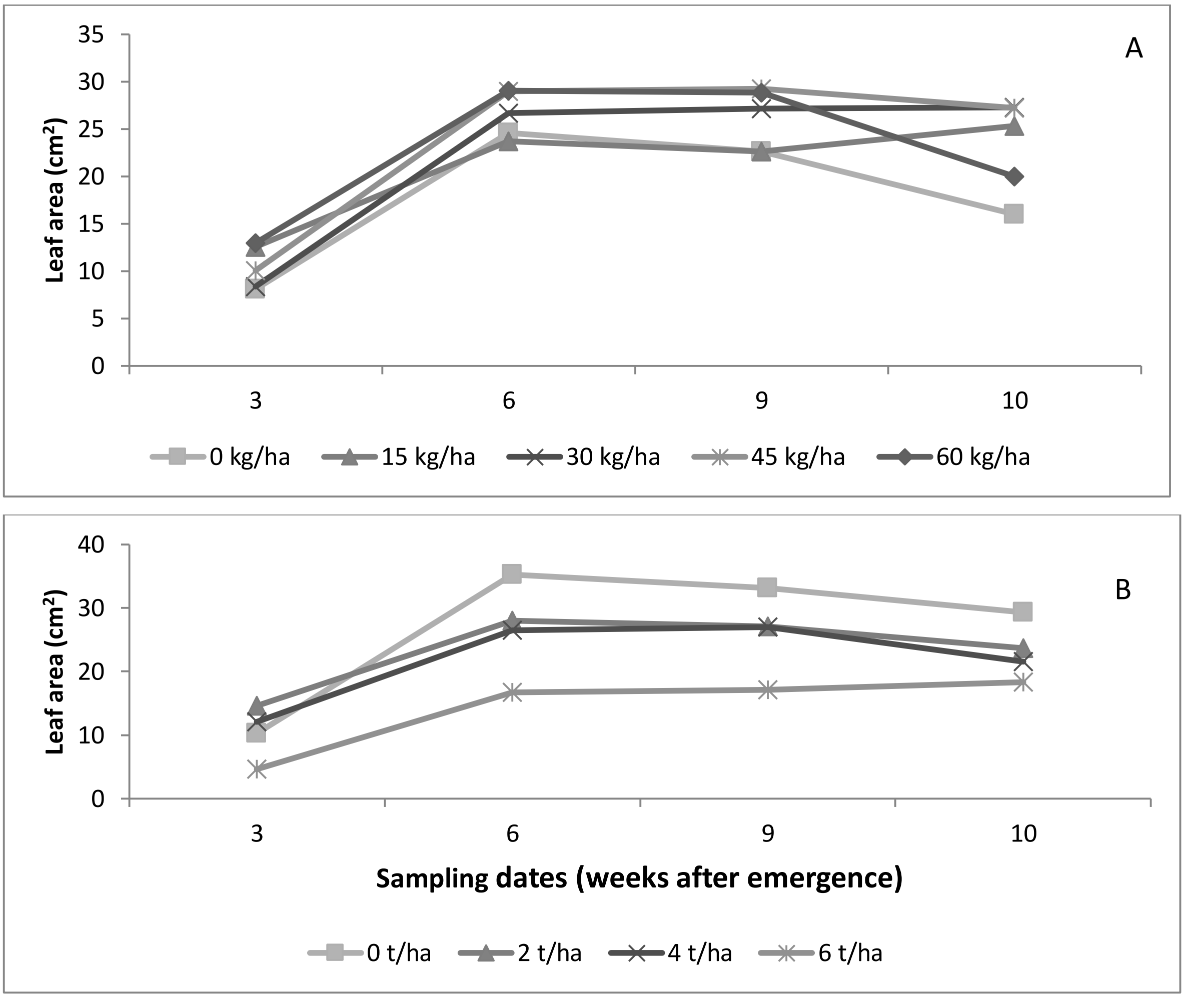


Figure 9: Effect of P rates (top) and lime rates (bottom) on leaf area during different sampling dates.

4.4 Effect of variable P and lime rates on cowpea growth parameters (during 2014/15 planting

4.4.1 Plant height

The results indicated that P application significantly affected the height of the three tagged cowpea plants, PL1, PL2 and PL3. The tallest cowpea plant of 27.72 cm and 38.30 cm for the first and second plant, respectively was obtained from P application rate of 60 kg ha^{-1}, but was statistically comparable to the plant height at 45 kg ha^{-1} (Table 2a). The results shows that the height obtained for the third plant at the application of 45 and 60 kg P ha^{-1} did not differ significantly (Table 2b). Overall, the application of higher rate of 60 kg P ha^{-1} produced taller cowpea plants for all measured three plants. A significant ($p \leq 0.001$) effect of various lime rates was observed on cowpea plant height for PL1, PL2 and PL3. The 6 t ha^{-1} lime rate gave the highest plant height of 26.3 and 36.2 cm, respectively for PL1 and PL2, which did not differ significantly with 4 t ha^{-1} lime rate. Table 2b shows that application of 6 t ha^{-1} lime rate produced plant height of 41.37 cm for PL3, but was statistically similar to plant height at 4 t ha^{-1}.

4.4.2 Stem diameter

There was a significant effect of P application rates on stem diameter for three measured plants (Table 2a-b). Cowpea stem diameter of 3.16 mm for the first tagged plant (SD1) represented the thickest diameter and was observed at 60 kg P ha^{-1} application rate whilst soil pots with no P application (control) produced the least stem diameter of 2.69 mm. However, the measured stem diameter following 15 and 45 kg P ha^{-1} was statistically similar to the value obtained at 30 kg P ha^{-1}. Table 2b shows that 60 kg P ha^{-1} application produced the widest stem diameter (4.95 mm) and was statistically similar to the 4.88 mm stem diameter obtained at 45 kg P ha^{-1} thus suggesting that lime application significantly ($p \leq 0.001$) affected the stem diameter of the cowpea plants.

Application of 6 t ha^{-1} of lime consistently produced cowpea plants with the widest stem diameter whereas the narrowest plant stem diameter was found in soil pots without lime application. The results show that application of lime at 2 and 4 t ha^{-1} produced have similar stem diameter. The lowest stem diameter value of 4.56 mm recorded in soil without lime application did not differ significantly from the value at 2 t ha^{-1}.

4.4.3 Number of trifoliate leaves

The results show that lime application had a significant effect on number of trifoliate leaves (NT) for all three measured cowpea plants (Table 2a-b). The highest number of trifoliate leaves (1.90) obtained for the first tagged plant NT1 was recorded at lime rate of 6 t ha^{-1}; although, the number did not differ significantly to the number of trifoliate leaves at 2 and 4 t ha^{-1}. The number of trifoliate leaves at 2 t ha^{-1} and un-limed lime rates for NT1 did not differ significantly (Table 2a). The highest number of trifoliate leaves of 4.33 was obtained from the second tagged cowpea plant at lime rates of 6 t ha^{-1}, but was not significantly different from that recoded at 4 t ha^{-1}. Table 2b shows that the highest number of trifoliate leaves (6.10) for NT3 was recorded at 6 t ha^{-1} whilst the least value (5.43) was observed under un-limed control. The number of trifoliate leaves for NT3 at 2 and 4 t ha^{-1} lime rates did not differ significantly.

Phosphorus application significantly affected number of trifoliate leaves for NT1 and NT3 with the application of 60 kg P ha^{-1} producing the highest value (2.27), which was statistically similar to the value at 45 kg P ha^{-1}. The number of trifoliate leaves recorded at 15 and 30 kg P ha^{-1} did not differ significantly. The number of trifoliate leaves for NT2 was not significantly influenced ($p \leq 0.05$) by P fertilizer application (Table 2a). Application of 30, 45 and 60 kg P ha^{-1} rates produced statistically same number of trifoliate leaves for NT3. Although, the soil pot without P application produced the least number of trifoliate leaves (5.50), this recorded value did not differ from the value recorded at 15 kg P ha^{-1} rate (Table 2b).

4.4.4 Length of trifoliate leaves

The results from 2014/15 planting shows that soil pots applied with lime at 0, 4 and 6 t ha^{-1} produced comparable length of cowpea trifoliate leaves for LT1. The shortest length of trifoliate leaves (10.40 cm) was recorded at 2 t ha^{-1}. The length of trifoliate leaves for LT2 and LT3 at 2, 4 and 6 t ha^{-1} lime rates did not differ significantly. The observed shortest cowpea trifoliate leaf length was observed in soil pots without lime for both LT2 and LT3 (Table 2b).

Table 2a: Effect of P and lime rates on cowpea growth parameter at different growing stages during 2014/15 planting

Treatments	1st plant						2nd plant				
	Plant height (cm)	Stem diameter (mm)	No. of trifoliate leaves (pot^{-1})	Length of trifoliate leaves (cm)	Width of trifoliate leaves (cm)	Area of trifoliate leaves (cm^2)	Plant height (cm)	Stem diameter (mm)	No. of trifoliate leaves (pot^{-1})	Length of trifoliate leaves (cm)	Width of trifoliate leaves (cm)
Lime rates, L (t/ha)											
0	24.3b	2.94b	0.72b	11.9a	8.75a	107.8a	33.9b	3.74b	4.00b	14.86b	14.0ab
2	24.2b	2.71c	1.80ab	10.4b	8.35a	91.7b	34.0b	3.77b	4.07b	15.4a	13.65b
4	25.7a	2.81bc	1.88a	11.7a	8.78a	108.3a	35.8a	3.81b	4.13ab	15.6a	13.9ab
6	26.3a	3.20a	1.90a	11.7a	8.75a	108.4a	36.2a	4.22a	4.33a	15.7a	14.2a
Phosphorus rates, P (kg/ha)											
0	21.0d	2.69c	1.12c	10.4b	7.48c	80.5c	30.5e	3.60c	4.04a	14.4c	12.9b
15	24.2c	2.89b	1.73b	10.6b	7.31c	78.5c	34.0d	3.91ab	4.04a	15.1b	14.2a
30	25.8b	2.95b	1.88b	12.0a	9.03b	111.0b	35.3c	3.89b	4.21a	15.3b	14.0a
45	26.8ab	2.90b	2.13a	12.1a	9.56ab	120.2ab	36.8b	3.95ab	4.31a	15.6ab	14.0a
60	27.7a	3.16a	2.27a	12.4a	9.90a	130.2a	38.3a	4.09a	4.06a	16.3a	14.5a
Significance (p≤0.05)											
Phosphorus	***	**	***	***	***	***	***	***	ns	***	**
Lime rate	***	***	*	**	ns	ns	***	***	*	*	ns
P x L interaction	*	*	ns	ns	ns	ns	ns	ns	ns	**	ns

*Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05). Measurements taken on tagged plants 1 and 2*

Table 2b: Effect of P and lime rates on cowpea growth parameters at different growing stages during 2014/15 planting

Treatments	2nd plant cont.…	3rd plant					
	Area trifoliate leaves (cm^2)	Plant height (cm)	Stem diameter (mm)	No. of trifoliate leaves (pot^{-1})	Length of trifoliate leaves (cm)	Width of trifoliate leaves (cm)	Area of trifoliate leaves (cm^2)
Lime, L (t/ha)							
0	209.88ab	39.07c	4.56c	5.43c	16.94b	16.04a	274.92a
2	196.39b	40.39b	4.68bc	5.78b	17.55a	15.66a	276.35a
4	218.09a	40.73ab	4.77b	5.82b	17.68a	15.90a	283.07a
6	223.92a	41.37a	4.99a	6.10a	17.74a	16.24a	289.2a
Phosphorus, P (kg/ha)							
0	182.55c	37.18d	4.47c	5.50c	16.64c	14.97b	251.15c
15	204.46b	39.43c	4.73c	5.67bc	17.26bc	16.21a	281.11b
30	214.11b	40.46b	4.73c	5.79ab	17.36b	15.98a	278.38b
45	221.51ab	42.01a	4.88ab	6.04a	17.83ab	16.16a	289.07ab
60	237.73a	42.87a	4.95a	5.90ab	18.32a	16.53a	304.73a
Significance ($p \leq 0.05$)							
Phosphorus	***	***	***	**	***	***	***
Lime rate	*	***	***	***	*	ns	ns
P x L interaction	ns	**	ns	ns	**	ns	ns

*Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$).*

The results show that there was significant influence of P application rates on length of trifoliate leaves for all measured cowpea plants. However, the length of trifoliate leaves at 30, 45 and 60 kg P ha^{-1} rates did not differ significantly ($p \leq 0.05$). The length of trifoliate leaves measured from the second and third plants was increased at 60 kg P ha^{-1}, but did not differ significantly to the length measured at 45 kg P ha^{-1}. Moreover, the value recorded at 45 kg ha^{-1} was statistically comparable to the length recorded at 15 and 30 kg P ha^{-1} rates (Table 2a). Un-amended P control pots produced the shortest length of trifoliate leaves of 14.41 cm for second and third (16.64 cm) tagged plants. Table 2b reveals that the various lime rates exerted significant effect on length of trifoliate leaves for the three tagged plants.

4.4.5 Width of trifoliate leaves

Statistical analysis on data generated during 2014/15 planting indicated that there was no significant ($p \leq 0.05$) effect of various lime rates on width of trifoliate leaves for WT1, WT2 and WT3. The results however revealed significant effect of P fertiliser application on width of trifoliate leaves measured on all three cowpea plants (Table 2a-b). Application of 60 kg ha^{-1} produced the widest trifoliate leaves (9.90 cm) for WT1, which was however, statistically similar to the width measured at 45 kg P ha^{-1}. Similarly, the recorded value at 45 kg ha^{-1} was also comparable to the 9.03 cm width at 30 kg P ha^{-1} rate. The narrowest leaf width for WT1 was found in soils with P application of 15 kg ha^{-1} and less. Application of 15, 30, 45 and 60 kg P ha^{-1} produced statistically comparable trifoliate leaf width for WT2 and WT3 while the narrowest leaf width was recorded in un-amended P control pots (Table 2a-b).

4.4.6 Area of trifoliate leaves

During 2014/15 planting, lime application did not have a significant ($p \leq 0.05$) effect on the trifoliate leaf area for the first and third tagged cowpea plants. However, lime application only had a significant ($p \leq 0.05$) effect on the leaf area for AT2 with the 6 t ha^{-1} lime rate producing the highest leaf area of 223.92 cm^2, which did not differ significantly from the leaf area obtained at 4 t ha^{-1} lime rate and un-amended control. Application of variable P rates significantly ($p \leq 0.001$) affected trifoliate leaf area for the three tagged cowpea plants in 2014/15. Table 2a indicates that application of 60 kg P ha^{-1} produced the highest leaf area (130.17 cm^2) for AT1. Nonetheless, this value did not differ significantly from the leaf area measured at 45 kg P ha^{-1}. The trifoliate leaf area for AT1 (78.5 cm^2) at 15 kg ha^{-1} was significantly comparable to the area produced in soil without P fertilization. Table 2b shows that the leaf area for both AT2 and AT3 was highest at P application of 60 kg ha^{-1}, with respective values of 237.73 and 304.73 cm^2. However, the measured areas for AT2 and AT3 at 60 kg ha^{-1} were significantly similar to the measured areas of trifoliate leaves at 45 kg ha^{-1}, respectively. The leaf area for both AT2 and AT3 did not differ significantly at 15, 30 and 45 kg P ha^{-1} rates (Table 2b). Soil with no P application produced the least leaf area for AT2 (182.55 cm^2) and AT3 (251.15 cm^2).

4.5 Treatment effects on cowpea leaf chlorophyll content

The various P rates applied did not exert any significant effect on the chlorophyll content of cowpea during flowering and pod formation but was significantly ($p \leq 0.001$) affected by the different lime rates (Table 3). The results show that the high leaf chlorophyll content during flowering (81.62 CCI) and pod formation (69.32 CCI) was found in pots with 6 t ha^{-1} lime application rate. The chlorophyll content of cowpea leave measured was lowest in soil with no lime application during both flowering (63.54 CCI) and pod formation (51.54 CCI). However, the leaf chlorophyll content measured in cowpea plants in pots without lime application did not differ significantly with the chlorophyll content recorded at 2 t ha^{-1} for both flowering and pod formation, respectively. However, the measured chlorophyll content in cowpea leaves was generally higher at flowering than at pod formation.

Table 3: Effect of P and lime rates on chlorophyll content (CCI) of cowpea during flowering and pod formation during 2014/15 planting

Treatments	Flowering	Pod formation
Lime, L (t/ha)		
0	63.54c	51.54c
2	66.27c	53.97c
4	72.65b	60.35b
6	81.62a	69.32a
Phosphorus, P (kg/ha)		
0	68.53a	56.23a
15	69.85a	57.55a
30	71.36a	59.19a
45	69.87a	57.83a
60	75.48a	63.18a
Significance(p≤0.05)		
P rate	ns	ns
L rate	***	***
P x L interaction	***	***

*N: B. Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05).*

4.6 Effect of variable P and lime rates on phenological parameters

4.6.1 Duration to 50 and 100% flowering

Cowpea duration to 50% and 100% flowering significantly ($p \leq 0.001$) responded to variable rates of P and lime application (Table 4). Application at 60 kg P ha^{-1} resulted in reduced duration to 50% (60 days) and 100% (66 days) flowering. The duration to flowering in cowpea plants (50 and 100%) at 30 and 45 kg P ha^{-1} rates differed significantly while the 15 kg ha^{-1} and unfertilized P control also produced statistically comparable duration to attainment of 100% flowering. A much earlier duration to 50% flowering (60 days) was observed at 2 t ha^{-1} lime application rate than the 69 days in cowpea plants in pots without lime application. Similarly, the duration to 100% flowering (66 days) was reduced with 2 t ha^{-1} lime application compared to 74 days for cowpea plants in pots without lime application while 6 t ha^{-1} lime rate further hastened the duration to 100% flowering to 70 days.

4.6.2 Duration to 50 and 100% pods formation

Analysis of variance showed a significant ($p \leq 0.001$) effect of increasing P and lime application rates on the duration to 50 and 100% pod initiation (Table 5). Application of 60 kg P ha^{-1} produced cowpea plants that reached 50% (63 days) and 100% (71 days) pod initiation much earlier than soil without P application. Soils with 30 and 45 kg P ha^{-1} produced cowpea plants with statistically similar duration to 50 and 100% pod initiation. On the other hand, the duration to 50 and 100% pod initiation was significantly reduced with 2 t ha^{-1} lime application to 62 and 70 days, respectively as opposed to 72 and 78 days, respectively with no lime application. The duration to 100% pod initiation at 2 and 4 t ha^{-1} lime rates did not differ significantly.

Table 4: Effect of P and lime application rates on chlorophyll content at different growing stages during 2014/15 planting

Treatments	Duration to 50% flowering (days)	Duration to 100% flowering (days)
Lime, L (t/ha)		
0	69.0a	74.0a
2	60.0d	66.0c
4	62.0c	67.0c
6	66.0b	70.0b
Phosphorus, P (kg/ha)		
0	67.0a	72.0a
15	67.0a	71.0a
30	64.0b	69.0b
45	64.0b	69.0b
60	60.0c	66.0c
Significance($p \leq 0.05$)		
P rate	***	***
L rate	***	***
P x L interaction	***	***

N: B. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *** = $p \leq 0.001$

Table 5: Cowpea phenological parameters at different growing stages during trial planting in 2014/15 planting

Treatments	Duration to 50% pod formation (days)	Duration to 100% pod formation (days)
Lime, rates, L (t/ha)		
0	72.0a	78.0a
2	62.0d	70.0c
4	65.0c	71.0c
6	69.0b	74.0b
Phosphorus rates, P (kg/ha)		
0	69.0a	75.0a
15	69.0a	75.0a
30	66.0b	73.0b
45	67.0b	73.0b
60	63.0c	71.0c
Significance(p≤0.05)		
P rate	***	***
L rate	***	***
P x L interaction	***	***

*N: B. Means followed by the same letter in a column are not significantly different at p≤0.05, *** = p≤ 0.001*

4.7 Effect of variable P and lime rates on cowpea yield attributes

4.7.1 Fresh and oven-dried plant biomass

The results of biomass data collected during 2013/14 showed significant ($p \leq 0.05$) differences in oven-dried and fresh biomass following incremental P application (Figure 10). The highest fresh (2.18 g pot^{-1}) and dried (0.43 g pot^{-1}) biomass yield was obtained at 45 kg P ha^{-1} rate while soil without P application gave least the fresh (0.94 g pot^{-1}) and dry (0.23 g pot^{-1}) biomass yield. Figure 10 shows that both fresh and oven-dried plant biomass weight increased in soil-filled pots without lime application and decreased with incremental lime rates.

Table 6 indicates that lime application rate of 4 t ha^{-1} produced the highest plant biomass values of 12.43 g and 4.32 g, respectively for fresh and oven-dried biomass.

These biomass yields did not differ significantly to fresh and dry plant biomass produced when lime was applied at 6 t ha^{-1} rate.

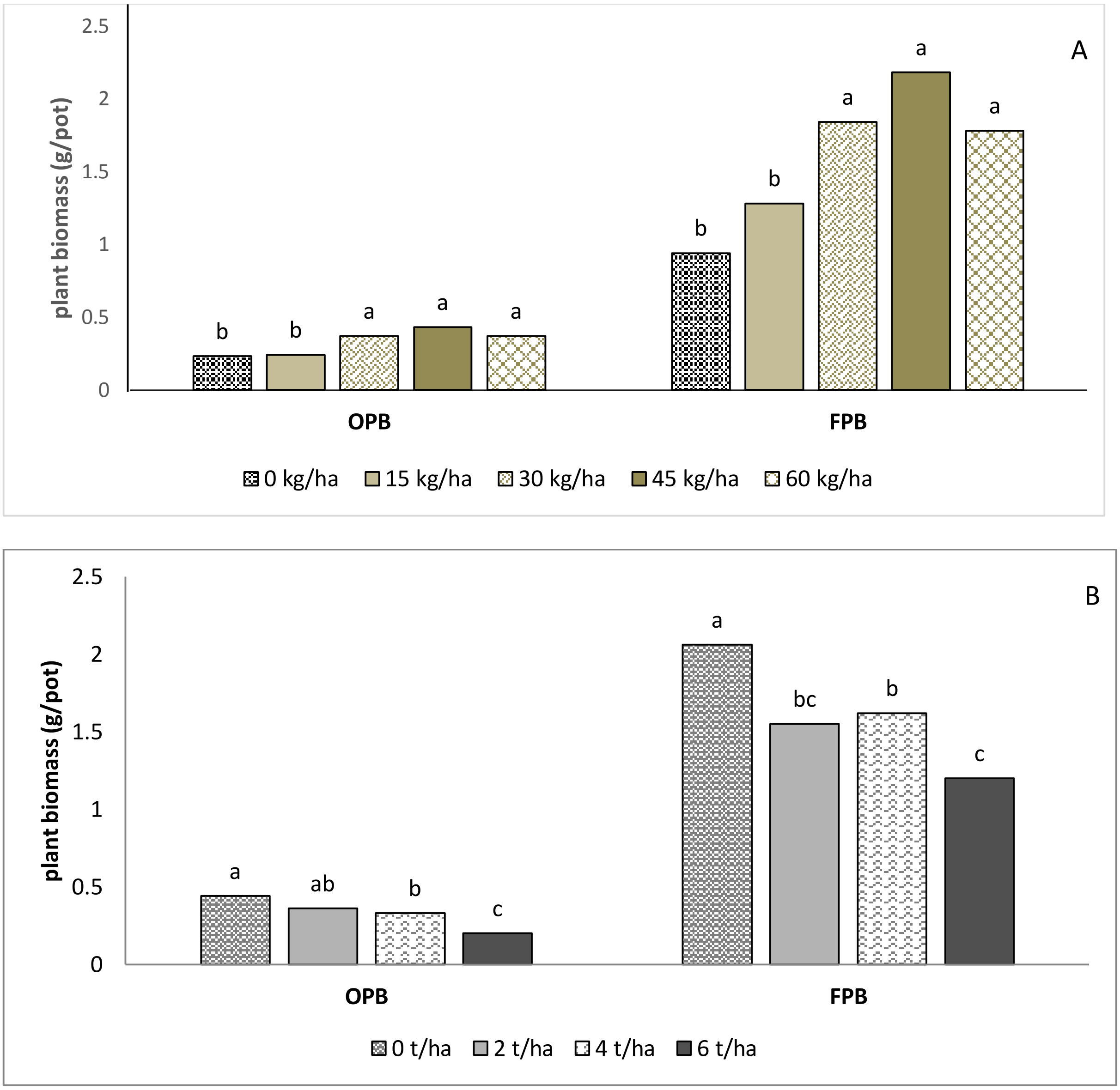


Figure 10: Effect of P rates (top) and lime rates (bottom) on plant biomass during 2013/14. *(OPB and FBP connote oven-dried and fresh plant biomass, respectively). Bars followed by the same letter are not significantly different at p≤0.05*

Table 6: Effect of variable P and lime rates on yield components of cowpea during 2014/15 planting

Treatments	Fresh plant biomass (g pot^{-1})	Oven-dried plant biomass (g pot^{-1})	Fresh root biomass (g pot^{-1})	Oven-dried root biomass (g pot^{-1})	Number of pods per plant (no pot^{-1})	Pods weight per plant (g pot^{-1})	Number of seeds per plant (no pot^{-1})	Seed weight (g pot^{-1})
Lime rates , L(t/ha)								
0	11.33b	3.08b	1.81b	0.11c	2.03b	1.20a	9.83b	2.47a
2	10.41c	2.62c	1.63c	0.10c	2.25ab	1.19a	11.28b	0.93a
4	12.43a	4.32a	2.08ab	0.20a	2.30ab	1.35a	11.13b	0.97a
6	12.09ab	3.98a	2.27a	0.17b	2.50a	1.30a	12.85a	1.19a
Phosphorus rates, P (kg/ha)								
0	9.90b	2.62b	1.56b	0.10c	1.56b	1.17b	8.37d	1.15a
15	9.31b	2.48b	1.92a	0.15b	2.25a	1.26ab	10.29c	2.86a
30	12.48a	4.01a	1.96a	0.13b	2.54a	1.18b	11.25b	0.94a
45	12.96a	4.07a	2.20a	0.15b	2.54a	1.37a	13.71a	0.95a
60	13.17a	4.32a	2.09a	0.20a	2.44a	1.32ab	12.75ab	1.05a
Significance ($p \leq 0.05$)								
P rates	***	***	***	***	***	*	***	ns
L rates	***	***	***	***	***	ns	***	ns
P x L interaction	**	***	**	***	ns	ns	ns	ns

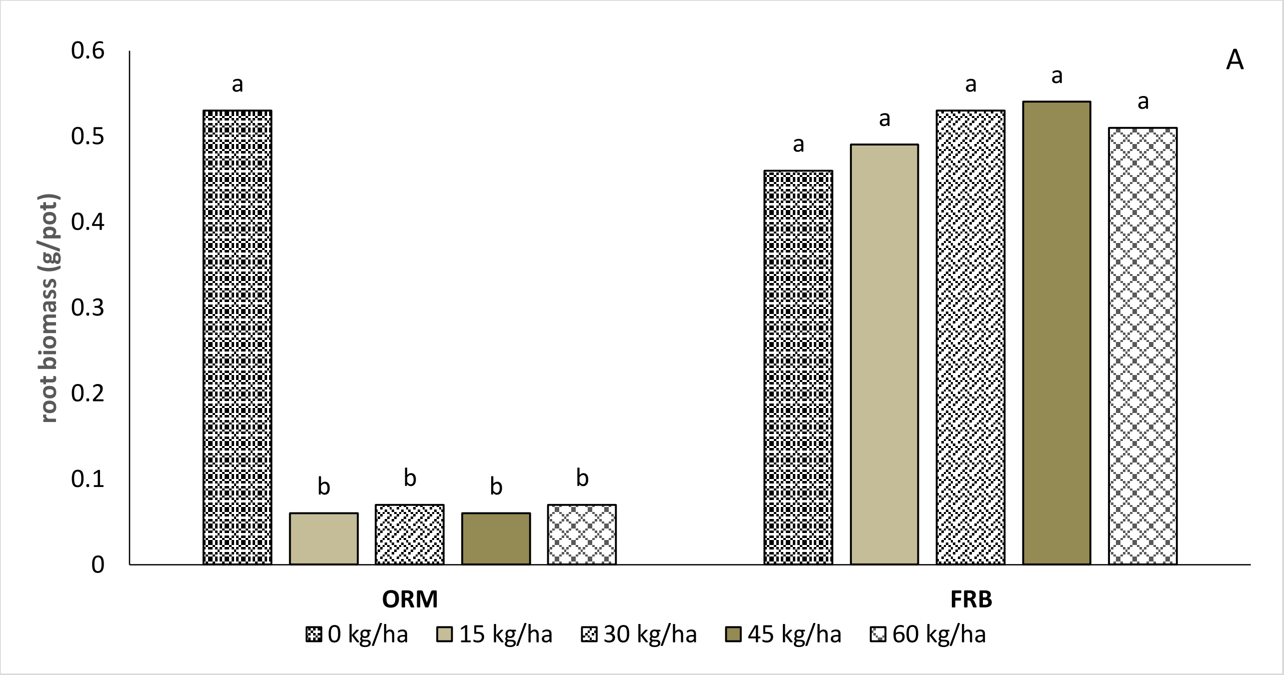
*N: B. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$).*

4.7.2 Fresh and oven-dried roots biomass

During 2013/14 planting, the fresh root biomass was not significantly ($p \leq 0.05$) affected by incremental P fertiliser and lime rates while oven-dried root biomass was significantly ($p \leq 0.05$) affected by P fertiliser rates (Figure 11). Increase in the rates of lime application significantly ($p \leq 0.05$) affected the oven-dried root biomass with the highest (0.45 g pot^{-1}) dried biomass obtained at 2 t ha^{-1} lime rate. However, the oven-dried root biomass at 0, 4 and 6 t ha^{-1} rates of lime application did not differ significantly. However, statistical analysis of 2014/15 data similarly revealed a significant ($p \leq 0.001$) effect of incremental P and lime application rates on both fresh and oven-dried plant biomass. The highest fresh biomass yield of 13.17 g pot^{-1}and oven-dried biomass yield of 4.32 g pot^{-1}were obtained at 60 kg P ha^{-1} rate. These yields were however, statistically similar to yields produced at 30 and 45 kg P ha^{-1} rates (Table 6). Furthermore, it was observed that fresh root biomass yielded the highest biomass at lime application of 6 t ha^{-1} with the mean value of 2.27 g while the lowest fresh biomass was observed with lime application rate of 2 t ha^{-1} having mean value of 1.63 g. Similarly, oven-dried root biomass significantly increased when lime was applied at 4 t ha^{-1} with a mean value 0.20 g. The lowest mean value of 0.10 g for oven-dried root biomass was observed with lime at 2 t ha^{-1}, which was however statistically similar to 0.11 g achieved in soil pots without lime application.

4.7.3 Number of pods per plant

There was significant ($p \leq 0.001$) effect of P fertilization on number of pods per plant. Application of P at 15, 30, 45 and 60 kg ha^{-1} produced statistically comparable values for number of pods per plant. The least number of pods per plant was recorded at 1.85 without P application ^{1} (Table 6). The results show that the variable lime rates applied had a significant ($p \leq 0.001$) effect on number of pods per plant with the highest mean (2.50) obtained when 6 t ha^{-1} lime was applied, which did not differ significantly from the values recorded at 2 and 4 t ha^{-1} lime application rates. The lowest mean number of pods per plant (2.03) recorded in soil pots without lime application was statistically comparable to the number recorded at 2 and 4 t ha^{-1} lime rates.



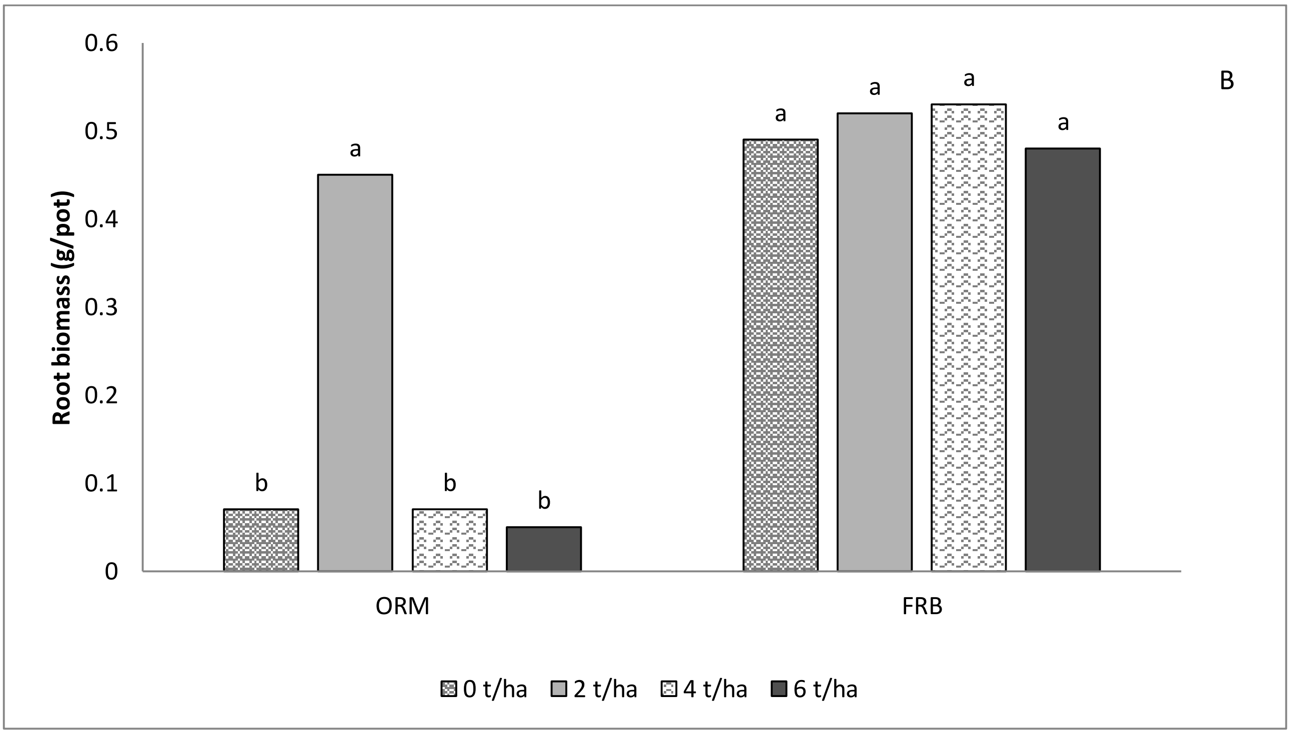


Figure 11: Effect of P rates (top) and lime rates (bottom) on root biomass during 2013/14. *(ORB and FRP connote oven-dried and fresh root biomass, respectively). N: B Bars followed by the same letter are not significantly different at p≤0.05.*

4.7.4 Pod weight per plant

Pod weight per plant was significantly ($p \leq 0.05$) influenced by P application. Cowpea plants that received 45 kg P ha^{-1} resulted in the highest pod weight per plant (1.37 g pot^{-1}), which was statistically comparable to the pods weight at 15 and 60 kg P ha^{-1} (Table 6). The unfertilized P soil-filled pot showed the least pod weight per plant. The variable lime rates did not have a significant effect on cowpea pods weight per plant (Table 6).

4.7.5 Number of seed per plant

The number of seeds per cowpea plant was significantly affected ($p \leq 0.001$) by the variable P and lime application rates. The highest mean number of seeds per plant (13.71) was achieved at 45 kg P ha^{-1} application rate, which was statistically similar to the mean number (12.75) recorded at 60 kg P ha^{-1}. The mean number of seeds produced per cowpea plant at 15 and 30 kg P ha^{-1} rates were 10.29 and 11.25, respectively (Table 6). The least mean number of seeds per plant (8.37) was recorded in soil pots without P fertilization. Increased number of seeds per cowpea plant (12.85) was recorded at 6 t ha^{-1} lime rate whilst ~~to~~ the least number of seeds per plant (9.45) was obtained in soil pots without lime application. The mean number of seeds recorded at 2 and 4 t ha^{-1} lime application rates was statistically comparable.

4.7.6 Seed weight per pot

There was no significant effect of incremental P fertilizer application and lime application rates on cowpea seed weight per pot (Table 6).

4.8 Effect of variable P and lime rates cowpea root attributes

4.8.1 The 3rd root branching density

Statistical analysis showed that P application had no significant ($p \leq 0.05$) effect on third root branching density in 2013/14. However, lime application rates significantly ($p \leq 0.001$) affected the third root branching density at 20 cm. The results revealed that application of lime at 6 t ha^{-1} resulted in reduced third branching density of cowpea at 20 cm. However, the third branching density at 20 cm was better increased by lime application at 2 and 4 t ha^{-1} with respective mean values of 2.15 and 1.48 mm (Table 7).

Table 7: Effect of variable P and lime application rates on root characteristics of cowpea during 2013/14 planting

Treatments	3rd BD (cm)	AAD (°)	ABR (°)	NOBR (no pot^{-1})	SD(cm)	TRD(mm) 5cm	TRD(mm) 10cm	1.5 mm BD5 (cm)	1.5 mm BD 10 (cm)	SS	DS	NOND (no pot^{-1})	TRD (mm)15 cm	TRD (mm) 20 cm
Lime rates, L (t/ha)														
0	2.78a	5.22a	23.29a	4.77a	2.65a	0.83a	0.19ab	6.77a	4.95a	1.04a	1.45a	0.32a	0.04a	__
2	2.15ab	3.33a	23.50a	4.60a	2.59a	0.75a	0.16b	6.02ab	3.17b	0.97a	0.93b	0.53a	0.02a	__
4	1.48b	2.33a	22.67a	4.40a	2.57a	0.68a	0.16b	5.67ab	3.30b	0.83ab	1.58a	0.10b	0.02a	__
6	0.73c	4.83a	16.92b	3.59b	2.19b	0.68a	0.52a	5.17b	1.60c	0.65b	0.83b	0.09b	0.02a	__
Phosphorus rates, P (kg/ha)														
0	1.46a	1.46b	23.33a	4.69a	2.43a	0.77a	0.12b	5.85a	3.15b	1.08a	1.04b	0.17bc	0.02a	__
15	2.06a	1.82b	23.10a	4.59a	2.64a	0.74a	0.14b	6.41a	2.98b	0.79a	1.14b	0.37ab	0.04a	__
30	1.84a	7.41a	50.52a	4.29a	2.48a	0.80a	0.14b	6.11a	3.01b	0.91a	1.12b	0.22abc	0.02a	__
45	2.17a	6.35a	20.52a	4.27a	2.50a	0.64a	0.78a	6.06a	4.83a	0.81a	1.65a	0.46a	0.05a	__
60	1.42a	2.60b	20.44a	3.85a	2.46a	0.74a	0.10b	5.08a	2.31b	0.77a	1.04b	0.08c	0.01a	__
Significant ($p \leq 0.05$)														
P rates	ns	**	ns	ns	ns	ns	**	ns	*	ns	*	*	ns	ns
Lime rates	***	ns	**	**	**	ns	ns	*	***	*	***	**	ns	ns
P x L interaction	**	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	*	**	ns

N: B. Means followed by the same letter in a column are not significantly different at *p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05)*. AAD= angle of adventitious roots; ABR= angle of basal roots; NOBR= number of basal roots; SD=stem diameter; TRD5= taproot diameter at 5 cm; TRD10= taproot diameter at 10 cm; TRD15= taproot diameter at 15 cm; TRD20= taproot diameter at 20cm; 1.5mm BD5=1.5mm branching roots at 5cm; 1.5mm BD10=1.5mm branching roots at 10cm; 3rd BD= *3rd branching roots density at 20 cm*, SS= shallow score; DS= deep score and NOND= number of nodules

Table 8 shows that there was significant ($p \leq 0.001$) effect of P fertilization on the 3rd root branching roots density of cowpea during 2014/15 planting. Application of 30 kg P ha^{-1} produced the highest branching density (3.65 mm), but did not differ significantly to the density at 15 and 60 kg P ha^{-1}. The 3rd branching roots density was reduced the lowest at 2.38 mm in soil pots without P application. Lime application significantly ($p \leq 0.01$) influenced the 3rd branching roots density of cowpea. It was observed that the 3rd branching roots density at 20 cm did not differ significantly when lime is applied at 2, 4 and 6 t ha^{-1} (Table 8). However, the third root density of cowpea at 20 cm was significantly reduced (2.13 mm) in soil pots without lime application.

4.8.2 Angle of adventitious roots

The results from 2013/14 planting indicated that P application significantly ($p \leq 0.01$) affected the angle of adventitious root. It was observed that the angle of adventitious roots was highly increased with P application of 30 kg ha^{-1} with the recorded mean value of 7.41°. However, the above recorded angle was statistically comparable to the angle of adventitious roots at P application of 45 kg ha^{-1}. Unfertilised P control produced the shallowest angle of adventitious roots at 1.46°, but was statistically compared to the angle measured at 15 and 60 kg ha^{-1}. During 2013/14 planting the angle of adventitious roots was not significantly affected by various lime application rates (Table 7). The 2014/15 planting however, revealed that both P and lime application rates exerted no significant influence on the angle of adventitious roots of cowpea plants (Table 8).

Table 8: Effect of variable P and lime rates on root characteristics of cowpea during 2014/15 planting.

Treatments	AAD (°)	ABR (°)	NOBR (no pot^{-1})	SD(cm)	TRD mm at 5 cm	TDR mm at 10 cm	1.5 (mm) BD5 cm	1.5 (mm) BD10 cm	SS	DS	NOND (no pot^{-1})	TDR (mm) at 15 cm	TRD (mm) at 20 cm	3rd BD (cm)
Lime rate, L (t/ha)														
0	30.00a	9.08b	2.40b	4.17a	2.01b	1.04a	10.05a	10.83b	1.46a	2.13a	6.78b	0.22a	0.02a	2.13b
2	32.87a	16.50a	3.68a	4.26a	2.14ab	1.19a	11.88a	11.97b	1.48a	2.37a	13.77a	0.38a	0.01a	3.63a
4	29.41a	17.25a	4.28a	4.16a	2.17ab	1.13a	10.95a	13.48a	1.92a	2.27a	15.38a	0.32a	0.01a	3.15a
6	32.20a	16.32a	3.92a	4.30a	2.37a	1.26a	11.71a	13.35a	1.52a	2.38a	14.50a	0.42a	0.06a	3.13a
Phosphorus, P (kg/ha)														
0	33.65a	16.13a	4.02a	4.04c	2.03a	0.98a	9.87a	11.83a	1.63a	2.02a	11.06b	0.19a	0.01a	2.38c
15	29.38a	15.21a	3.75a	4.11bc	2.22a	1.27a	12.10a	12.65a	1.54a	2.50a	13.04ab	0.38a	0.08a	3.42a
30	31.92a	12.19a	2.94a	4.37a	2.16a	1.13a	11.79a	12.88a	1.96a	2.39a	15.04a	0.36a	0.08a	3.65a
45	30.31a	12.50a	2.98a	4.31ab	2.24a	1.19a	11.00a	11.96a	1.50a	2.06a	12.15b	0.42a	0.01a	2.52bc
60	29.10a	17.92a	4.17a	4.27abc	2.19a	1.21a	10.98a	12.73a	1.35a	2.46a	11.06b	0.31a	0.03a	3.10ab
Significance ($p \leq 0.05$)														
Phosphorus	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	**	ns	ns	***
Lime rate	ns	**	***	ns	*	ns	ns	***	ns	ns	***	ns	ns	**
P x L interaction	ns	ns	ns	ns	ns	ns	ns	*	*	ns	ns	ns	ns	ns

N: B. Means followed by the same letter in a column are not significantly different at *$p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$)*. AAD= angle of adventitious roots; ABR= angle of basal roots; NOBR= number of basal roots; SD=stem diameter; TRD5= taproot diameter at 5 cm; TRD10= taproot diameter at 10 cm; TRD15= taproot diameter at 15 cm; TRD20= taproot diameter at 20cm; 1.5mm BD5= 1.5mm branching roots at 5cm; 1.5mm BD10=1.5 mm branching roots at 10cm; 3rd BD=3rd branching roots density at 20 cm, SS= shallow score; DS= deep score and NOND= number of nodules

4.8.3 Angle of basal roots

The results of the angle of basal roots measured during both 2013/14 and 2014/15 plantings indicated that there was no significant ($p \leq 0.05$) difference in angle of basal roots of cowpea plants among the P rates. Nevertheless, lime application exerted significant effect on the angle of basal roots of cowpea during both planting seasons (Table 7 & 8). Lime application at 2 t ha^{-1} resulted in increased angle of basal roots (23.50°) relative to the control but decreased at higher lime rate of 6 t ha^{-1}. The angle of basal roots measured at 2 and 4 t ha^{-1} was statistically similar. Table 8 indicates that application of lime at 4 t ha^{-1} produced the highest angle (17.25°) of basal roots, but was statistically comparable to the angle measured when lime is applied at 2 and 6 t ha^{-1}. The angle of basal roots was significantly reduced (9.08°) in soil pots without lime application.

4.8.4 Number of basal roots

The number of basal roots of cowpea during 2013/14 as well as 2014/15 planting did not respond significantly to various P application rates during 2013/14, but there was a significant ($p \leq 0.01$) effect of lime rates on number of basal roots in cowpea. Number of basal roots did not differ significantly with lime application of 0, 2, and 4 t ha^{-1}. However, application of 6 t ha^{-1} produced the least number of basal roots at the value of 3.59 (Table 7).

In 2014/15 lime application significantly influenced number of basal roots at p-value of ≤ 0.001. The results indicate that the number of basal roots was highly increased (4.28) with lime application of 4 t ha^{-1}. However, the number of basal roots at 4 t ha^{-1} was statistically comparable to the number recorded at 2 and 6 t ha^{-1}. Number of basal roots was significantly reduced (2.40) in soil pots without lime application.

4.8.5 Stem diameter

Table 7 showed that there was no significant ($p \leq 0.05$) difference of P application rates on cowpea stem diameter in 2013/14 season. Nonetheless, there was a significant ($p \leq 0.01$) difference of lime application on cowpea stem diameter. Application of lime at 2 and 4 t ha^{-1} produced better stem diameter of 2.59 and 2.57 mm, respectively as compared to stem diameter (2.19 mm) produced with lime application of 6 t ha^{-1}. However, the stem diameter measured at lime application of 2 and 4 t ha^{-1} was statistically comparable to diameter measured in soil pots without lime application.

However, statistical analysis of 2014/15 planting showed that P application had significant ($p \leq 0.05$) effect on cowpea stem diameter while lime application had no significant effect (Table 8). The widest stem diameter of 4.37 mm was observed with P application of 30 kg ha^{-1}, but did not differ significantly to stem diameter obtained at 45 and 60 kg ha^{-1}. The narrowest stem diameter of 4.04 mm was obtained in soil pots without P fertilization. However, the stem diameter measured in unfertilised soils was statistically comparable to the diameter at P application of 15 and 60 kg ha^{-1} (Table 8).

4.8.6 Taproot diameter at 5, 10, 15 and 20 cm

Application of both P and lime rates had no significant ($p \leq 0.05$) effect on taproot diameter at 5 cm, 15 cm and 20 cm during both 2013/14 and 2014/15 planting seasons (Table 7 & 8). Nevertheless, taproot diameter at 10 cm showed significant ($p \leq 0.01$) response to P application rates with 45 kg ha^{-1} producing the widest stem of 0.78 mm. Application of P at 0, 15, 30 and 60 kg ha^{-1} produced statistically similar taproot diameter at 10 cm. However, tap root diameter at 10 cm was not significantly affected by application of lime rates.

Conversely, lime application showed significant ($p \leq 0.05$) difference on tap root diameter at 5 cm. The results show that the widest taproot diameter at 5 cm (2.37 mm) was measured at lime application of 6 t ha^{-1}, but was statistically compared to the diameter measured when lime is applied 2 and 4 t ha^{-1}. The narrowest diameter of 2.01 mm was recorded in soil pots without lime application.

4.8.7 The 1.5 mm branching density at 5 and 10 cm

In 2013/14, P application exerted no significant influence on 1.5 mm branching density of cowpea plant roots at 5 cm, but exerted significantly ($p \leq 0.05$) effect at 10 cm depth. The rate 45 kg P ha^{-1} produced the highest (4.83 mm) branching density at 10 cm (Table 7). Lime application had significant effect on branching density of cowpea roots at 5 and 10 cm. Nevertheless, application of 2 and 4 t ha^{-1} results in better branching density of cowpea roots at 5 and 10 cm.

In 2014/15, P application exerted no significant effect on 1.5 mm branching density of cowpea plant roots at both 5 cm and 10 cm (Table 8). The various lime application rates similar to 2013/14 planting exerted significant ($p \leq 0.001$) effect on the 1.5 mm branching density of cowpea plant roots at 10 cm. The 1.5 mm branching density of cowpea plant roots at 10 cm was increased (13.48 mm) when lime is applied at 4 t ha^{-1} relative to the un-limed control. However, the density measured at 4 t ha^{-1} was statistically comparable to the value at 6 t ha^{-1}. The least value of 10.83 mm for branching density at 10 cm was measured in soil pots without lime, but did not differ significantly to the density measured at lime application of 2 t ha^{-1} (Table 8).

4.8.8 Shallow score

The cowpea plant root shallow score measured during 2013/14 planting was not significantly affected by the different P application rates but was significantly ($p \leq 0.05$) affected by lime application rates (Table 7). The shallow score recorded when lime was applied at 0, 2 and 4 produced statistically comparable values. However, the least value (0.65) was observed with application of lime at 6 t ha^{-1}. The above recorded value at 6 t ha^{-1} was statistically compared to the shallow score at lime application of 4 t ha^{-1}. There was no significant ($p \leq 0.05$) difference of P and lime application rates on shallow score in 2014/15 planting.

4.8.9 Deep score

During 2013/14 the results showed significant effect of P application rates on deep score of cowpea (Table 7). The maximum deep score was observed at 45 kg P ha^{-1} application rate with the value of 1.65 (Table 7). Also, statistical analysis showed a significant effect since lime application rate of 4 t ha^{-1} showed an increase in deep score with the mean value of 1.58. However, during 2014/15 treatments did not have any significant ($p \leq 0.05$) effect on deep score when P and lime rates were applied.

4.8.10 Number of nodules

Statistical analysis of nodule counts during 2013/14 and 2014/15 showed significant difference on number of nodules with P and lime rates (Table 7). Application of 45 P ha^{-1} caused an increase in number of nodules with values of 0.46 but the 30 kg P ha^{-1} gave the highest mean number of nodules (15.04). Lime application had a significant ($p \leq 0.001$) influence on the mean number of nodule of cowpea plant with highest mean count of 15.38 obtained at the rate of 2 t ha^{-1}.

4.9 Post-harvest soil analysis results

4.9.1 Soil pH

Table 9 shows that there was no significant effect of P application on soil pH (KCl and H_2O). However, the addition of lime rates had a significant ($p \leq 0.001$) effect on soil pH (KCl and H_2O). Soil pH for both KCl (5.76) and H_2O (4.67) was significantly increased with application of lime at 6 t ha^{-1}. Application of lime at 2 and 4 t ha^{-1} gave soil pH (KCl) of 5.30 and 5.54, respectively. However, application of 2 and 4 t ha^{-1} produced statistically similar values of soil pH for H_2O. Soil pH (KCl and H_2O) was significantly reduced in soil pots without P fertilizer application.

4.9.2 P-availability

Phosphorus application at varying rates significantly ($p \leq 0.001$) affected P availability in the soil. The results in Table 9 shows that P availability in the soil was increased (2.71 mg kg^{-1}) when P was applied at higher rate of 60 kg ha^{-1} but was statistically comparable to P availability at 30 kg ha^{-1}. Moreover, P availability at 30 kg ha^{-1} did not differ significantly to soil P recorded when P is applied at 45 kg ha^{-1}. Reduced P levels of 1.46 and 1.47 mg kg^{-1} were obtained with low P applications rates of 0 and 15 kg ha^{-1}, respectively. Lime application at various rates had no significant effect on P availability (Table 9).

4.9.3 Electrical conductivity (EC)

Electrical conductivity was significantly ($p \leq 0.001$) affected by P fertilizer application. Application of P at 15, 30, 45 and 60 kg ha^{-1} produced statistically comparable values for EC (Table 9). However, EC was significantly reduced (0.73 mS cm) in control unfertilised P pots. Various lime application rates significantly ($p \leq 0.001$) influenced the amount of EC in the soil. High application of lime at 6 t ha^{-1} resulted in increased EC with a highest value of 1.15 mS cm. The amount of EC in soil post applied with lime at 2 and 4 t ha^{-1} did not differ significantly. Un-amended lime control pots produced the least amount of EC at 0.56 mS cm.

4.9.4 Mineral nitrogen

There was no significant effect of P and lime application on mineral nitrogen (Table 9).

4.9.5 Total organic carbon

Total organic carbon (TOC) was significantly ($p \leq 0.001$) affected by P and lime rates. The total organic carbon was highly increased (0.79 mg kg^{-1}) with high application P rate of 60 kg ha^{-1}. However, the amount of TOC at 60 kg ha^{-1} did not differ significantly to TOC at P application of 30 and 45 kg ha^{-1}. Soil TOC was found to be lowest (0.56 mg kg^{-1}) in soil pots without P fertilizer application, but was statistically comparable to the TOC at P application of 15 kg ha^{-1} (Table 9). The total organic carbon was significantly increased with increasing application of lime (Table 9). The highest TOC value of 1.05 mg kg^{-1} was obtained when lime is applied at 6 t ha^{-1}. Application of 2 and 4 t ha^{-1} gave TOC of 0.60 and 0.68 mg kg^{-1}, respectively whilst the TOC was significantly reduced (0.42 mg kg^{-1}) in un-limed soil pots.

4.9.6 Organic matter

The percentage of organic (OM) matter in the soil was significantly ($p \leq 0.001$) influenced by P application and various lime rates. Application of P at 60 kg ha^{-1} resulted in increased percentage of OM (1.35%) but was statistically comparable to the percentage of OM recorded in soil pots applied with 30 and 45 kg ha^{-1}. The percentage of OM was found lowest at 0.96% in soils without P application, however, was not significantly different to percentage of OM at 15 kg ha^{-1} (Table 9). The results show that the percentage of (OM) in the soil increased with increasing of lime application. The highest percentage of OM at 1.80% was obtained with lime rate of 6 t ha^{-1} while the lowest percentage (0.72%) was recorded with in soil pots without lime.

Table 9: Effect of variable P and lime rates on post-harvest soil chemical properties

Treatments	pH (H_2O)	pH (KCl)	Bray P1 (mg kg^{-1})	EC (µs/cm)	EC (mS cm)	NH_4N (µg/kg)	TOC (mg kg^{-1})	OM (%)
Lime rates, L (t/ha)								
0	4.63d	3.66d	2.08a	560.2c	0.56c	0.39a	0.42d	0.72d
2	5.30c	4.02b	1.82a	990.7b	0.99b	0.46a	0.60c	1.04c
4	5.54b	4.40b	2.21a	972.8b	0.97b	1.35a	0.68b	1.18b
6	5.76a	4.67a	2.11a	1144.7a	1.15a	1.30a	1.05a	1.80a
Phosphorus rates, P (kg/ha)								
0	5.23a	4.19a	1.46c	732.40b	0.73b	0.39a	0.56b	0.96b
15	5.28a	4.21a	1.47c	944.79a	0.95a	0.46a	0.62b	1.06b
30	5.32a	4.18a	2.37ab	923.33a	0.92a	0.41a	0.74a	1.27a
45	5.36a	4.16a	2.27b	994.08a	0.99a	0.37a	0.74a	1.27a
60	5.33a	4.16a	2.71a	990.75a	0.99a	0.40a	0.79a	1.35a
Significance ($p \leq 0.05$)								
P rates	ns	ns	***	***	***	ns	***	***
L rates	***	***	ns	***	***	ns	***	***
P x L interaction	ns	*	ns	***	***	ns	*	*

***N: B**. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$) **P**=phosphorus, **EC**=electric conductivity, **NH_4N** =mineral nitrogen, **TOC**= soil organic carbon and **OM**= percentage of organic matter*

4.10 Treatment interaction effects on all measured cowpea plant and post-harvest soil variables

4.10.1 Emergence

The interactive effect of P fertiliser and lime rates during 2013/14 and 2014/15 planting seasons significantly ($p \leq 0.01$) affected days to emergence of cowpea (Table 10). The results showed that in 2013/14, the interaction between 60 kg P ha^{-1} x 0 t ha^{-1} lime rate as well as 0 kg P ha^{-1} x 2 t ha^{-1} lime rate resulted in delayed duration (6.08 days) to 50% cowpea emergence while the duration to 50% emergence was much earlier (3.08 days) in pots with application of both 60 kg P ha^{-1} x 6 t ha^{-1} lime rate. However during 2014/15 planting, the 15 kg P ha^{-1} x 4 t ha^{-1} lime rate, 15 kg P ha^{-1} x 6 t ha^{-1} lime rate and 30 kg P ha^{-1} x 0 t ha^{-1} lime rate produced early duration to 50% emergence within 3.25 days. The longest duration to 50% plant emergence (7.50 days) was recorded in soil pot with 60 kg P ha^{-1} x 0 t ha^{-1} lime rate.

4.10.2 Plant height

During 2013/14 planting, the P x lime interaction exerted significant effect on cowpea plant height at 3, 6, 9 and 10 WAE. The tallest cowpea plants were observed at 45 kg P ha^{-1} x 2 t ha^{-1} lime application rate (Table 11). Application of 60 kg P ha^{-1} x 6 t ha^{-1} lime produced the shortest plant height (7.42 cm) at 3 WAE while the shortest plant height was obtained in soil pot containing 30 kg P ha^{-1} x 6 t ha^{-1} lime at 6 and 9 WAE.

The 2014/15 results also revealed significant P application and lime rates interactive effects on cowpea plant height. It was observed that 60 kg P ha^{-1} x 4 t ha^{-1} lime rate produced the highest plant height (30.03 cm) for PL1, but was comparable statistically with plant height measured in soil pots containing 45 kg P ha^{-1} x 4 t ha^{-1} and 60 kg P ha^{-1} x 6 t ha^{-1} lime rates. The shortest cowpea plant height (19.36 cm) was measured in soil pots without P and lime application. Table 12 indicates that the highest plant height (44.02 cm) for PL3 was recorded at 60 kg P ha^{-1} x 4 t ha^{-1} lime rate but was statistically comparable to the measured height at 60 kg P ha^{-1} x 6 t ha^{-1} lime rate. The shortest plant height (34.21 cm) for PL3 was also observed in soil pot containing unfertilised P without lime application.

Table 10: Interaction effect of P and lime rates on days to emergence

Treatment			
Lime (t/ha)	P-rates (kg /ha)	**EMG1**	**EMG 2**
0	0	4.67abc	4.25d
0	15	4.50bcd	6.00bc
0	30	5.25abc	3.25f
0	45	4.92abc	6.00bc
0	60	6.08a	7.50a
2	0	6.08a	3.50ef
2	15	4.50bcd	4.25d
2	30	5.04abc	6.00bc
2	45	4.67abc	4.25d
2	60	4.17cd	4.00e
4	0	4.91abc	6.50ab
4	15	4.33cd	3.25f
4	30	4.33cd	4.25d
4	45	4.04cd	5.50c
4	60	4.17cd	4.25d
6	0	4.17cd	3.50ef
6	15	5.17abc	3.25f
6	30	5.34abc	5.00cd
6	45	6.00ab	5.75b
6	60	3.08d	4.25d
Significant(p≤0.05)		*	*
LSD		0.96	2.81
CV (%)		23.31	32.26

N: B. *Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05).* EMG1 and 2 = emergence during 2013/14 planting and emergence during 2014/15 planting.

Table 11: Interaction effect of P and lime rates on plant height during 2013/14 planting

Treatment		**Plant height (cm)**			
lime rates (t ha^{-1})	P-rates (kg ha^{-1})	3 WAE	6 WAE	9 WAE	10 WAE
0	0	11.33d	14.85f	15.88e	15.08de
0	15	12.25c	18.92c	18.92c	19.39ab
0	30	12.08cd	21.08b	20.81abc	17.85bc
0	45	10.17e	19.54bc	19.54bc	16.89c
0	60	12.25c	21.78ab	21.92ab	17.37bc
2	0	10.42de	11.67g	12.5fg	9.583g
2	15	13.08b	19.95abc	19.58bc	17.61bc
2	30	10.75de	15.38ef	15.38e	14.88de
2	45	14.83a	23.25a	23.25a	20.40a
2	60	12.58abc	17.54cd	17.54d	16.75c
4	0	11.00d	14.77f	14.77f	14.28e
4	15	11.00d	16.71e	16.71de	15.71cde
4	30	13.17b	17.88cd	17.63cd	18.55b
4	45	11.25d	17.79cd	20.21b	16.74c
4	60	14.08ab	15.08f	15.08ef	16.50cd
6	0	9.92f	14.78f	12.87fg	12.78f
6	15	9.75fg	12.87fg	12.87fg	13.68ef
6	30	7.83g	9.54h	9.54gh	12.68f
6	45	10.33de	15.42ef	15.42e	15.53de
6	60	7.42h	11.50g	11.50g	10.74efg
Significant($p \leq 0.05$)		***	***	**	**
LSD		2.27	3.63	3.55	3.67
CV (%)		10.31	27.27	26.55	29.29

*N: B. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$); 3, 6, 9 and 10 WAE denotes 3, 6, 9 and 10 week after emergence*

Table 12: Interaction effect of P and lime rates on cowpea growth parameters during 2014/15 season

Treatments		1st plant		2nd plant	3rd plant	
Lime rates (t/ha)	P rates (kg/ha)	Plant height 1(cm)	Stem diameter (mm)	Length of trifoliate leaves (cm)	Plant height 3 (cm)	Length of trifoliate leaves (cm)
0	0	19.36g	2.61g	13.46ef	34.21g	15.95f
0	15	24.23ed	3.01d	15.06cd	37.25f	17.11d
0	30	25.96d	2.86e	14.80de	39.59ed	16.87cd
0	45	25.38cde	3.10bc	14.42f	41.68bc	16.67e
0	60	26.42c	3.10abc	16.05c	42.61b	18.12a
2	0	21.25ef	2.81e	14.88e	38.30def	17.08d
2	15	22.89f	2.64ef	15.37d	40.10cde	17.55abc
2	30	24.44e	2.52fg	14.50f	39.87ed	16.64e
2	45	26.08cd	2.64ef	16.17b	42.28bc	18.68ab
2	60	26.13cd	2.96cd	15.62d	41.39bcd	17.83abc
4	0	20.63g	2.35h	14.40f	37.54f	16.40f
4	15	23.16f	2.74f	14.45f	38.72ef	16.64e
4	30	26.58b	2.92cd	16.16bc	41.82c	18.26ab
4	45	28.05abc	2.76de	15.30d	41.57d	17.50abc
4	60	30.03a	3.30ab	17.61a	44.02a	19.62a
6	0	22.81f	2.99cd	14.89e	38.65def	17.11d
6	15	26.44c	3.18ab	15.65d	41.67bc	17.72abc
6	30	26.35c	3.49a	15.55d	40.54e	17.67abc
6	45	27.54bc	3.10bc	16.25b	42.53b	18.48ab
6	60	28.31ab	3.27ab	15.92d	43.46ab	17.70abc
Significant(p≤0.05)		*	*	**	**	**
LSD		2.08	0.39	1.35	1.86	1.32
CV (%)		10.31	16.47	10.95	5.73	9.39

*N: B. Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05). .*

4.10.3 Stem diameter

Cowpea plant stem diameter measured in 2013/14 planting was significantly ($p \leq 0.001$) affected by P x lime interactive effect at 3, 6 and 9 WAE. The widest stem diameter (2.96 cm) at 3 WAE was measured in soil pots without P application x 2 t ha^{-1}, but was statistically comparable to diameter at P x lime of 0 kg ha^{-1} x 4 t ha^{-1} and 0 kg P ha^{-1} x 6 t ha^{-1} (Table 13). At 6 and 9 WAE, 0 kg P ha^{-1} x 2 t ha^{-1} lime interaction effects produced the narrowest stem diameter of 2.51 cm while the widest stem diameter was obtained at 30 kg P ha^{-1} x 4 t ha^{-1} lime rate.

The results during 2014/15 showed significant increase in stem diameter with increasing application of P x lime (Table 12). The widest stem diameter for the first tagged plant (SD1) was obtained at 30 kg P ha^{-1} x 6 t ha^{-1} lime rate, which did not differ significantly from the diameter measured at 60 kg P ha^{-1} x 4 t ha^{-1}, 60 kg P ha^{-1} x 6 t ha^{-1} and 15 kg P ha^{-1} x 6 t ha^{-1} lime rate application. The narrowest stem diameter was produced in soil pot containing unfertilised P control pots x 4 t ha^{-1} lime rate with a mean value of 2.35 cm.

4.10.4 Number of trifoliate leaves

The results from 2013/14 planting showed that the number of trifoliate leaves per cowpea plant was significantly affected by the interaction between P and lime application rates during 3, 6 and 9 WAE (Table 14). The interaction between 30 kg P ha^{-1} x 0 t ha^{-1} lime rate, 15 kg P ha^{-1} x 2 t ha^{-1} lime rate, 60 kg P ha^{-1} x 2 t ha^{-1} lime rate, 15 kg P ha^{-1} x 4 t ha^{-1} lime rate, 30 kg P ha^{-1} x 4 t ha^{-1} lime rate, 60 kg P ha^{-1} x 4 t ha^{-1} lime rate produced statistically comparable number of trifoliate leaves at 3 WAE. The least mean number of trifoliate leaves (0.33) was observed at 15 kg P ha^{-1} x 6 t ha^{-1} lime rate at 3 WAE. The 60 kg P ha^{-1} x 0 t ha^{-1} interaction effect gave the highest mean number of trifoliate leaves at 2.34 and 2.50 at 6 and 9 WAE, respectively. The lowest mean number of trifoliate leaves (0.67) recorded in soil pot containing unfertilized P x 2 t ha^{-1} lime rate interaction at both 6 and 9 WAE. During 2014/15 planting season the number of trifoliate leaves showed no response to P and lime application interaction.

Table 13: Interaction effect of P and lime rates on stem diameter during 2013/14 planting

Treatment		**Stem diameter (mm)**		
Lime (t ha^{-1})	P(kg ha^{-1})	3 WAE	6 WAE	9 WAE
0	0	1.95ef	2.80e	2.76fg
0	15	2.26d	2.86de	2.86f
0	30	2.06e	3.16c	3.08de
0	45	2.04e	2.65ef	2.65g
0	60	2.63b	3.36ab	2.60gh
2	0	2.96a	2.51g	2.51h
2	15	2.25d	3.19abc	3.19cd
2	30	2.42c	3.11c	3.11de
2	45	2.34cd	3.21abc	3.21cd
2	60	2.13de	2.95d	2.95ef
4	0	2.54abc	3.23abc	3.23c
4	15	2.46bc	3.35ab	3.35abc
4	30	2.51b	3.39a	3.60ab
4	45	2.38cd	3.13c	3.25bc
4	60	2.47b	3.11c	3.11d
6	0	2.79ab	3.16c	2.93ef
6	15	2.38cd	3.29b	3.29b
6	30	2.43c	3.03cd	3.03de
6	45	2.46bc	2.99cd	2.99e
6	60	2.42c	2.60g	2.60gh
Significant($p \leq 0.05$)		***	***	***
LSD		0.34	0.38	0.38
CV (%)		17.63	239	15.29

*N: B. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($p \leq 0.05$);* 3, 6 and 9 WAE denotes that stem diameter at 3, 6 and 9 week after emergence.

Table 14: Interaction effect of P and lime rates on number and length of trifoliate leaves during 2013/14 planting

Treatment		**Number trifoliate leaves**			**Length of trifoliate leaves (cm)**		
Lime rates (t ha^{-1})	P rates (kg ha^{-1})	**3 WAE**	**6 WAE**	**9 WAE**	**3 WAE**	**6 WAE**	**9 WAE**
0	0	0.75abcd	1.08de	1.67abc	3.26cde	7.65b	6.19e
0	15	0.92ab	2.00b	2.00b	4.19c	6.75de	6.75d
0	30	1.00a	2.00b	2.08ab	4.65bc	8.48ab	8.43ab
0	45	0.92ab	2.00b	2.00b	3.23de	6.54e	6.54de
0	60	0.92ab	2.34a	2.50a	4.30c	8.04abc	8.22abc
2	0	0.83abc	0.67ef	0.67e	4.12c	3.58h	3.58g
2	15	1.00a	1.50cd	1.67abc	5.55a	7.46bc	7.22c
2	30	0.58cde	1.75abc	1.75abc	2.88ef	6.50e	6.50de
2	45	0.75abcd	2.08ab	2.08ab	4.73b	8.74a	8.74a
2	60	1.00a	1.75abc	1.75abc	5.36ab	7.28cd	7.28bc
4	0	0.50de	1.50cd	1.50c	2.16f	6.33e	6.33e
4	15	1.00a	1.75abc	1.75abc	4.81abc	5.68f	5.68ef
4	30	1.00a	1.92b	2.00b	4.85abc	7.29c	7.88b
4	45	0.92ab	1.58c	1.67abc	3.95cd	6.89de	7.06cd
4	60	1.00a	1.50cd	1.50c	5.63a	7.09d	7.09cd
6	0	0.75abcd	1.67abc	1.75abc	3.04e	5.88ef	5.97ef
6	15	0.33e	1.25d	1.25cd	1.53g	5.51fg	5.51f
6	30	0.50de	1.00e	1.00d	1.30h	3.38i	3.38g
6	45	0.75abcd	1.75abc	1.75abc	3.48d	5.95ef	5.95ef
6	60	0.67bcd	1.33d	1.33cd	1.88fg	5.48g	5.48fg
Significant(p≤0.05)		**	***	***	***	***	***
LSD		0.29	0.53	0.53	1.49	1.79	1.73
CV (%)		44.30	40.47	38.77	49.48	34.11	33.14

*N: B. Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05); 3, 6 and 9 WAE denotes that number/length of trifoliate leaves at 3, 6 and 9 week after plating.*

4.10.5 Length of trifoliate leaves

The length of trifoliate leaves from cowpea plants measured during 2013/14 planting was significantly ($p \leq 0.001$) affected by P and lime interaction effect at 3, 6 and 9 WAE (Table 14). The highest length of trifoliate was measured (5.63 cm) at 60 kg P ha^{-1} x 4 t ha^{-1} lime rate at 3 WAE; this was however, statistically comparable to the measured length at 15 kg P ha^{-1} x 2 t ha^{-1} lime rate, 15 kg P ha^{-1} x 4 t ha^{-1} lime rate and 30 kg P ha^{-1} x 4 t ha^{-1} lime rate. The shortest length of trifoliate leaves observed (1.30 cm) was at 30 kg P ha^{-1} x 6 t ha^{-1} lime rate. The highest length of trifoliate leaves (8.74 cm) was in soil pots containing 45 kg P ha^{-1} x 2 t ha^{-1} lime rate at both 6 and 9 WAE. Moreover, the shortest length (3.38 cm) obtained at 3 and 9 WAE was observed at 30 kg P ha^{-1} x 6 t ha^{-1} lime rate.

The 2014/15 results indicate that P x lime application significantly affected the length of trifoliate leaves of only tagged plants 2 and 3. It was observed that application of 60 kg P ha^{-1} x 4 t ha^{-1} lime rate resulted an increase in the length of trifoliate leaves for both LT2 and LT3 with 17.61 and 19.62 cm, respectively relative to the control i.e. unfertilized P and un-limed soil pot (Table 12).

4.10.6 Width of trifoliate leaves

The results from 2013/14 planting indicate that the width of trifoliate leaves was significantly ($p \leq 0.001$) affected by the interaction effect of P x lime during 3 and 6 WAE. The width of trifoliate leaves was increased highly (3.36 cm) by P x lime of 60 kg ha^{-1} x 4 t ha^{-1} but did not differ significantly to the width of trifoliate leaves measured at P x lime of 15 kg ha^{-1} x 2 t ha^{-1}, 60 kg ha^{-1} x 2 t ha^{-1} and 15 kg ha^{-1} x 4 t ha^{-1}(Table 15). The least value for width of trifoliate leaves was recorded at 0.63 cm at P x lime of 15 kg ha^{-1} x 6 t ha^{-1}. For 6 WAE the width was better increased with the interaction of P and lime at 30 kg ha^{-1} x 4 t ha^{-1} with a mean value of 3.99 cm, whilst the narrowest width (1.38 cm) was observed with P x lime of 30 kg ha^{-1} x 6 t ha^{-1}. Width of trifoliate leaves was not significantly affected by P x lime during 9 and 10 WAE. Interaction of P x lime had no significant effect ($p \leq 0.05$) on width of trifoliate leaves for WT1, WT2 and WT3 during 2014/15 planting.

4.10.7 Area of trifoliate leaves

The area of trifoliate leaves was significantly ($p \leq 0.01$) affected by P and lime interaction during 3 and 9 WAE (Table 15). The results show that the area of trifoliate leaves at 3 WAE was increased (20.10 cm^2) at 60 kg P ha^{-1} x 4 t ha^{-1} relative to the control, but was statistically comparable to the leaf area measured in soil pot with 15 kg P ha^{-1} x 2 t ha^{-1} lime rate. However, the area of trifoliate leaves at 3 WAE was reduced (2.09 cm^2) by the interaction effect of 15 kg P ha^{-1} x 6 t ha^{-1} lime rate, which was statistically comparable to the leaf area measured at 30 kg P ha^{-1} x 6 t ha^{-1} lime rate. The area of trifoliate leaves at 9 WAE was highly increased (37.87 cm^2) when 45 kg P ha^{-1} x 2 t ha^{-1} lime rate was applied. Application of 30 kg P ha^{-1} x 6 t ha^{-1} lime produced the least (7.07 cm^2) trifoliate leaf area at 9 WAE. The area of trifoliate leaves measured on the three tagged plants showed no significant response to P x lime application rates interaction effect during 2014/15 planting.

4.10.8 Chlorophyll content

Figure 12 shows the interaction effect of P x lime application rates on chlorophyll content during flowering during 2014/15 planting. Cowpea leaf chlorophyll content of 95.84 CCI obtained from unfertilised P pots and 6 t ha^{-1} lime rate was highest but statistically comparable to the recorded value under 60 kg P ha^{-1} x 6 t ha^{-1} lime rate. The least chlorophyll content (52.28 CCI) measured at flowering was obtained at the interaction of 45 kg P ha^{-1} and un-limed control pots. The cowpea leaf chlorophyll content during pod formation was significantly ($p \leq 0.001$) affected by P x lime application rates (Figure 13). Nonetheless, the results show that the leaf chlorophyll content measured in soils without P application x 6 t ha^{-1}, 60 kg P ha^{-1} x 6 t ha^{-1} and 45 kg P ha^{-1} x 4 t ha^{-1} did not differ significantly. The least chlorophyll content of 41.58 CCI was also recorded at the interaction of 45 kg P ha^{-1} and un-limed control pots. Overall, cowpea leaf chlorophyll content of measured during flowering and pod formation was increased when high lime rate (6 t ha^{-1}) was applied together with various P rates.

Table 15: Interaction effect of P and lime rates on width and area of trifoliate leaves during 2013/14 planting

Treatments		Width of trifoliate leaves (cm)		Area of trifoliate leaves (cm^2)	
Lime rates (t/ha)	P rates (kg/ha)	3 WAE	6 WAE	3 WAE	9 WAE
0	0	1.43e	4.40a	7.12e	32.47b
0	15	2.50b	3.17c	14.39b	27.24c
0	30	2.30c	3.82b	11.03cd	37.56a
0	45	1.74d	3.45bc	7.04e	31.90b
0	60	2.34c	3.80b	11.89c	36.46ab
2	0	2.29c	1.81fg	12.62c	12.29fg
2	15	3.28ab	3.22c	19.62a	24.99cd
2	30	1.47e	2.98cd	7.85de	27.67c
2	45	2.48b	3.78b	16.25b	37.87a
2	60	3.03ab	3.81b	16.72b	32.60b
4	0	1.07f	3.20c	4.80ef	21.83de
4	15	2.58abc	2.63d	14.23b	18.93e
4	30	2.42bc	3.99ab	12.41c	36.19ab
4	45	1.95cd	3.16c	8.91d	28.78bc
4	60	3.36a	3.63b	20.10a	29.27bc
6	0	1.74d	3.00cd	7.81de	23.92d
6	15	0.63g	2.92cd	2.09g	19.23e
6	30	0.66g	1.38g	2.20g	7.07g
6	45	1.86d	2.41e	7.04e	18.33ef
6	60	0.93fg	2.51d	3.04f	16.99f
Significant(p≤0.05)		***	***	**	**
LSD		0.99	0.98	6.60	11.53
CV (%)		61.12	38.66	78.81	58.98

*N: B. Means followed by the same letter in a column are not significantly different at p≤0.05, *= p≤0.05, ** = p≤ 0.01, *** = p≤ 0.001, ns = non-significant (p≤0.05); 3, 6 and 9 WAE denotes that width/area at 3, 6 and 9 week after planting.*

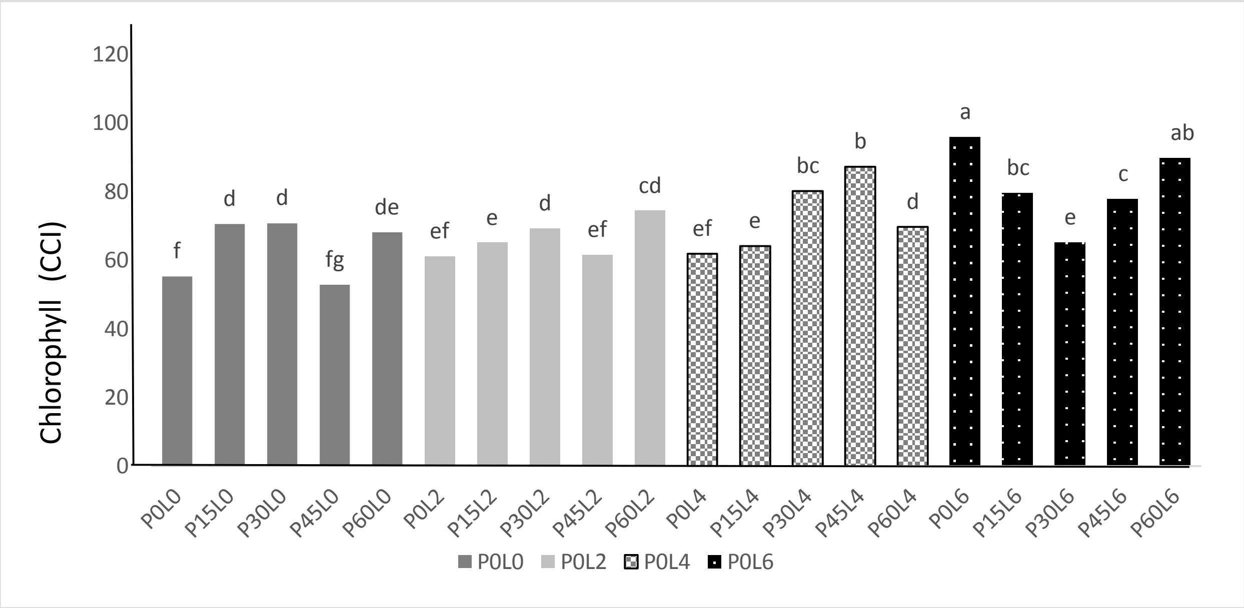


Figure 12: Interaction effect of P and lime rates on chlorophyll content during flowering. *Bars followed by the same letter are not significantly different at p≤0.05. P0, P15, P30, P45 and P60 implies phosphorus application at 0,15,30,45 and 60 kg ha^{-1}.Also L0, L2, L4 and L6 implies lime application at 0, 2, 4 and 6 t ha^{-1}.*

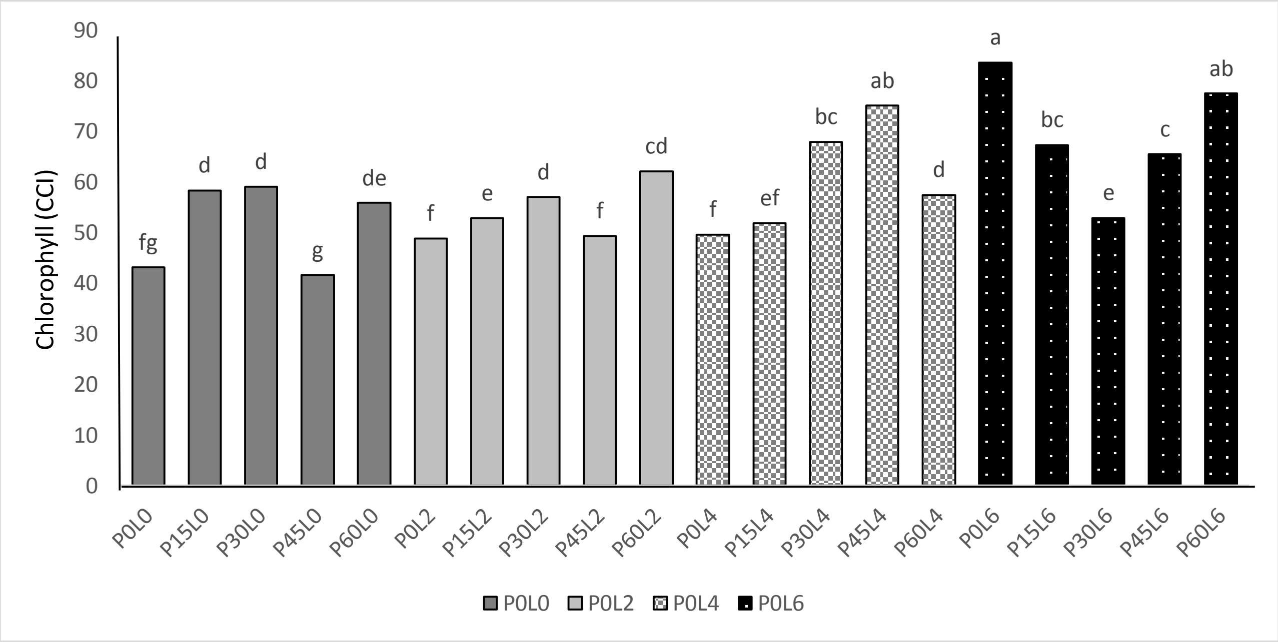


Figure 13: Interaction effect of P x lime rates on chlorophyll content during pod formation..*Bars followed by the same letter are not significantly different at p≤0.05. P0, P15, P30, P45 and P60 implies phosphorus application at 0, 15, 30, 45 and 60 kg ha^{-1}.Also L0, L2, L4 and L6 implies lime application at 0, 2, 4 and 6 t ha^{-1}.*

4.10.9 Flower formation

Interaction effect of P x lime application rates significantly ($P \leq 0.001$) affected the duration to 50 and 100% flower initiation. The results indicated that the duration to 50 and 100% flower initiation were significantly reduced with high P x lime rates of 60 kg ha^{-1} x 6 t ha^{-1} at 56 and 62 days, respectively (Table 16). The duration to 50% (72 days) and 100% (78 days) flower initiation were both delayed in soil pots without P x lime application. Generally the results indicate that the duration to flowering in cowpea plants were reduced by the interaction of P x lime at high application rates and delayed in soil pots without P and lime application.

4.10.10 Pod formation

Statistical analysis showed significant ($P \leq 0.001$) interaction effect of P x lime application rates on the duration to 50 and 100% pods formation. The duration to 50 and 100% pod formation in cowpea plants were significantly reduced with the interaction of 60 kg ha^{-1} x 6 t ha^{-1} at 59 and 67 days, respectively. However, the durations of cowpea to reach both 50 and 100% pod formation were increased in soil pots without P and lime application rates (Table 16). The latest duration to 50% pod formation was observed at 75 days and at 81 days for 100% pod formation.

Table 16: Interaction effect of P and lime rates on cowpea phenological development during 2014/15 planting

Treatment		Duration to 50% flowering	Duration to 50% pod formation	Duration to 100% flowering	Duration to 100% pod formation
Lime (t/ha)	P(Kg/ha)				
0	0	72.0a	75.0a	78.0a	81.0a
0	15	68.0b	71.0b	74.0abc	78.0bc
0	30	64.0c	67.0cd	70.0cd	75.0bcd
0	45	71.0ab	73.0ab	75.0ab	79.0ab
0	60	71.0ab	73.0ab	75.0ab	79.0ab
2	0	62.0cd	65.0d	67.0d	71.0d
2	15	61.0d	63.0e	67.0de	71.0d
2	30	61.0d	63.0de	66.0e	71.0de
2	45	58.0ef	61.0f	64.0edf	69.0e
2	60	58.0ef	60.0efg	65.0edf	70.0e
4	0	68.0b	71.0bc	72.0bc	75.0bcd
4	15	68.0b	71.0b	72.0c	75.0bcd
4	30	59.0e	61.0ef	64.0f	68.0e
4	45	59.0ef	61.0f	64.0edf	69.0e
4	60	57.0f	59.0g	63.0fg	68.0ef
6	0	65.0abc	67.0c	69.0cd	74.0cd
6	15	70.0ab	73.0ab	73.0abc	77.0bc
6	30	71.0ab	73.0ab	74.0ab	78.0bc
6	45	69.0ab	72.0b	72.0bc	76.0c
6	60	56.0f	59.0g	62.0g	67.0f
Significant (p<0.001)		***	***	***	***
LSD		3.33	3.25	1.71	3.48
CV (%)		3.65	3.44	3.50	3.35

*N: B. Means followed by the same letter in a column are not significantly different at *** = p≤ 0.001, ns = non-significant (p≤0.05)*

4.10.11 Fresh and oven-dried plant biomass

Interaction effect of P and lime exerted no significant effect on the fresh plant biomass per pot at trial termination but significantly affected ($p \leq 0.05$) the oven plant biomass during 2013/14 season. Application at 60 kg P ha^{-1} without lime produced the highest (0.66 g) oven-dried plant biomass but observed value did not differ significantly from biomass at 45 kg P ha^{-1} in un-limed control pots (Table 17). The least oven-dried plant biomass of 0.17 g pot^{-1} was obtained from 15 kg P ha^{-1} x 6 t ha^{-1} and control P x 4 t ha^{-1} treatments interaction pots. Figure 14a shows that P x lime rates interaction exerts significant ($p \leq 0.05$) effect on the fresh plant biomass during 2014/15 planting season with the 30 kg P ha^{-1} x 6 t ha^{-1} produced the highest fresh plant biomass (9.59 g), although statistically comparable to biomass obtained from 60 kg P ha^{-1} x 6 t ha^{-1}, 45 kg P ha^{-1} x 4 t ha^{-1} and 60 kg P ha^{-1} x 0 t ha^{-1} treatments Interaction.

The lowest fresh plant biomass was produced in soil pots without P and lime application. Figure 14b shows the interaction effect of P and lime on oven-dried plant biomass during 2014/15 season. Application of 30 kg P ha^{-1} x 6 t ha^{-1} produced the highest oven-dried plant biomass (5.49 g pot^{-1}), however statistically similar to values recorded under 60 kg P ha^{-1} x 6 t ha^{-1}, 60 kg P ha^{-1} x 0 t ha^{-1} and 45 kg P ha^{-1} x 4 t ha^{-1} treatment interaction. The lowest oven-dried plant biomass (1.65 g pot^{-1}) was recorded in pot containing control P and un-limed soil (Figure 14b).

4.10.12 Fresh and oven-dried root biomass

The fresh roots biomass did not significantly respond to P and lime interaction during 2013/14 planting season (Table 17). However, the oven-dried roots biomass was significantly ($p \leq 0.05$) affected by P x lime application interaction effect. The results indicated that soil pot containing 2 t ha^{-1} lime application with control P pots produced the highest oven dried root biomass (0.11 g pot^{-1}) whilst other treatment interaction gave statistically comparable amount of dried-oven biomass (Table 17). During 2014/15 season, the P and lime rates interaction significantly affected only the oven-dried root biomass. Figure 15 shows that 60 kg P ha^{-1} x 4 t ha^{-1} lime application rate produced the highest oven-dried roots biomass (0.37 g) but was statistically comparable to dried root biomass obtained in 45 kg P ha^{-1} x 4 t ha^{-1} lime rate. The oven-dried biomass was significantly reduced (0.06 g) in soil pots without P x lime application.

Table 17: Interaction effect of P and lime rates on cowpea biomass per pot at trial termination during 2013/14 planting

Treatment		**FBP**	**OPB**	**FRB**	**ORM**
Lime (t/ha)	P (kg/ha)	**(g)**	**(g)**	**(g)**	**(g)**
0	0	1.06 f	0.21f	0.48abc	0.06b
0	15	1.45de	0.31d	0.47bc	0.06b
0	30	2.1bc	0.46b	0.52abc	0.09b
0	45	2.59ab	0.55ab	0.48abc	0.07b
0	60	3.10a	0.66a	0.53abc	0.08b
2	0	0.77fg	0.37cd	0.47abc	0.11a
2	15	1.58d	0.27de	0.52abc	0.07b
2	30	2.05c	0.42c	0.51abc	0.09b
2	45	2.14b	0.44b	0.63a	0.08b
2	60	1.19ef	0.3de	0.48abc	0.05b
4	0	1.01f	0.17g	0.51abc	0.05b
4	15	1.08f	0.21f	0.48abc	0.06b
4	30	1.98c	0.43b	0.56ab	0.07b
4	45	2.37abc	0.49bc	0.53abc	0.07b
4	60	1.67cd	0.34d	0.57ab	0.08b
6	0	0.94f	0.18f	0.40c	0.06b
6	15	1.03f	0.17g	0.49abc	0.05b
6	30	1.24e	0.18f	0.53abc	0.03b
6	45	1.60d	0.24e	0.52abc	0.04b
6	60	1.18ef	0.21f	0.48abc	0.06b
Significant($p\leq0.05$)		ns	*	ns	*
LSD		0.89	0.19	0.16	0.7
CV (%)		39.13	40.4	313	23.13

*N: B. Means followed by the same letter in a column are not significantly different at $p\leq0.05$, *= $p\leq0.05$, ** = $p\leq 0.01$, *** = $p\leq 0.001$, ns = non-significant ($p\leq0.05$); FPB=fresh plant biomass; OPB=oven-dried plant biomass; FRB=fresh root biomass and ORM= oven-dried root biomass.*

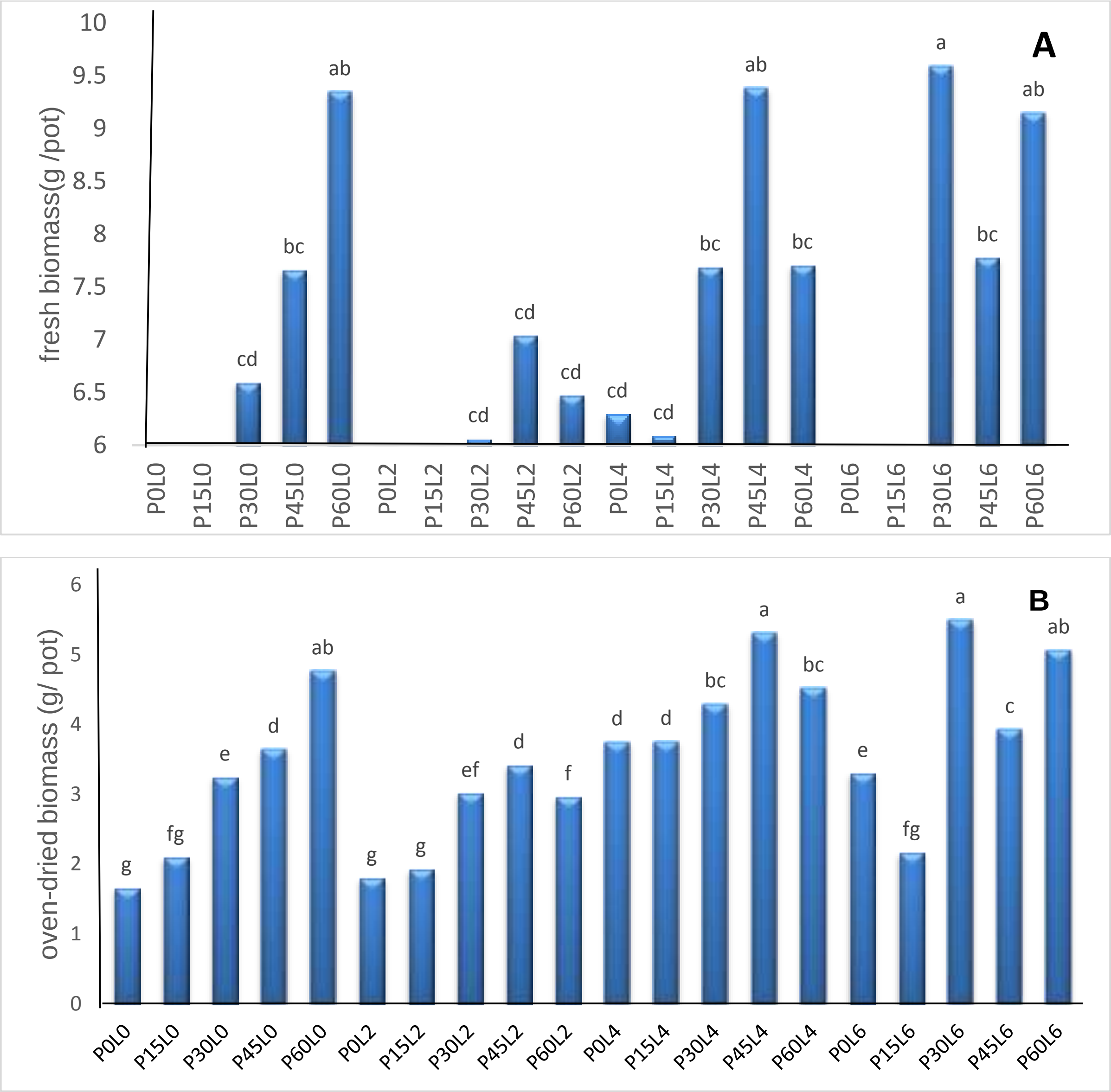


Figure 14: Interaction effect of P x lime rates on cowpea fresh plant biomass (top) and (bottom) oven-dried plant biomass during 2014/15. *Bars followed by the same letter are not significantly different at p≤0.05.* NB: P0, P15, P30, P45 and P60 implies phosphorus application at 0,15,30,45 and 60 kg ha^{-1}. Also L0, L2, L4 and L6 implies lime application at 0, 2, 4 and 6 t ha^{-1}.

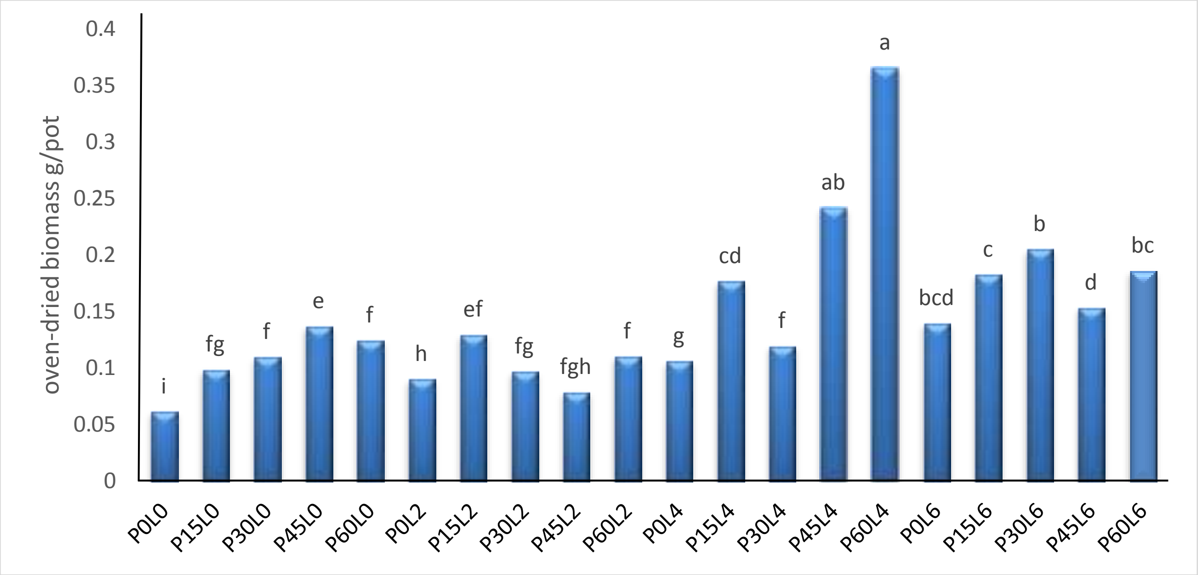


Figure 15: Interaction effect of P and lime rates on cowpea dry root biomass during 2014/15 planting. *Bars followed by the same letter are not significantly different at P≤0.05. NB:* P0, P15, P30, P45 and P60 implies phosphorus application at 0, 15, 30, 45 and 60 kg ha^{-1}. Also L0, L2, L4 and L6 implies lime application at 0, 2, 4 and 6 t ha^{-1}.

4.10.13 Yield component

The yield components of cowpea plants did not respond significantly to the P x lime treatment interaction effect.

4.10.14 Root parameters

The results from 2013/14 planting are presented in Table 18 while Table 19 shows the results from 2014/15 season. During 2013/14 the interaction effect of P and lime significantly affected the 3rd branching roots; taproot diameter at 10 cm; deep score and number of nodule (Table 18). The results showed that interaction of P x lime at 45 kg P ha^{-1} and un-limed control pots produced more 3rd branching roots density at 3.67 while the least value for the 3rd root branching density of cowpea was obtained with the interaction of 30 kg P ha^{-1} x 6 t ha^{-1}. The interaction effect of P x lime had a significant ($p \leq 0.001$) effect on tap root diameter at 10 cm. It was observed that the widest taproot diameter at 10 cm (2.34 mm) was obtained at 45 kg P ha^{-1} x 6 t ha^{-1} lime interaction effects. The narrowest taproot diameter at 10 cm (0.05 mm) was at application of 30 kg P ha^{-1} combined with 6 t ha^{-1} lime application but was not significantly different from values obtained under the other treatments interaction effects. The highest deep score of 2.25 was achieved at 45 kg P ha^{-1} x 4 t ha^{-1} whilst the lowest deep score of cowpea roots (0.42) was obtained with 60 kg P ha^{-1} x 2 t ha^{-1} (Table~~:~~ 19). Number of nodules was significantly ($p \leq 0.001$) affected by P x lime interaction with 45 kg P ha^{-1} x 2 t ha^{-1} interaction producing the highest mean number of nodules (1.42) per cowpea plant. The least number of nodules (0.07) was recorded at 30 kg ha^{-1} x 2 t ha^{-1} (Table 18).

Statistical analysis showed a significant ($p \leq 0.05$) interactive effect of P and lime application rates on branching roots at 10 cm during 2014/15 season. Table 19 indicates that 60 kg P ha^{-1} x 4 t ha^{-1} interaction resulted in highest (15.50 cm) increased 1.5 mm branching root density of cowpea plant, which was statistically similar to branching root density (14.75 cm) at 60 kg P ha^{-1} x 6 tha^{-1} interaction effect. The least value of branching density at 10 cm (9.25 cm) was obtained at 45 kg P ha^{-1} in soils without lime application (Table 19). A significant ($p \leq 0.05$) interaction effect of P and lime application was similarly observed on shallow score of cowpea roots during 2014/15 planting. Application of 45 kg P ha^{-1} x 4 t ha^{-1} and 30 kg P ha^{-1} x 6 t ha^{-1} treatments interaction produced the highest shallow score of 2.17 while the lowest shallow score of 0.67 was achieved from 60 kg P ha^{-1} x 2 t ha^{-1} interaction effect (Table 19).

Table 18: Interaction effect of P and lime rates on cowpea root attributes during 2013/14 planting

Treatment		3rd BD (cm)	TRD10 (cm)	DS	NoND (no pot^{-1})
Lime rate (t ha^{-1})	P- rates (kg ha^{-1})				
0	0	3.08ab	0.14b	1.50abc	0.25cd
0	15	2.82abc	0.20b	1.54abc	0.25cd
0	30	2.12bcd	0.23b	1.26bcdef	0.71bc
0	45	3.67a	0.20b	1.50abc	0.25cd
0	60	2.25abcd	0.17b	1.42abcd	0.17cd
2	0	0.75def	0.11b	0.50ef	0.17cd
2	15	3.17ab	0.09b	0.58def	1.00ab
2	30	2.25abcd	0.20b	1.33bcde	0.07d
2	45	2.92abc	0.32b	1.83ab	1.42a
2	60	1.67bcde	0.08b	0.42f	0.08d
4	0	0.50ef	0.90b	0.75cdef	0.17cd
4	15	0.92def	0.22b	1.83ab	0.08d
4	30	3.00abc	0.15b	1.33bcde	0.17cd
4	45	1.25def	0.24b	2.25a	0.08d
4	60	1.75bcde	0.10b	1.75ab	0.08d
6	0	1.50cdef	0.14b	1.42abcd	0.08d
6	15	1.33def	0.07b	0.58def	0.25cd
6	30	0.50ef	0.05b	0.58def	0.08d
6	45	0.83def	2.34a	1.00bcdef	0.10d
6	60	0.50ef	0.07b	0.58def	0.08d
Significant($p\leq0.05$)		**	**	*	**
LSD		1.48	0.76	0.83	0.54
CV (%)		105.08	373.32	87.61	262.7

*N: B. Means followed by the same letter in a column are not significantly different at $p\leq0.05$, *= $p\leq0.05$, ** = $p\leq0.01$, *** = $p\leq0.001$, ns = non-significant ($p\leq0.05$).* ***3rd BD****=3rd branching roots***;** ***TRD10****= taproot diameter at 10 cm***;** ***DS****= deep score and* ***NOND****= number of nodule*

Table 19: Interaction effect of P and lime rates on roots parameters during 2014/15 planting

Treatment		1.5mm Branching density at 10 cm soil depth (cm)	Shallow score
Lime rates (t/ha)	P rates (kg/ha)		
0	0	10.25f	1.42abcd
0	15	11.00def	1.33abcd
0	30	12.75c	2.08ab
0	45	9.25g	1.00cd
0	60	10.92ef	1.50abcd
2	0	12.42bcd	2.08ab
2	15	13.50bc	2.08ab
2	30	11.58def	1.50abcd
2	45	12.58cd	1.08cd
2	60	9.75fg	0.67d
4	0	12.75c	2.08ab
4	15	12.75c	1.58abcd
4	30	12.67cd	2.08ab
4	45	13.75bc	2.17a
4	60	15.50a	1.67abc
6	0	11.92e	0.92cd
6	15	13.33bc	1.17bcd
6	30	14.50ab	2.17a
6	45	12.25bcd	1.75abc
6	60	14.75ab	1.58abcd
Significant($p \leq 0.05$)		*	*
LSD		2.81	0.96
CV (%)		28.18	74.74

*N: B. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$, *= $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$, ns = non-significant ($P \leq 0.05$).*

4.10.15 Post-harvest soil analysis results

Table 20 shows that there was no significant interaction effect of P x lime on pH for H_2O, but significantly ($p \leq 0.05$) affected soil pH for KCl. Application of P and lime at 15 kg ha^{-1} x 6 t ha^{-1} resulted in increased soil pH at 4.82 but was not significantly different to the soil pH in soil pots applied with 45 kg ha^{-1} x 6 t ha^{-1}, unfertilized P control pots x 6 t ha^{-1} and 30 kg ha^{-1} x 6 t ha^{-1}. Soil pH (KCl) was significantly reduced (3.41) in soil pots without P and lime application. P availability in the soil was not significantly affected by application interaction of lime and P (Table 20).

There was a significant effect of P and lime interaction on electrical conductivity (EC) of the soil. It was observed that interaction of P and lime produced the highest EC value of 1.37 mS cm at 30 kg ha^{-1} x 2 t ha^{-1} but was statistically comparable with the EC at 60 kg ha^{-1} x 6 t ha^{-1} and 45 kg ha^{-1} x 4 t ha^{-1}. EC was significantly reduced (0.38 mS cm) in soil pots applied with P and lime interaction of 15 kg ha^{-1} and un-limed control pots. There was no significant difference of P x lime on mineral nitrogen (Table 20). However, the interactive effect of P and lime had a significant ($p \leq 0.05$) influence on the total organic carbon. Application of P and lime at 60 kg P ha^{-1} x 6 t ha^{-1} produced high amount of total organic carbon (1.33 mg kg^{-1}) in the soil while the total organic carbon (0.29 mg kg^{-1}) decreased greatly in control P and lime pots. The interactive effect of P x lime also had a significant ($p \leq 0.05$) influence on the organic matter. Application of P x lime at 60 kg ha^{-1} and 6 t ha^{-1} resulted in increased organic matter of 2.28% whereas the least percentage (0.49%) of organic matter was found in soil pots without P and lime application.

Table 20 Interaction effect of P and lime rates on post-harvest soil analysis

Treatments		**pH (H_2O)**	**pH (KCl)**	**P (mg/kg)**	**EC (µs/cm)**	**EC (mS cm)**	**NH_4N (µg/kg))**	**TOC (mg/kg)**	**OM (%)**
Lime rates (t/ha)	P-rates (kg/ha)								
0	0	4.37i	3.41i	1.78d	573.80fg	0.58fg	0.32c	0.29l	0.49l
0	15	4.45h	3.78g	1.55ef	377.30h	0.38h	0.70a	0.35kl	0.60kl
0	30	4.73g	3.68h	2.10cd	439.00g	0.44g	0.55ab	0.56hij	0.97hij
0	45	4.72g	3.66h	2.44b	581.20fg	0.58fg	0.33c	0.46ijkl	0.79ijk
0	60	4.87f	3.78g	2.43abc	829.70ef	0.83ef	0.36bc	0.43jkl	0.74jkl
2	0	5.33de	4.21de	1.01g	677.20f	0.68f	0.41bc	0.57hij	0.98hij
2	15	5.27de	3.86f	1.20g	1084.40bc	1.09bc	0.42bc	0.54hij	0.93hij
2	30	5.66b	4.12e	2.30bc	1364.10a	1.37a	0.39bc	0.62ghi	1.06ghi
2	45	5.16e	3.84f	2.16c	980.40cd	0.98cd	0.38bc	0.75defg	1.30defg
2	60	5.07ef	4.06ef	2.43b	847.40ef	0.85ef	0.44bc	0.54hij	0.92hij
4	0	5.68b	4.46bc	1.72e	592.20fg	0.59fg	0.36bc	0.47ijk	0.81ijk
4	15	5.51cd	4.41c	1.34f	1239.10abc	1.24abc	0.36bc	0.69fgh	1.18fgh
4	30	5.37d	4.37cd	2.79ab	831.00ef	0.83ef	0.36bc	0.69fgh	1.19fgh
4	45	5.57bc	4.42c	2.23bc	1273.40ab	1.27ab	0.43bc	0.71efgh	1.23efgh
4	60	5.59bc	4.34d	2.98a	928.10e	0.93e	0.42bc	0.85cdef	1.46cdef
6	0	5.54c	4.68abc	1.32g	1086.50bc	1.09bc	0.47bc	0.91cd	1.56bcd
6	15	5.91ab	4.82a	1.78d	1078.40bc	1.08bc	0.37bc	0.89cde	1.53cde
6	30	5.51cd	4.58b	2.31bc	1059.30c	1.06c	0.34c	1.09b	1.87b
6	45	6.01a	4.74ab	2.26bc	1141.30b	1.14b	0.36bc	103bc	1.77bc
6	60	5.82abc	4.46bc	2.88ab	1357.80a	1.35a	0.39bc	1.33a	2.28a
Significant($p≤0.05$)		ns	*	ns	***	***	ns	*	*
LSD		0.48	0.3	0.78	171.74	0.17	0.2	0.18	0.31
CV (%)		6.39	5.10	26.81	13.23	13.29	35.66	18.24	18.23

*N: B. Means followed by the same letter in a column are not significantly different at $p≤0.05$, *= $p≤0.05$, ** = $p≤ 0.01$, *** = $p≤ 0.001$, ns = non-significant ($p≤0.05$); P=phosphorus; EC= electric conductivity; NH_4N=ammonium nitrate; TOC=total organic carbon and OM= organic matter.*

4.11 Quadratic polynomial regression analysis for the yield measured parameters

Figures 16 to 23 show the response curve of yield component to P and lime application variable rates. All the measured yield parameters showed positive correlation in terms of response to P and lime application with R^2 values range of 0.20 to 0.98 for P application rates (Table 21) and values ranging 0.40 to 0.95 for lime application rates (Table 22). Based on the quadratic models, the estimated highest optimum fresh and oven-dried plant biomass as well as fresh root biomass was 55 mg pot^{-1}, 18 mg pot^{-1} and 0.7 mg pot^{-1} respectively at optimum estimated P rate of 517 mg, 406 mg and 203 mg P pot^{-1}. Similarly, the highest mean number of pods (0.12 pot^{-1}) and the mean number of seeds (0.20 pot^{-1}) per plant were achieved at estimated P rate of 9.1 and 45 mg P pot^{-1}, respectively while the estimated highest seed weight (0.045 g pot^{-1}) was achieved at 6 mg P pot^{-1}. Conversely, the predicted highest fresh plant biomass yield (38 mg pot^{-1}) was obtained at an optimum lime rate of 0.1 mg lime pot^{-1}. Also, the estimated optimum fresh (6.9 mg pot^{-1}) and oven dried root biomass (0.67 mg pot^{-1}) was obtained at estimated optimum lime rate of 3.6 mg and 30 mg lime pot^{-1}, respectively. In addition, the optimum mean number of pods per plant (0.011 pot^{-1}) from the model was achieved at lime application of 55 mg lime pot^{-1} while the predicted maximum pod weight per plant (0.1 mg pot^{-1}) was obtained at 106 mg lime pot^{-1}. Similarly, the predicted highest seed weight (2.6 mg pot^{-1}) was achieved at optimum of lime rate of 14 mg pot^{-1}.

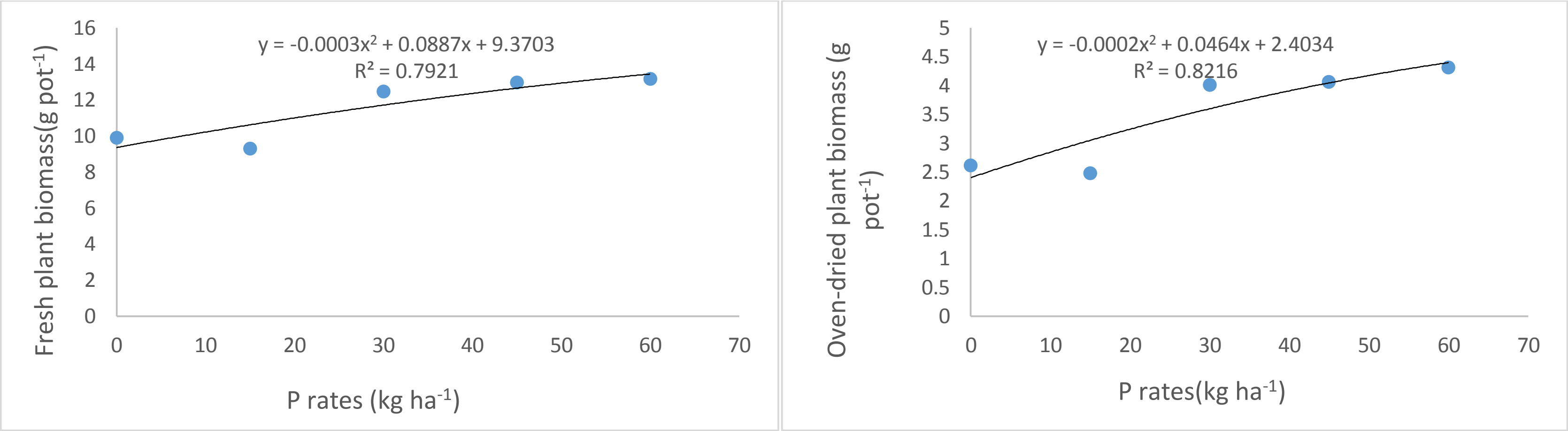


Figure 16: Quadratic polynomial of fresh (left) and oven-dried (right) plant biomass versus phosphorus rates

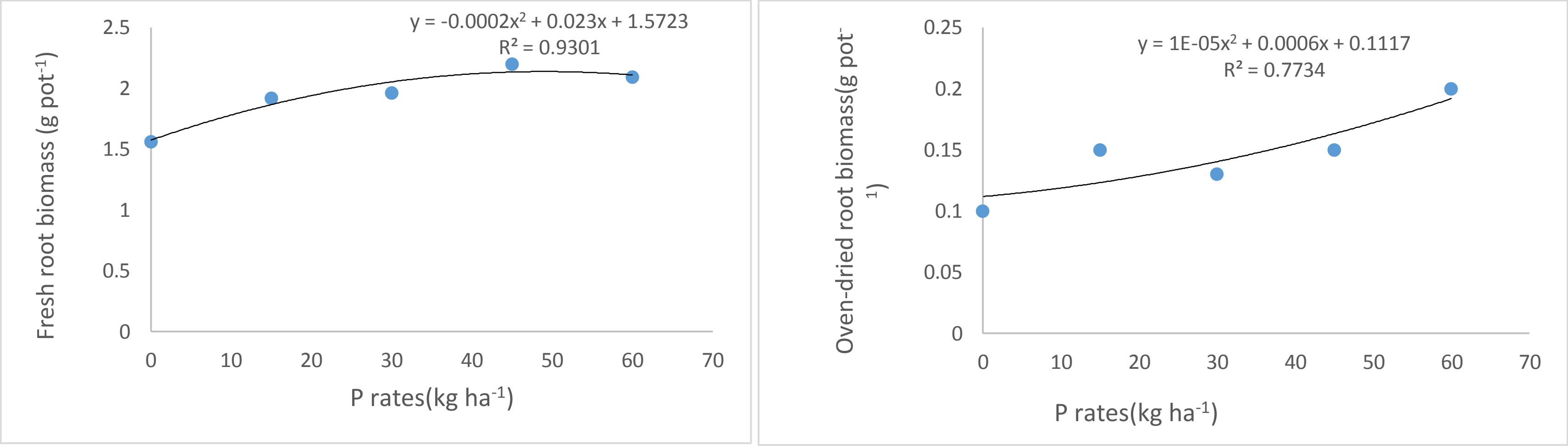


Figure 17: Quadratic polynomial of fresh (left) and oven-dried (right) root biomass versus phosphorus rates

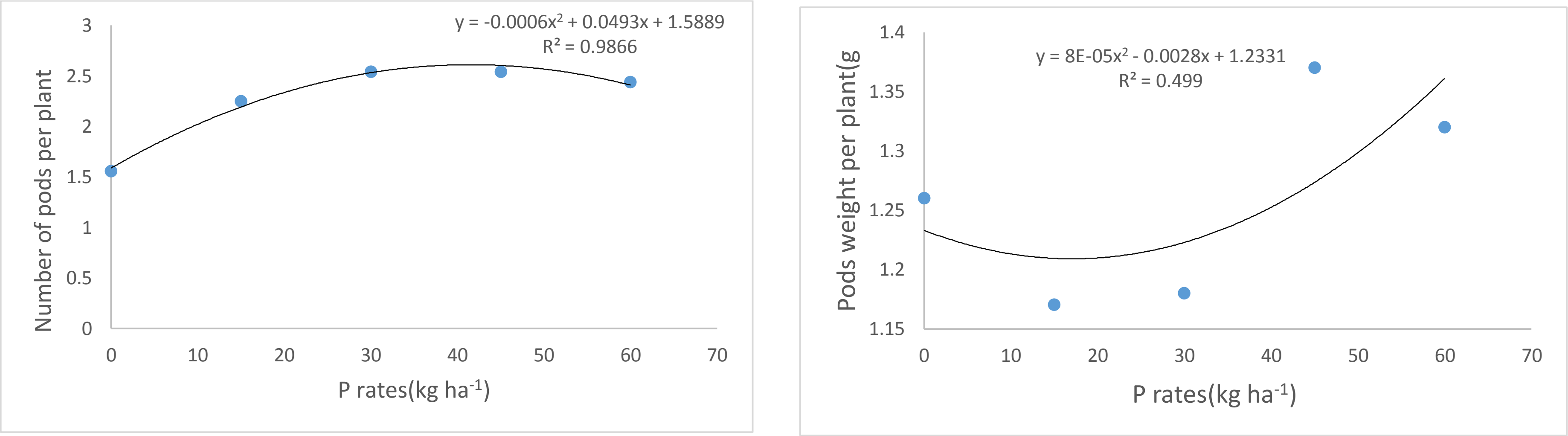


Figure 18: Quadratic polynomial of number (left) and weight (right) of pods per plant versus phosphorus rates

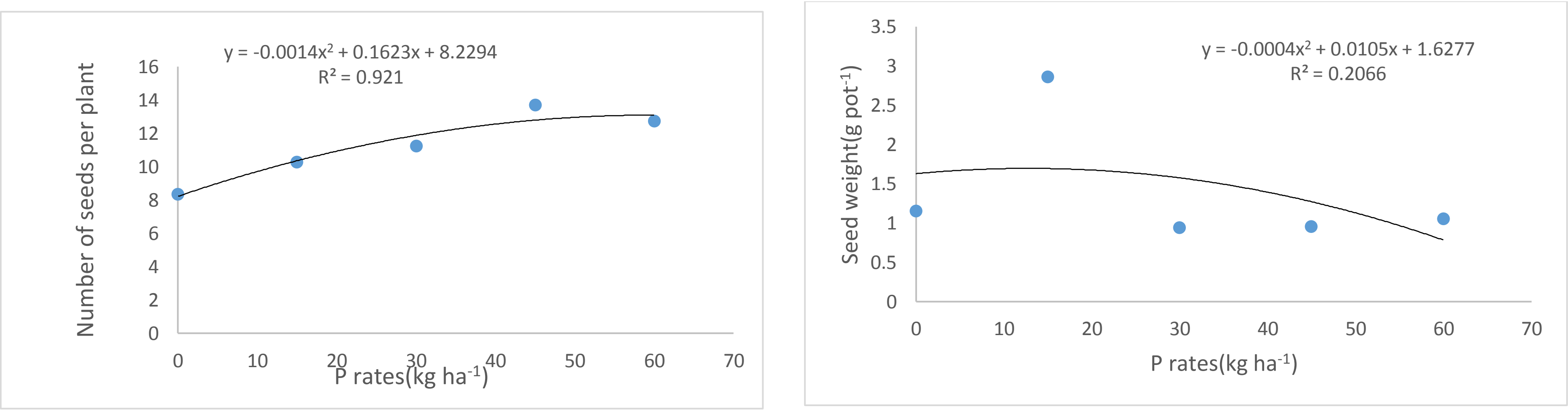


Figure 19: Quadratic polynomial of number (left) and weight (right) of seed versus phosphorus rates

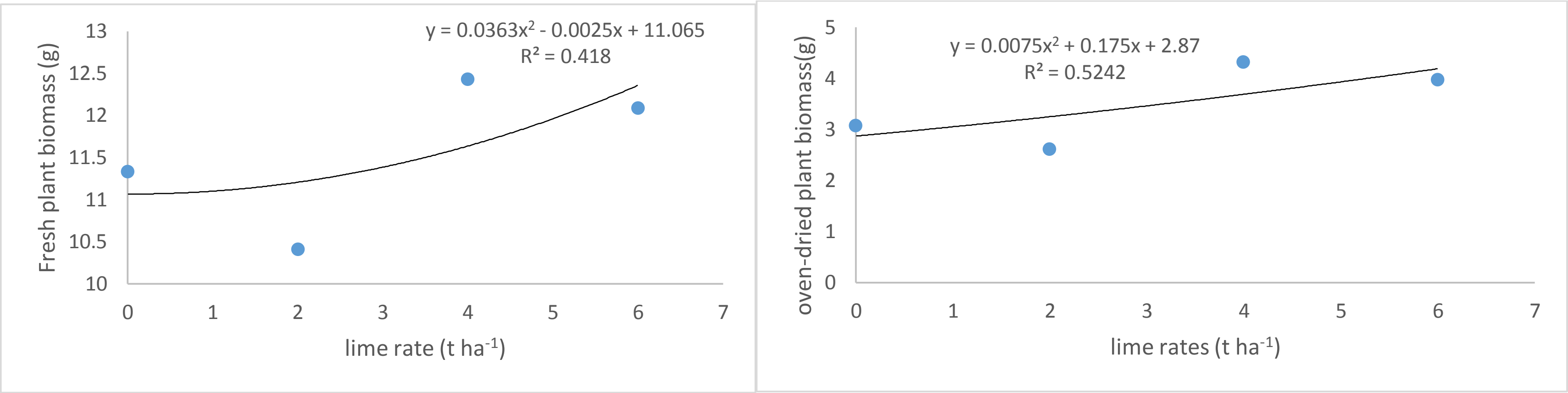


Figure 20: Quadratic polynomial of fresh (left) and oven-dried (right) plant biomass versus lime rates

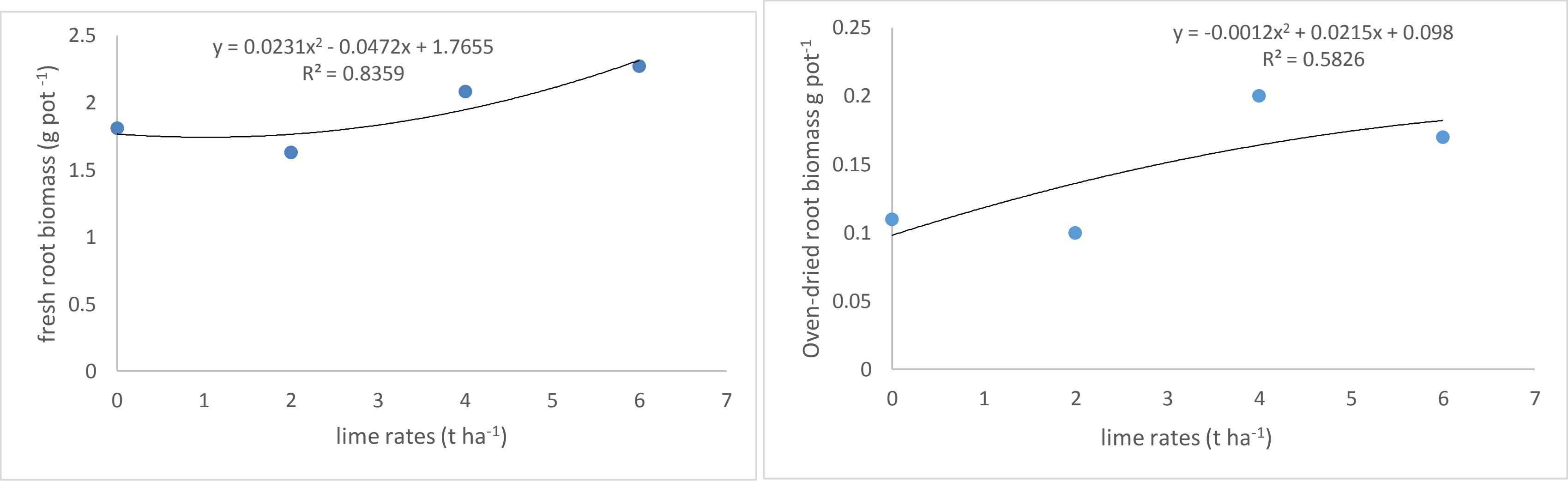


Figure 21: Quadratic polynomial of fresh (left) and oven-dried (right) root biomass versus lime rates

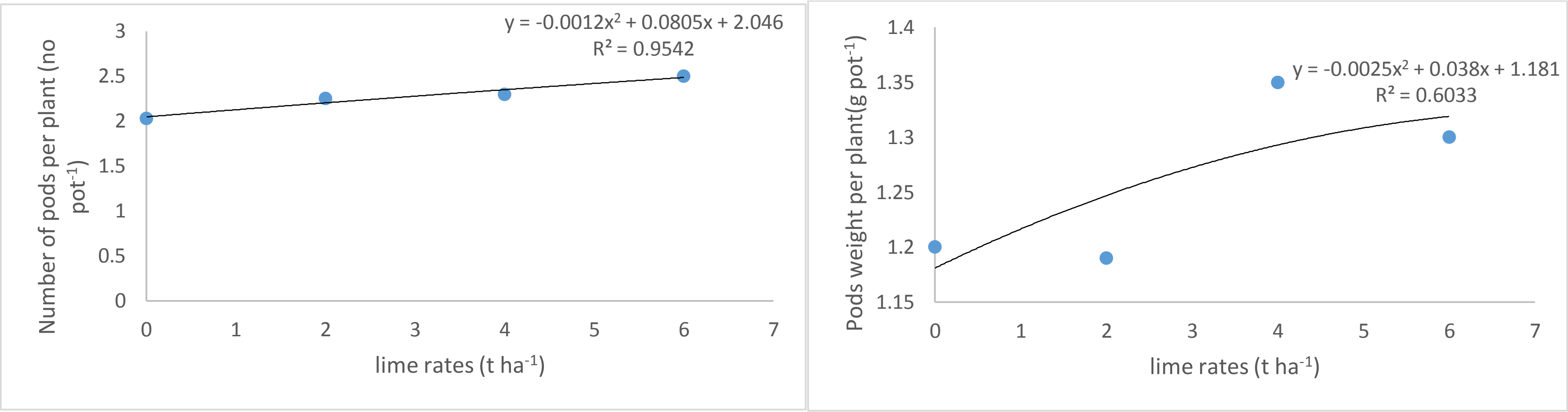


Figure 22: Quadratic polynomial of number (right) and weight (left) of pods per plant versus lime rates

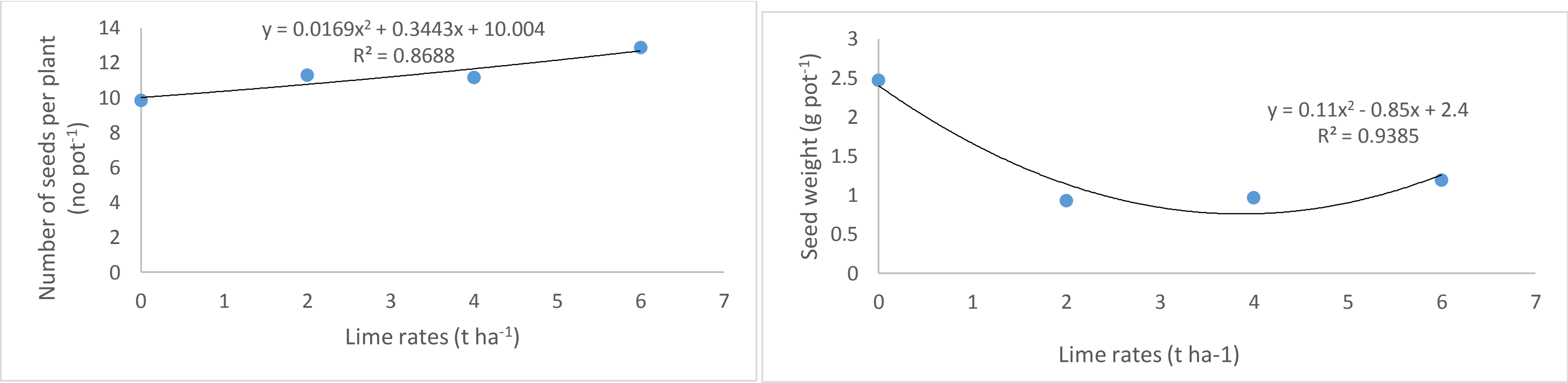


Figure 23: Quadratic polynomial number (top) and weight (bottom) of seeds per plant versus lime rates

Table 21: Quadratic equation of the various response parameters with the P rates as independent variable and the corresponding R^2 values of the equation, estimates of optimum P rate (X) and yield parameters (Y) based on the tested model

PARAMETER	REGRESSION EQUATION	R^2	p-value	Y	X
Fresh plant biomass	$y = 9.3703+0.0887x-0.0003x^2$	0.792	0.0000	15.93	147.83
Oven-dried plant biomass	$y = 2.4034+0.0464x-0.0002x^2$	0.822	0.0000	5.10	116.00
Fresh root biomass	$y = 1.5723+0.023x-0.0002x^2$	0.930	0.0007	2.23	58.00
Oven-dried root biomass	$y = 0.1117+0.0006x-1E05x^2$	0.773	0.0000	0.11	1.5
Number of pods per plant pot^{-1}	$y = 1.5889+0.0493x-0.0006x^2$	0.987	0.0000	2.60	41.08
Pods weight per plant	$y = 1.2331-0.0028x-8E05x^2$	0.499	0.0383	0.059	70
Number of seeds per plant pot^{-1}	$y = 8.2294+0.1623x-0.0014x^2$	0.921	0.0000	12.93	57.96
Seed weight	$y = 1.6277+0.0105x-0.0004x^2$	0.207	0.4840	1.70	13.13

p= significant value; R^2= measured response

Table 22: Quadratic equation of the various response parameters with the lime rates as independent variable and the corresponding R^2 values of the equation, estimates of optimum lime rate (X) and yield parameters (Y) based on the tested mode

PARAMETER	REGRESSION EQUATION	R^2	p-value	Y	X
Fresh plant biomass	$y = 11.065- 0.0025x+0.0363x^2$	0.418	0.0000	11.06	0.03
Oven-dried plant biomass	$y = 2.87+ 0.175x+0.0075x^2$	0.524	0.0000	1.85	-11.66
Fresh root biomass	$y = 1.7655- 0.0472x+0.0231x^2$	0.836	0.0000	1.74	1.02
Oven-dried root biomass	$y = 0.098+ 0.0215x-0.0012x^2$	0.583	0.0000	0.19	8.96
Number of pods per plant pot^{-1}	$y = 2.046+ 0.0805x-0.0012x^2$	0.954	0.0081	3.02	15.83
Pods weight per plant	$y = 1.181+ 0.038x-0.0025x^2$	0.603	0.0831	0.03	30.40
Number of seeds per plant pot^{-1}	$y = 10.004+ 0.3443x+0.0169x^2$	0.869	0.0019	24.03	-40.75
Seed weight	$y = 2.4 - 0.85x +0.11x^2$	0.939	0.4743	0.76	3.86

p= significant value; R^2= measured response

CHAPTER 5

DISCUSSION

5.1 Phenological attributes

Sole application of either P or lime did not affect the number of days to emergence in both planting seasons. This is because P and lime have no direct influence on crop emergence since germination processes depend mainly on the seed viability, adequate moisture, proper temperature and good aeration at the time of planting. This is supported by Ghaderi-Far et al. (2010) who emphasized that environmental factors such as temperature, pH, and soil moisture greatly affect seed germination and emergence; hence, justified the non-significant response of P and lime application on seed emergence during this study. Numbers of days to flower initiation, pods initiation, 100% flowering and 100% pod formation were not recorded during 2014 session due to cold damage to plants which led to early termination of the experiment. During 2014/15 planting, the duration (number of days) to flower initiation, pods initiation, and 100% pod formation were significantly reduced with high P (60 kg ha^{-1}) and lime (6 t ha^{-1}) rates including their interactions. This could be attributed to the fact that P is mobile in plants and is essential for cell division (Ayodele and Oso, 2014), which thus increases vegetative growth which stimulates early flowering, podding and maturity. High rate of lime application also reduces the duration to flowering and physiological maturity by decreasing toxicity effects of soil acidity (Legesse et al., 2013). These findings agree with Karikari et al. (2015) and Ndakidemi and Dakora (2007) who reported similar findings on cowpea. Ayodele and Oso (2014) reported that cowpea plants that flower earlier would better utilize available soil water and nutrients for pod formation, seed set and sustaining the pods to maturity before the dry season when water stress could be very severe.

5.2 Plant growth attributes

The 2013/14 evaluation of cowpea growth parameters such as plant height, stem diameter, number of trifoliate leaves, width of trifoliate leaves, length of trifoliate leaves and area of trifoliate leaves showed unstable response to P and lime application across all sampling dates. Most of the parameters did not show significant difference to P and lime at moderate to high application rates. However, all growth parameters were lowest without P and lime application for all sampling dates. This shows that cowpea plants slightly managed to withstand low greenhouse temperatures by responding to lime and P fertiliser application at varying sampling dates. Furthermore, this may possibly indicate that P fertiliser application and lime application may enhance plant tolerance to cold or winter damage under acid soil conditions.

The positive significant response of plant height and stem diameter to high application rates of P and lime during 2014/15 planting shown that cowpea plant utilized both P nutrition and lime benefits to increase plant vigour by overcoming adverse effect of soil acidity. Meena and Chand (2014) reported increased plant height of fodder cowpea by 12.3% with application of P up to 20 kg P_2O_5 ha^{-1}. The increased plant height and stem diameter at higher P application may be due to increased internodal length and accumulative effect of P in the process of cell division and balanced nutrition (Zhao, 2003). Castro and Crusciol (2015) reported increased plant height in soybean and maize with dolomitic lime application of 1.5 t lime ha^{-1} as compared to the control. The positive interactive effect of lime and P application on plant height and stem diameter was also confirmed by Kassa et al. (2014) in dry bean.

One of P deficiency effects was the reduction in the number of leaves, rate of leaf expansion and photosynthesis per unit leaf area in olives (Boussadia et al., 2010). In the present study it was observed that P application overcame such deficiency by increasing the number of trifoliate leaves, the width and length of trifoliate leaves and area of trifoliate leaves. These observations are in line with the findings of Nkaa et al (2014) who reported increased number and area of cowpea leaves with increasing P fertilization up 80 kg P ha^{-1} in the period of 11 weeks. Tairo and Ndakidemi (2013) also reported increased number of leaves, leaf area and leaf area index due to increase in P fertilization on soybean in both screen house and field experiments. Cowpea leaf parameters were also increased with increasing lime application and its interaction with P. Pimentel et al (2016) reported significant increase of number of pinnate and lanceolate leaves with interaction of P and lime application in Macaw palm (*Acrocomia aculeata* (Jacq.) Lodd. The high values of percent CV on selected cowpea growth parameters namely number and length of trifoliate leaves, biomass and cowpea root architectural characteristics mostly during 2013/14 was possibly attributed more to the cold and frost incidences that occurred at the critical growth stage of cowpea plants.

Samaee et al. (2003) and Pandey et al. (2008), respectively reported similarly high percent CV of 71.27% for pod width in olive and 99.81% for the number of pods per plant for ash gourd (*Benincasa hispida*), which attributed to environmentally dependent inherent traits expressions.

5.3 Chlorophyll content

External application of P proves to significantly increase the chlorophyll contents of legume crops. Chlorophyll is the outmost important pigment required for photosynthesis and amino acid synthesis (Hokmalipour and Darbandi, 2011). According to Uchida (2000), P regulates carbohydrate metabolism in plant leaves and plays important role in energy storage and transfer during photosynthesis for plant use during growth and reproductive stages. The chlorophyll content during flowering and pod formation was recorded high with application of 60 kg P ha^{-1} but did not differ statistically with other application rates. Such response may suggest that P application in this experiment could be increased above the rate of 60 kg P ha^{-1} in order to witness its significant effect on chlorophyll content of cowpea.

Nyoki and Ndakidemi (2016) reported that application of P alone without rhizobia inoculation decreased chlorophyll content of cowpea plants grown in screen house compared to the field experiment. However, the greatest value of chlorophyll content was recorded with the interaction of *B. japonium* supplied with 40 kg ha^{-1} relative to the control in the screen house. Nyoki and Ndakidemi (2016) further stated that there was limited amount of nitrogen in the small volume of soil in the pots compared with the field experiment where the plant roots can move far searching for nitrogen and consequently chlorophyll content of plant leaves was improved in both inoculated and un-inoculated treatments in the field trial. Mfilinge et al. (2014) reported that application of P at 30 kg ha^{-1} increased the total leaf chlorophyll content of three bush bean varieties grown in screen and field conditions. Thus, there may be a need to incorporate rhizobia inoculation, since the supply of P did not influence availability of mineral nitrogen (Table 10) and also to test the treatment effects of this experiment under field conditions.

Application of lime with or without P significantly increased the chlorophyll content of cowpea during both flowering and pod formation. The results are in conformity with those of Bambara and Ndakidemi (2009) who found that application of lime at 2 and 3 ton lime ha^{-1} increased the leaf chlorophyll content of dry bean by 14 and 22.3% respectively, as compared to the control in a glasshouse. The increment of chlorophyll content was due to the application of Ca^{2+} in the form of lime (Bambara and Ndakidemi 2009). According to Gabara et al. (2003) and Liu et al. (2011), calcium is essential for carbohydrate storage and synthesis in leaves and also play important role in water oxidation during the process of photosynthesis. Xiao Jun et al. (2004); and Bambara and Ndakidemi (2009) also reported significant increase of photosynthesis and photosynthetic efficiency due to adequate supply of Ca^{2+} in rice and dry bean, respectively. The positive effects of lime on soil include neutralizing of the toxicity effect of aluminium, increasing of P availability, increasing of pH dependent CEC resulting in absorption and hydrolysis of Ca^{2+} and Mg^{2+} for improved nutrient uptake by plants (Oluwatoyinbo et al. 2005).

5.4 Yield and yield components

During 2013/14 planting season, yield attributes such as number of pods per plant, pod weight per plant, number of seeds per plant and seed weight per pot were not recorded because plants were damaged by cold before reaching reproductive stage. However, the significant increment of number of pods per plant, pod weight per plant and number of seeds per plant in response to P application was observed during 2014/15 season. These results are in conformity with findings of Karikari et al. (2015) who reported that high P fertilization of 60 g P pot^{-1} applied as SSP increased number of pods, pod weight per pot and number of seeds in cowpea. Significant increases in the yield attributes following P application were also reported by Ndor et al. (2012) and Aduloju et al. (2009) on common bean and soybean, respectively. The significant effect of P fertiliser application on yield characters of cowpea could be attributed to the role of P in seed formation and grain filling (Haruna and Usman, 2013). Despite the increase in the above mentioned yield parameters, seed weight per pot was not significantly influenced by varying P application. The results contradict with Karikari et al (2015) who found that application of 40 and 60 kg P ha^{-1} P_2O_5 produced significantly higher seed weight compared to low application of 0 and 20 kg P ha^{-1} in cowpea. The poor response of seed weight to P fertilization suggests that P utilization despite the improved soil conditions following liming may have been hindered by other factors beyond P limitation. Such other factors may include micronutrient deficiency such as

Zn possibly due to poor mycorrhizae colonization. Nevertheless, Singh et al. (2011) also reported statistically similar seed weight with P application of 0, 20 and 40 kg P ha^{-1} in cowpea.

The significant effect of lime application on number pods per plant and number of seeds per pod could be due to the fact that application of lime increased concentration of soil available P, soil organic carbon and percentage of organic matter which attributed to vigorous plant growth and increased yield. The results are in line with the earlier findings of Bekere (2013) who reported that application of 2.6 t lime ha^{-1} $CaCO_3$ resulted in increased number of pods per plant and number of seeds per pod with or without inoculation of soybean with *Bradyrhizobia* bacteria. Wijanarko and Taufiq (2016) further related the significant increase of number of pods per plant and seed yield to the reduction of aluminium toxicity when lime was incorporated in soybean production. Findings in the present study are also supported by Costa and Rosolem (2007); Legesse et al. (2013) and Anetor and Akinrinde (2006) who indicated that lime application significantly increased yield attributes of legumes grown under acidic soils. Failure of pod weight and seed weight response to lime application and the non-significant effect of P x lime application on yield attributes could probably be due to the fact that main treatment effects and P x lime interaction did not have a significant influence on availability of mineral nitrogen in the soil (Table 7). Nitrogen is a very important macro nutrient largely involved in metabolic actions and protein synthesis, resulting in increased vegetative and reproductive growth, which can eventually leads to increased crops yield (Tripathi et al., 2015). Thus, there may be a need to increase application of lime above 6 t ha^{-1} to realise its effect on some of yield attributes of cowpea. The economic feasibility of such increases however, needs to be evaluated. Moreover, incorporation of rhizobia inoculation with P x lime would probably increase N availability under existing acid soil conditions.

Combined P and lime showed a positive and significant correlation with related parameters such as number of pods and seeds per plant, pod weight per plant and seed~~s~~ weight. Application of P fertiliser showed a strongly positive correlation on number of pods per plant (R^2=0.987) and number of seeds per plant (R^2=0.921) but weak correlation was observed with seed weight (R^2=0.207). This suggests that the production of greater number of pods per plant and number of seeds per pod does not guarantee high seed weight at higher P fertiliser application since some of these seeds may be poorly formed (pod abortion). The observed poor and/or negative response of the number of seeds to P application may be related to genetic trait. Kumar and Hirochika (2001) and Kamel and Abbas (2012) reported similar findings concerning the number of pods in cowpea and chickpea, respectively. Results of the present study indicated that P application at the rate of 40 kg ha^{-1} and greater enhances cowpea seed weight while lime rate of 4 t ha^{-1} or more on soil with pH of 3.82 similarly promoted increase cowpea yield.

5.5 Biomass production

Accumulation of oven dried root biomass during the 2013/14 was increased in soil pots without P whist the fresh root biomass did not respond to P application as opposed to 2014/15 planting season. This was probably due to cold damage to cowpea plants which could have restricted root biomass accumulation in the off season. According to Hatfield et al. (2011), the reduction in biomass could be due to minimum air temperature during the night time which reduces plant respiration rates. The positive increment in fresh and oven-dried root biomass with P application during the two planting seasons concurred with previous findings reported on cowpea (Nkaa et al., 2014) and soybean (Shujie and Yunfa, 2011). Similar findings were reported by Kongpun et al (2011) who reported that shoot dry weight of cowpea was increased due to high shoot P concentration following 141 mg P pot^{-1} application. Plant biomass is also an important factor for soil fertility amelioration when ploughed into the soil as crop residues in the field.

Contrary to the poor (negative) responses of most of the measured parameters to increased lime rates observed during 2013/14, increased root and fresh biomass was observed during 2014/15 season. The negative responses characterized by stunted plant growth were possibly triggered by early extreme cold winter witnessed that led to frost damage during that season. On the other hand, the increased root and biomass reported in 2014/15 is in agreement with Oyeyiola et al. (2014) and may be attributed to early planting and better soil environment created for cowpea growth through the lime application that favoured improved soil pH and P availability. The regression analysis showed positive and significant correlation on biomass in respect to P and lime application. P showed a very strong correlation on fresh root biomass (R^2=0.9301), as the P content increases the biomass also increases. In support, Kugblenu et al. (2014) have shown that low P decreases biomass. Achakzai and Kayani (2002) and Bekere et al. (2012) strongly highlighted the direct relationship of P availability to biomass yield and shoot and root dry matter yield of soyabean. A significant quadratic relationship was found between lime application and yield biomass. However oven-dried plant biomass showed negative prediction on lime application this could be due to low amount of lime rate. Similarly, Nkheloane and Marake (2010) emphasized that increase in lime rate results in increase in plant yield and significant effects of positive quadratic relationship. Negative response can be viewed if more lime is added. Goulding et al. (2008) suggested that soil pH should be maintained at 6 to 6.5 to maximize nutrient availability and yield by applying correct and suitable lime amount to maintain soil acidity.

5.6 Root attributes

Adequate supply of P in the soil is associated with increased root development to explore soil nutrients and moisture. During the 2013/14 the angle of adventitious roots, taproot at 10cm, 1.5 mm branching density at 10 cm and deep score were recorded the highest with 45 kg P ha^{-1}. In 2014/15, P application only affected the stem diameter, number of nodules per pot and 3rd branching roots. In contrast to the off season results, the above mentioned parameters were significantly increased with low to moderate application of 15 and 30 kg P ha^{-1}. The results are in line with Miller et al. (2003) who found that under low soil P availability, P-efficient common bean genotypes showed superior growth of adventitious root, increased taproot diameter, basal roots and lateral branching of adventitious roots. Alloush (2003) reported that branching density of chickpea was significantly increased in response to P stress compared to P sufficient plants, but also found that the lateral root branches were shorter in P deficit plant as compared to high P plants. Zhu and Lynch (2004) reported extensive lateral rooting systems, increased root hairs and adventitious roots as important adaptive traits that enhance P uptake from low P soils. Application of P in this study did not have a significant influence on soil pH. Thus, lack of response to P fertilizer application observed on most cowpea root parameters during the two seasons was probably due to acid toxicity and P fixation especially under pots applied with low P rates. The negative effects of soil acidity on root morphological characteristics and development are well reported (Kidd and Proctor, 2011; Haling et al., 2011). There may be a need to test various cowpea genotypes under similar environmental conditions since responses of root characteristics to P application differ across crop genotypes (Kugblenu et al., 2014; Gahoonia. and Nielsen, 2004).

Root parameters such as angle of ABR, NOBR, SD, 3rd BD, SS, DS and NOND were significantly increased at lime application rate not greater than 2 t ha^{-1} during the 2013/14 planting season. However in 2014/15, root parameter ABR, NOBR, TRD5, BD10, NOND and 3rd BD were significantly increased with increasing lime application. Results of study by Onwuka et al. (2009) contradict the findings during 2013/14 season, which revealed increased $CaCO_3$ in root parameters of maize following an increase in lime rate which also aligned with those of 2014/15 season.

5.7 Soil physico-chemical properties

Improving soil fertility is a basic practice to achieve long term food security while mitigating environmental degradation (Lal, 2010). The pre-harvest soil properties indicated that the soil used for this study was strongly acidic, poor in macro nutrients and rich in toxic elements such as Al. However, the chemical soil analyses after harvest indicated that P application had no significant influence on soil pH (H_2O and KCl). The results agree with those of Aliyu and Singh (2008) who stated that P application up to the rate of 75 kg P ha^{-1} did not have a significant effect on soil pH in cowpea production. Also, Opara-Nadi et al. (2000) indicated that inorganic fertiliser treatments either retained same or decreased soil pH compared with control especially under prevailing acid soil conditions where P fixation can be negatively affected. The significant increment of soil P availability with increasing P application is in conformity with the early findings of Anetor and Akinrinde (2006) who reported that application of single super phosphate resulted in increased soil P ranging from 40.41 to 47.23 mg kg^{-1} compared to the control with soil P ranging from 11.02 to 12.40 mg kg^{-1}. Despite this positive increase, the values for available P varied from 1.46 to 2.71 mg kg^{-1} which according to Aune and Lai (1995) are lower than critical soil available P of 8.0 mg kg^{-1} required for proper growth and development of cowpea.

Venter et al. (2001) revealed that approximately 5 million ha of South African agricultural soils are severely acidified while a further 11 million ha are moderately acidified. The implication of these statistics is that soil acidity is a serious problem on crop lands with undesirable consequences on soil properties such as reduction in cation exchange capacity, increases Al^{3+} and Mn^{+} toxicity and decrease soil microbial activity which ultimately results in decreases crop productivity. Soil organic matter, organic carbon and electrical conductivity influences physical, chemical and biological soil properties that relate to water absorption, available water content, nutrient retention and availability (Ayodele and Oso, 2014; Nkaa et al. 2014). Application P at higher rates significantly affected electric conductivity, soil organic carbon and percentage of organic matter. These findings are in agreement with those reported by Eghball (2002) and Yang et al. (2012).

Lime is generally used to ameliorate soil acidification in agricultural production. Soil pH which is a primary indicator for soil acidity was significantly increased by increasing lime application. The increment is probably due to the fact that liming materials contain basic cations and basic anions (CO_3^{-2}) that are able to pull H^+ from exchange sites to form water and carbon dioxide, thereafter cations occupy the space left behind by H^+ on the exchange (Fageria, et al*.,* 2007). Onwuka et al (2009) found that the soil pH was significantly increased from 5.20 to 8.04 with application 8 t ha^{-1} of calcium carbonate. Kisinyo et al. (2015) also reported that lime at the rates of 0.77 and 1.55 t ha^{-1} resulted in increased pH values of 5.7 and 6.0, respectively as compared to the value of 5.44 with the control. Increasing lime application by 6 t ha^{-1} significantly increased electric conductivity, percent soil organic carbon and organic matter contents (Wijanarko and Taufiq, 2016; Moreira and Fageria, 2010; Hazelton and Murphy, 2007). Insignificant effect of lime with or without P application on soil available P and mineral nitrogen could be attributable to the slow solubility of lime and hence low mobility within the soil (Yorst and Ares, 2007) and given the fact that P is also immobile in the soil. However, the result presented by Kisinyo (2016) shows that increasing both P and lime increased soil available P while Moreira et al., (2008) reported increase of minerals with both application of P and lime. Interactive effect of P and lime application increased soil pH, electrical conductivity, soil organic carbon and percentage of organic matter.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

Two similar studies showed differential responses to P and lime application rates during different seasons (2013/14 and 2014/15) as plant growth, phenological data and root distribution were not similar even when similar treatments and soil were utilised. The results of soil analysis after planting showed a significant increase in P and lime application resulted in increase in soil pH, available-P, electric conductivity, soil organic carbon, total organic matter and mineral nitrogen. The highest pH (H_2O) of 5.76 was recorded when lime was applied as 6 t lime ha^{-1} while the lowest value of 4.63 with no lime application. Furthermore, 2.71 mg kg^{-1} was recorded as the highest P value at 60 P kg ha^{-1} and the lowest value of 1.46 mg kg^{-1} was recorded at no P application. Inconsistent growing pattern during 2013/14 was observed as they showed poor growth which influences phenological data, yield components and root growth. This was attributed to winter experienced towards the peak of the growing season since most parameters such as plant height, stem diameter, number of leaves, plant biomass, root biomass and etc. showed poor response to P and lime application.

Also root attributes showed a poor response to P and lime application during 2013/14 since most parameters showed non-significant response to both P and lime application rates, excluding number of nodule, 1.5 mm branching density at 10 cm and deep score as they both showed better response as compared to AAD; ABR; SD; TRD at 5, 10, 15 and 20 cm; 3rd BD; 1.5 mm BD at 5 cm; SS an NOBR. Conversely, 2014/15 parameters showed a better response on the same parameters since mean value of 15 number of nodules was observed during 2014/15 on lime application of 4 and 6 t ha^{-1} while only mean of 1 of nodule was observed. In addition P application rate also showed a better response since mean value of 15 of nodules was also observed in 2014/15 as compared to 2013/14. However, during the 2014/15 experiment the duration to flower initiation, plant height, number of leaves per plant, stem diameter, root biomass, number of seeds per plant and etc. were all significantly increased by increase in P and lime rates. Based on the two studies, 2014/15 planting season showed that application of 60 kg P ha^{-1} and 6 t ha^{-1} of lime appeared to be the optimum rate for cowpea growth on low P soil as most plant growth, yield and root parameters showed to produce the highest in those rates.

Application of P and lime combined results in better cowpea growth, root distribution and yield as compared to the singly application. The 2013/14 and 2014/15 planting buttressed the P increase in the soil which was made available through lime application. Application of lime to acidic soil has profound to influence soil condition through reduction of toxic nutrients which fixes P. This study recommends the combined use of any P and lime sources combined rather than separate application on acidic soil. Application P and lime rates lower than 60 kg P ha^{-1} and 6 t lime ha^{-1}, respectively is therefore recommended to grow cowpea around the Sokhulumi area also low in soil P. The combination of both P and lime rates helped to improve the soil pH, P availability as well as other essential soil properties and ultimately, increase cowpea growth and yield. Furthermore, results of this study also suggest breeding of cowpea varieties which are acid and cold tolerant in order to reduce problem of food insecurity in most undeveloped countries. Since cowpea showed some degree of tolerance to cold stress, it suggest that late planting is possible as off season crop for leaf consumption only in many rural poor households since the cold stress only delays flowering. Future research could also focus on determining the biological nitrogen fixation of cowpea under the prevalent soil conditions since the application of both P and lime affected nodulation of cowpea in this study.

LIST OF REFERENCES

Abayomi, Y.A. and T.O. Abidoye. 2009. Evaluation of cowpea genotypes for soil moisture stress tolerance under screen house conditions. *African Journal of Plant Science,* 3: 229-237.

Achakzai, A.K.K. and S.A. Kayani. 2002. Effect of fertiliser and inoculation on nodulation, growth, yield and yield attributes and correlation studies of pot culture soybean. *Pakistan Journal of Agricultural Research,* 18: 83-93.

Adeyemi, S.A., Lewu, F.B., Adebola, P.O., Bradley, G. and A.L. Okoh. 2012. Protein content variation in cowpea genotypes (*Vigna unguiculata L. Walp*.) grown in the Eastern Cape province of South Africa as affected by mineralised goat manure. *African Journal of Agricultural Research*, 7: 4943-4947.

Aduloju, M.O., Mahmood, J. and Y.A. Abayomi. 2009. Evaluation of Some soya-beans (*GlyCine max (L.) Merril*) g\Genotypes for adaptability to a Southern Guinea Savanna

Agbenin, J.O. and S.O Igbokwe. 2006. Effect of soil-dung manure incubation on the solubility and retention of applied phosphate by a weathered tropical semi-arid soil. *Geoderma*, 133: 191-203.

Aikins, S.H.M. and J.J. Afuakwa. 2010. Effect of Four Different Tillage Practices on Cowpea Performance. *World Journal of Agricultural Sciences,* 6: 644-651.

Ajiboye, B., Akinremi, O.O., Hu, Y. and D.N. Flaten. 2007. Phosphorus speciation of sequential extracts of organic amendments using nuclear magnetic resonance and X-ray absorption near-edge structure spectroscopies. *Journal of Environmental Quality*, 36: 1563-1576.

Ali, H., Randhawa, H.A. and M. Yousaf. 2004. Quantitative and qualitative traits of sunflower (*Helianthus annuus L.*) as influenced by planting dates and nitrogen application. *International Journal of Agriculture and Biology,* 6: 410-412.

Aliyu, L.S. and A. Singh 2008. Yield and yield components of cowpea (*Vigna unguiculata (L.) Walp.)* as influenced by Sokoto Phosphate Rock and placement method in the Semi-arid zone of Nigeria. *Nutrient Cycling in Agro-ecosystem,* 81:255-265.

Alloush, G.A. 2003. Dissolution and effectiveness of phosphate rock in acidic soil amended with cattle manure. *Plant and Soil,* 251: 37-46.

Anderson, J.M. and J.S.I. Ingram. 1996. Tropical soil biology and fertility: A Handbook of Methods. 2nd Edition. CAB International Publication. pp. 221.

Andraski, T.W. and L.G. Bundy. 2003. Relationships between phosphorus levels in soil and in runoff from corn production systems. *Journal of Environmental Quality*, 32: 310-316.

Anetor, M. O. and E.A. Akinrinde. 2006. Response of Soybean (*Glycine max* (L.) Merrill) to lime and phosphorus fertiliser treatments on an acidic Alfisol of Nigeria. *Pakistan Journal of Nutrition, 5*: 286-293.

Appunu, C., Reddy, L.M.L., Reddy, C.V.C.M., Sen, D. and B. Dhar. 2009. Symbiotic diversity among acid-tolerant bradyrhizobial isolates with cowpea. *Journal of Agricultural Sciences,* 4: 126-131.

Araújo, A.P., and M.G. Teixeira. 2008. Relationships between grain yield and accumulation of biomass, nitrogen and phosphorus in common bean cultivars. *Brazilian Journal of Soil Science,* 32: 1977-1986.

Araújo, M.B., Pearson, R.G., Thuiller, W. and M. Erhard. 2005. Validation of species-climate impact models under climate change. *Global Change Biology*, 11: 1504-1513.

Asiwe, J.A.N. 2009a. Insect mediated outcrossing and gene-flow in cowpea (*Vigna unguiculata (L.) Walp*): Implication for seed production and provision of containment 230.structures for genetically transformed cowpea. *African Journal of Biotechnology,* 8: 226-230.

Asiwe, J.A.N. 2009b. Needs assessment of cowpea production practices, constraints and utilization in South Africa. *African Journal of Biotechnology*, 8: 5383-5388.

Asuming-Brempong, S., Wiafe, Y. and K. Aggrey-Martin. 2013. Nodulation of cowpea (*Vigna unguiculata [L.] walp*) at different levels of phosphorus in a Typic Kandiustalf. *Agricultural Science Research Journal*, 3: 387- 394.

Aune, J.B. and R. Lai. 1995. The Tropical Soil Productivity Calculator-a Model for Assessing Effects of Soil Management Ion Productivity. In: Soil Management Experimental Basis for Sustainability and Environmental Quality, Lai, R. and B.A. Stewart (Eds.). Chapter 17, Lewis Publishers, Boca Raton, FL., USA.

Ayodele, O.J. and A.A. Oso. 2014. Cowpea responses to phosphorus fertiliser application at Ado-Ekiti, South-West Nigeria. *Journal of Applied Science Agriculture,* 9: 485-489.

Ayuke, F.O., Karanja, N.K. and S.W. Bunyasi. 2007. Evaluating effect of mixtures of organic resources on nutrient release patterns and uptake by maize. In: Bationo et al, (eds). Advances in integrated soil fertility management in Sub-Saharan Africa: Challenges and Opportunities. Springer. pp. 833-844.

Bado, B.V., Bationo, A. and M.P. Cescas. 2006. Assessment of cowpea and groundnut contributions to soil fertility and succeeding sorghum yields in the Guinean savannah zone of Burkina Faso (West Africa). *Biology and Fertility of Soils*, 43:171-176.

Baldwin, J.C., Athikkattuvalasu, S.K., and K.G. Raghothama. 2001. LEPS2, a phosphorus starvation-induced novel acid phosphatase from tomato. *Plant Physiology*, 125: 728-737.

Bambara, S. and P.A. Ndakidemi. 2009. Effect of rhizobium lime and moleybdenum on photosynthesis and chlorophyll content of *Phaseolus vulgaris L. African Journal of Microbiology Research*, 3: 791-798.

Befekadu, D. and N. Berhanu. 2000. Annual report on the Ethiopian economy, 1999/2000. Addis Ababa: Ethiopian Economic Association.

Bekere, W., Wolde-meskel, E. and T. Kebede. 2012. Growth and nodulation response of soybean (*Glycine max* L.) to *Bradyrhizobium* inoculation and phosphoruslevels under controlled condition in South Western Ethiopia. *African Journal of Agricultural Research,* 30: 4266-4270.

Beukes, D.J. 1995. Benefits from identifying and correcting soil acidity in agriculture. ISBN 1 86849 021 1. Agricultural Research Council, Pretoria, South Africa.

Bierman, P.M. and J.R. Carl. 2005. Nutrient cycling and maintaining soil fertility. Fruit and vegetable crop systems, University of Minnesota.

Bogayoko, M., Alvey, S., Nuemann, G. and A. Buerkert. 2000. Root-induced increases in the soil pH and nutrients availability to field-grown cereals and legumes on acid sandy soils of Sudano-Sahelian West Africa. *Plant soil*, 227: 117-217.

Bolan, N.S., Adriano, D.C. and D. Curtin. 2003. Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Advances in Agronomy,* 78: 215-272.

Bouker, O. and F. Fatokun. 2007. Strategies in cowpea breeding. In: Tadele, Z. (Ed.), New approaches to plant breeding of orphan crops in Africa. Proceedings of an international conference, 19-21 September 2007. , Bern, Switzerland. pp. 69.

Boussadia, O., Steppe, K., Zgallai, H., Ben El Hadj, S., Braham, M., Lemeur, R. and M.C. Van Labeke. 2010. Effects of nitrogen deficiency on leaf photosynthesis, carbohydrate status and biomass production in two olive cultivars 'Meski' and 'Koroneiki'. *Scientia Horticulturae,* 123: 336-342.

Brady, N. and R. Weil. 2002. The Nature and Properties of Soils, 13th Edition. Prentice Hall. Upper Saddle River, New Jersey. pp. 921-960.

Bremner, J.M. 1960. Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, 55: 11-33.

Buni, A. 2014. Effects of liming acidic soils on improving soil properties and yield of haricot bean. *Journal of Environmental and Analytical Toxicology*, 4: 1-4.

Butterworth, M.H., Semenov, M.A., Barnes, A., Moran, D., West, J.S. and B.D.L. Fitt. 2009. North-South divide: contrasting impacts of climate change on crop yields in Scotland and England J. R. Soc. Interfacedoi:10.1098/rsif.2009. 0111. Published online.

Campillo, C., Prieto, M.H., Daza, C., Moñino, M.J. and M.I. García. 2008. Using digital images to characterizing the canopy coverage and light interception in a processing tomato crop. *Hortscience*, 43: 1780-1786.

Castro, G.S.A. and C.A.C. Crusciol. 2015. Effects of surface application of dolomitic limestone and calcium-magnesium silicate on soybean and maize in rotation with green manure in a tropical region. *Bragantia,* 74: 311-321.

Costa, A. and C.A. Rosolem. 2007. Liming in the transition to no-till under a wheat–soybean rotation. *Soil and Tillage Research,* 97: 207-217.

Cordell, D., Drangert, J.O. and S. White. 2009. The story of phosphorus: global food security and food for thought. *Global Environmental Change,* 19: 292-305.

Crozier, C.R. and D.H. Hardy. 2003. Soil Facts: Soil acidity and liming-basic information for farmers and gardner's. Publication AGW-439-51, North Carolina Cooperative Extension. Available online: http://www.soil.ncsu.edu/publications/soilfacts/AG-439-51).

Dam-ampai, S., Nilnond, C. and C. Onthong. 2007. Effect of some soil amendments on soil properties and plant growth in southern Thailand acid upland soil. *Songklanakarin Journal of Science and Technology,* 29: 117-131.

Dinar, A., Hassan, R., Mendelsohn, R. and J. Benhin. 2008. Climate change and agriculture in Africa: impact assessment and adaptation strategies, EarthScan, London.

Department of Agriculture, Forestry and Fisheries (DAFF). 2011. Directrorate Plant Production. Production guide for Cowpea. Available online at http://www.nda.agric.za Accessed 26/03/2016.

Department of Agriculture, Forestry and Fisheries (DAFF). 2008. Cultivating cowpeas. Available online at http://www.daff.gov.za Accessed 24/08/2016.

Dube, E. and M. Fanadzo. 2013. Maximising yield benefits from dual-purpose cowpea. *Food security*, *5*: 769-779.

Dube, E.D.N., Madanzi, T., Kapenzi, A. and E. Masvaya. 2014. Root Length Density in Maize/Cowpea intercropping under a basin tillage system in a semi-Arid Area of Zimbabwe. *American Journal of Plant Sciences,* 5: 1499-1507.

Eghball, B. 2002. Leaching of phosphorus fractions following manure and compost applications*. Communications in Soil Science and Plant Analysis* (In review).

Egli, D.B. and W.P. Bruening. 2006. Temporal profiles of pod production and pod set in soybean. *European Journal of Agronomy*, 24: 11-18.

Emechebe, A.M. and S.T.O. Lagoke. 2002. Recent advances in research on cowpea diseases. In: Fatokun, C.A., Tarawali, S.A., Singh, B.B., Kormawa, P.M., and M. Tamo. (eds). Challenges and opportunities for enhancing sustainable cowpea production. Proceedings of the World Cowpea Conference III held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 4-8 September 2000. IITA, Ibadan Nigeria, pp. 94-123.

Epstein, E, and A.J. Bloom. 2005. Mineral Nutrition of Plants: Principles and Perspectives. Second Edition. Sinauer.

Fageria, N.K. and V. C. Baliger. 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. *Advances in Agronomy*, 99:345-399.

Fageria, N.K., Castro, E.M. and V.C. Baligar. 2004. Response of upland rice genotypes to soil acidity. In: M.J Wilson et al. (eds.), The Red Soils of China. Springer Netherlands, pp. 219-237.

Fageria, N.K., Baliger, V.C. and R.W. Zobel. 2007. Yield, nutrient uptake and soil chemical properties as influenced by liming and boron application in a no-tillage system. *Communication in Soil Science and Plant Analysis,* 38: 1637-1652.

Ferguson, B.J., Indrasumunar, A., Hayash, I.S., Lin, M.H., Lin, Y.H., Reid, D.E. and P.M. Gresshoff. 2010. Molecular analysis of legume nodule development and auto regulation. *Journal of International Plant Biology*, 52: 61-76.

Fertiliser Society of South Africa (FSSA). 2007. Fertiliser handbook. 6th revised edition. The Fertiliser Society of South Africa. pp. 298.

Fey, M.V. 2001. Acid soil degradation in South Africa: A threat to Agricultural productivity. *Fertiliser Society of South Africa Journal,* 1:37-41.

Food and Agricultural Organisation (FAO). 2005. Cowpea production database for Nigeria, Available online at http://www.faostat.fao.org pdf Accessed 02/04/2016.

Gabara, B., Sklodowska, M., Wyrwicka, A., Glinska, S. and M. Gapinska. 2003. Changes in the ultrastructure of chloroplasts and mitochondria and antioxidant enzime activity in *Lycopersicon esculentum Mill* leaves sprayed with acid rain. *Plant Science,* 164, 507-516.

Gahoonia, T.S. and N.E. Nielsen. 2004. Root traits as tools for creating phosphorus efficient crop varieties. *Plant Soil,* 260: 47-57.

Gahoonia, T.S., Asmar, F., Giese H., Nielsen, G.G. and N.E. Nielsen. 2000. Root-released organic acids and phosphorus uptake of two barley cultivars in laboratory and field experiments. *European Journal of Agronomy*, 12: 281-289.

Ge, Z., Rubio, G., and L.P. Lynch. 2000. The importance of root gravitropism for inter-root competition and phosphorus acquisition efficiency: Results from a geometric simulation model. *Plant Soil*, 218: 159-171.

Gbetibouo, G. and R. Hassan. 2005. Economic impact of climate change on major South African field crops: A Ricardian approach. *Global and Planetary Change,* 47:143-52.

George, T.S., Turner, B.L., Gregory P.J. Cade-Menun B.J., and A.E. Richardson. 2006. Depletion of organic phosphorus from Oxisols in relation to phosphatase activities in the rhizosphere. *European Journal of Soil Science*, 57:47-57.

Gerke, J., Beissner, L. and W. Römer. 2000. The quantitative effect of chemical phosphate mobilization by carboxylate anions on P uptake by a single root. II. The importance of soil and plant parameters for uptake of mobilized P. *Journal of Plant Nutrition and Soil Science,* 163: 213-219.

Ghaderi-Far, F., Gherekholoo, J. and M. Alimagham. 2010. Influence of environmental factors on seed germination and seedling emergence of yellow sweet clover *(Melilotus officinalis)*. *Planta Daninha*, 28: 13-21.

Gichangi, E.M. and P.N.S. Mnkeni. 2009. Effects of goat manure and lime addition on phosphate sorption by two soils from the Transkei Region, South Africa. *Communication in Soil Science and Plant Analysis*, 40: 3335-3347.

Giller, K.E. 2001.Nitrogen fixation in tropical cropping system. 2nd edition. CAB International.

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedure for agricultural research. 2nd edition. Wiley. New York. pp. 241-271.

Goulding, K., Jarvis, S. and A. Whitmore. 2008. Optimizing nutrient management for farm systems. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 363: 667-680.

Haling, R.E., Simpson, R.J., Lambers, H. and A.E. Richardson. 2011. Effect of soil acidity, soil strength and macro-pores on root growth and morphology of perennial grass species differing in acid-soil resistance. *Plant, Cell and Environment,* 34: 444-456.

Haruna, I.M. and A. Usman. 2013. Agronomic efficiency of cowpea varieties (*Vigna unguiculata (L.) Walp*) under varying phosphorus rates in Lafia, Nassarawa State, Nigeria. *Asian Journal of Crop Science,* 5: 209-215.

Hatfield, J.L. and J. H. Prueger. 2015. Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes,* http://dx.doi.org/10.1016/j.wace.2015.08.001i.

Hatfield, J.L., Boote, K.J., Kimball, B.A., Ziska, L.H., Izaurralde, R.C., Ort, D., Thomson, A.M. and D.W. Wolfe. 2011. Climate impacts on agriculture: Implications for crop production. *Agronomy Journal,* 103: 351-370.

Hazelton, P.A. and B.W. Murphy. 2007. Interpreting Soil Test Results: What do all the numbers mean. CSIRO Publishing, Collingwood, Victoria. pp. 160.

Hedley, M.J. and M.J. McLaughlin. 2005. Reactions of phosphate fertilisers and by-products in soils. pp.181-252. In: J.T. Sims & A.N. Sharpley (eds). Phosphorus: Agriculture and the Environment. Agronomy Monograph no 46, ASA-CSSA-SSSA, Madison, WI, USA.

Hinsinger, P., Plassard, C., Tang, C., and B. Jaillard .2003. Origins of root-mediated pH changes in the rhizosphere and their response to environmental constraints: A review. *Plant and Soil*, 248: 43-59.

Hochholdinger, F and R. Zimmermann. 2008. Conserved and diverse mechanisms in root development. *Current Opinion in Plant Biology*, 11: 70-74.

Hokmalipour, S. and M.H. Darbandi. 2011. Effects of nitrogen fertiliser on chlorophyll Content and other leaf indicate in three cultivars of maize (*Zea mays L*.). *World Applied Sciences Journal,* 15: 1780-1785.

Horst, W.J., Kollmeier, M. and N. Schmohl.2007. Significance of the root apoplast for aluminium toxicity and resistance of maize. In: Sattelmacher B, Horst W, editors. The apoplast of higher plants: compartment of storage, transport, and reactions. Dordrecht: Kluwer Academic Publishers. pp. 49-66.

Hua, K., de Lange, C.F.M., Niimi, A.J., Cole, G., Moccia, R.D., Fan M.Z. and D P Bureau. 2008. Factorial model to predict phosphorus waste output of rainbow trout (Oncorhynchus mykiss). *Aquaculture Research*, 39: 1059-1068.

Ibekwe, A.M., Angle, J.S., Chaney, R.L. and P. Van Berkum. 1997. Enumeration and N fixation potential of *Rhizobium leguminosarum biovartrifolii* grown in soil with varying pH values and heavy metal concentrations. *Agriculture, Ecosystems and Environment*, 61: 103-111.

Ibrahim, U., Auwalu, B.M. and G.N. Udom. 2010. Effect of stage and intensity of defoliation on performance of vegetable cowpea (Vigna unguilata (L.) Walp). *World Journal of Agricultural Science*, 6: 460-465.

Iqbal, M.T. 2012. Acid Tolerance Mechanisms in Soil Grown Plants. *Malaysian Journal of soil science*, 16: 1-21.

Jemo, M., Abaidoo, R. C., Nolte, C. and W. J. Horst. 2007. Aluminum resistance of cowpea as affected by phosphorus-deficiency stress. *Journal of Plant Physiology*, 164: 442-451.

Kamel, S.G. and R. Abbas. 2012. Evaluation of physiological characteristics and yield compo-nents of chickpea genotypes under rain-fed condition. *Current Opinion in Agriculture* 1:13–18.

Karikari, B., Arkorful, E. and S. Addy. 2015. Growth, nodulation and yield response of cowpea to phosphorus fertiliser application in Ghana. *Journal of Agronomy,* 14: 234-240.

Kassa, M., Yebo, B. and A. Habte. 2014. Effect of liming and phosphorus levels on yield and yield components of Haricot bean (*Pharsalus vulga*rism L.) varieties on nitosols at Wolaita Zone, Ethiopia. *Asian Journal of Crop Science*, 6: 245-253.

Kebe, K and M. Sembene. 2011. Cowpea field infestation by *Bruchids*: Biological and Ecological data. *Journal of Applied Bioscience,* 41: 2788 -2796.

Keller, G.B. 2004. African nightshade, eggplant and spider flower: Production and consumption aspects of traditional vegetables in Tanzania from the farmers' point of view. Goettingen: Georg-August Universitat, Germany.

Khan, A.A., Jilani, G., Akhtar, M.S., Naqvi, S.M.S. and P. Rasheed. 2009. Phosphorus solubilizing bacteria: occurrence, mechanisms and their role in crop production. *Journal of Agricultural Biological Science,* 1:48-58.

Kidd, P.S. and J. Proctor. 2000. Effects of aluminium on the growth and mineral composition of *Betula pendula Roth*. *Journal of Experimental Botany*, 51: 1057-1066.

Kisinyo, P.O. 2016. Long term effects of lime and phosphorus application on maize productivity in an acid soil of Uasin Gishu County, Kenya. *Sky Journal of Agricultural Research,* 5:048-055.

Kisinyo, P., Opala, P., Palapala, V., Gudu, S., Othieno, C. and E. Ouma. 2015. Micro-dosing of lime, phosphorus and nitrogen fertilisers effect on maize performance on an acid soil in Kenya. *Sustainable Agriculture Research*, 4:21-30.

Kochian, L.V., Hoekenga, O.A. and M.A. Piners. 2004. How do crop plants tolerate acid soils: Mechanism of aluminum tolerance and phosphorus efficiency? *Annual Review of Plant Biology,* 55: 459-493.

Kongpun, A., Dell, B. and B. Rerkasem. 2011. Alleviating acid soil stress in cowpea with a local population of arbuscular mycorrhizal fungi. *African Journal of Biotechnology,* 10: 14410-14418.

Krasilnikoff, G., Gahoonia, T. and N. Erik-Nelson. 2003. Variation in phosphorus uptake by genotypes of cowpea (V*igna unguiculata* (L.) Walp) due to differences in root and root hair length and induced rhizosphere processes. *Plant and Soil*, 251: 83-91.

Kugblenu, Y.O., Kumaga, F.K., Ofor, K. and J. J. Adu-Gyamfi, 2014. Evaluation of cowpea genotypes for phosphorus use efficiency. *Journal of Agricultural and Crop Research,* 2: 202-210.

Kumara, R., Dibyendu C., Kumawatb, N., Pandeyc, A., Aniruddha, R.and M. Kumara. 2014. Productivity, quality and soil health as influenced by lime in rice-bean cultivars in foothills of northeastern India. *The Crop Journal,* 2: 338-344.

Kumaga, F.K. and K. Ofori. 2004. Response of soybean (*Glycine max (L.) Merrill*) to

bradyrhizobia inoculation and phosphorus application. *International Journal of Agriculture and Biology,* 6: 324-327.

Kumar, A. and H. Hirochika. 2001. Applications of retrotransposons as genetic

tools in plant biology. *Trends in Plant Science,* 6: 127-134.

Kutu, F.R. 2012. Effect of conservation agriculture management practices on maize productivity and selected soil quality indices under South Africa dryland conditions. *African Journal of Agricultural Research*, 7: 3839-3846.

Landon, J.R. 1991. Booker Tropical Soil Manual. Longman Scientific and Technical Essex, UK. pp.474.

Lal, R. 2010. Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. *Food security,* 2: 169-177.

Langyintuo, A.S., Lowenberg-Deboer, J., Faye, M., Lambert, D., Ibro, G., Moussa, B. and G. Ntoukam. 2003. Cowpea supply and demand in West and Central Africa. *Field Crops Research*, 82: 215-231.

Legesse, H., Nigussie-Dechassa, R., Gebeyehu, S., Bultosa, G. and F. Mekbib. 2013. Response to soil acidity of common bean genotypes *(Phaseolus vulgaris L.)* under field conditions at Nedjo, Western Ethiopia. *Science, Technology and Arts Research Journal,* 2: 03-15.

Liao, H., Rubio, G., Yan, X., Cao, A., Brown, K.M and J.P. Lynch. 2001. Effect of phosphorus availability on basal root shallowness in common bean. *Plant and Soil,* 233: 69-79.

Li, M., Shinano T., and T. Tadano. 1997. Distribution of exudates of lupin roots in the rhizosphere under phosphorus deficient conditions. *Soil Science and Plant Nutrition*, 43: 237-245.

Lin, M.H., Gresshoff, P.M. and B.J. Ferguson. 2012. Systemic regulation of soybean nodulation by acidic growth conditions. *Plant Physiology,* 160: 2028-39.

Liu, L., Yang, T., Liu, R., Redden, B., Maalouf, F. and X. Zong. 2011. Food legume production in China. *The Crop Journal*, 1: 1-12.

Lopéz-Bucio, J., Cruz-Ramírez, A. and L. Herrera-Estrella. 2003. The role of nutrient availability in regulating root architecture. *Current Opinion in Plant Biology,* 6: 280-287.

Machado, C.T.D.T. and A.M.C. Furlani. 2004. Kinetics of phosphorus uptake and root morphology of local and improved varieties of maize. *Scientia Agricola,* 61: 69-76.

Mandiringana, O.T., Mnkeni, P.N.S., Mkile, Z., Van Averbeke, W., Van Ranst, E. and H. Verplancke. 2005. Mineralogy and fertility status of selected soils of the Eastern Cape Province, South Africa. *Communications in Soil Science and Plant Analysis*, 36: 2431-2446.

Matsumoto, H. 2002. Plant roots under aluminum stress: toxicity and tolerance. In: Waisel Y, Eshel A, Beeckman T, Kafkafi U, editors. Plant roots: the hidden half. 3rd edition. New York: CRC Press. pp. 821-34.

Meena, L.R. and R. Chand. 2014. Response of fodder cowpea to varying levels of nitrogen and phosphorus under rainfed condition of Rajasthan. *The Indian Journal of Small Ruminants*, 20: 121-123.

Mfilinge, A., Mtei, K. and P. Ndakidemi. 2014. Effect of *Rhizobium* inoculation and supplementation with phosphorus and potassium on growth and total leaf chlorophyll content of bush bean *Phaseolus vulgaris, L*. *Agricultural Sciences*, 5: 1413-1426.

Miller, C.R., Ochoa, I., Nielsen, K.L., Beck, A.D. and J.P. Lynch. 2003. Genetic variation for adventitious rooting in response to low phosphorus availability: potential utility for phosphorus acquisition from stratified soils. *Functional Plant Biology*, 30: 973-985.

Miller, S.S., Liu, J., Allan, D.L., Menzhuber, C.J., Fedorova, M., and C.P. Vance. 2001. Molecular control of acid phosphatase secretion into the rhizosphere of proteoid roots from phosphorus-stressed white lupin. *Plant Physiology*, 127: 594-606.

Mills, A.J. and M.V. Fey. 2004. Declining soil quality in South Africa: Effects of land use on soil organic matter and surface crusting. *South African Journal of Plant and Soil*, 21: 388-398.

Mkhabela, T.S. and S.A. Materechera. 2003. Factors influencing the utilization of cattle and chicken manure for soil fertility management by emergent farmers in the moist Midlands of KwaZulu-Natal Province, South Africa. *Nutrient Cycling in Agro-ecosyst*em. 65, 151-162.

Mohd-Aizat, A., Mohamad-Roslan, M.K., Wan Nor-Azmin S. and D. K. Singh. 2014. The relationship between soil pH and selected soil properties in 48 years logged-over forest. *International Journal of Environmental Sciences,* 4: 1129-1140.

Mokolobate, M.S. and R.J. Haynes. 2002. Comparative liming effect of four organic residues applied to an acid soil. *Biology and Fertility of Soils*, 35: 79-85.

Moreira, X., Abdala-roberts, L., Hernández, J., Maximilien, A.C., Cunglauser, G and B Benrey. 2008. Specificity of induced defenses, growth, and reproduction 1 in lima bean

(P*haseolus lunatus,* fabaceae) in response to multi-2 species herbivory. *Specificity of plant induced responses*, 28: 1-38.

Mupangwa, W.T and F. Tagwira. 2005. Groundnut yield response to single superphosphate, calcitic lime and gypsum on acid granitic sandy soil. *Nutrient Cycling in Agroecosystems,* 73: 161-169.

Msangi, J. P. 2014. Indigenous plant resources and food security among small-scale agricultural producers: Southern Africa. In *Food Security among Small-Scale Agricultural Producers in Southern Africa*, Springer International Publishing, pp. 75-104.

Ndakidemi, P. A. and F.D. Dakora. 2007. Yield components of nodulated cowpea (*Vigna unguiculata (L.) Walp*) and maize (*Zea mays*) plants grown with exogenous phosphorus in different cropping systems. *Australian Journal of Experimental Agriculture,* 47: 587-590.

Ndamani, F. and T. Watanabe. 2015. Farmers' Perceptions about Adaptation Practices to Climate Change and Barriers to Adaptation: A Micro-Level Study in Ghana. *Water*, 7: 4593-4604.

Ndor, E., Dauda, N., Abimuku, E., Azagatu D. and H. Anzaku. 2012. Effect of phosphorus fertiliser and spacing on growth, nodulation count and yield of cowpea (*Vigna unguiculata (L) Walp)* in Southern Guinea Savanna agroecological zone, Nigeria. *Asian Journal of Agricultural. Science,* 4: 254-257.

Nekesa, A. O. 2007. Effect of Minjingu phosphate rock and agricultural lime on maize,groundnut and soybean yields on acid soils of western Kenya. M. Phil Thesis, MoiUniversity, Eldoret, Kenya.

Nkaa, F.A., Nwokeocha, O.W and O. Ihuoma. 2014. Effect of phosphorus fertiliser on growth and yield of cowpea (Vigna unguiculata). Journal of Pharmacy and Biological Science, 9: 74-82.

Nkheloane, T. and M.V. Marake. 2010. Lime requirement of selected acid soils of Lesotho and response of field beansto lime application. Second RUFORUM Biennial Meeting 20 - 24 September 2010, Entebbe, Uganda.

Ntobela, Z. 2012. Growth and yield responses of cowpeas *(Vigna unguiculata L.)* to water stress and defoliation. MSc thesis, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Nyoki, D., Patrick, A. and R. Ndakidemi. 2013. Economic benefits of *Bradyrhizobium japonicum* inoculation and phosphorus supplementation in cowpea (*Vigna unguiculata* (L.) Walp) grown in northern Tanzania. *American Journal of Research*, 1: 173-189.

Nyoki, D. and P.A. Ndakidemi. 2016. Intercropping System, Rhizobia Inoculation, Phosphorus and Potassium Fertilization: A Strategy of Soil Replenishment for Improved Crop Yield. *International Journal of Current Microbiology and Applied Sciences,* 5: 504-522.

Nui, Y.F., Chai, R.S., Jin, G.L., Wang, H., Tang, C.X. and Y.S. Zhang. 2013. Responses of root architecture development to low phosphorus availability: a review. *Annals of Botany*, 112:391-408.

Nwoke, O.C., Diels, J., Abaidoo, R., Nziguheba, G. and R. Merckx. 2008. Organic acids in the rhizosphere and root characteristics of soybean (*Glycine max*) and cowpea (*Vigna unguiculata*) in relation to phosphorus uptake in poor savanna soils. *African Journal of Biotechnology,* 7: 3620-3627.

Odhiambo, J.J. 2011. Potential use of green manure legume cover crops in smallholder maize production systems in Limpopo province, South Africa*. African Journal of Agricultural Research,* 6: 107-112.

Okalebo, J.R., Gathua, K.W. and P.L. Woomer. 2002. Laboratory Methods of Soil and Plant Analysis: A Working Manual; TSBF-KARI, Nairobi, Kenya.

Olaleye, O., Fagbola, O., Abaidoo, R.C., and N. Ikeorah. 2012. Phosphorus response efficiency in cowpea genotypes. *Journal of Agricultural Science*, 4: 81-90.

Oluwatoyinbo, F.I., Akande, M.O. and J.A. Adediran, 2005. Response of okra (*Abelmoschus esculentus*) to lime and phosphorus fertilization in acid soil. *World Journal of Agricultural Science*, 1: 178-183.

Omadi, J.R., Obuo, J. E. and H. Okurut- Akol. 2001. Agriculture in Uganda, Volume II, Fountain publishers/CTA/NARO. pp. 157.

Onuh, M.O. and K.M. Donald. 2009. Effects of water stress on the rooting, nodulation potentials and growth of cowpea *(Vigna unguiculata (L) Walp)*. *Science World Journal*, 4: 1597-6343.

Onwuka, M. I., Osodeke, V. E. and A.O. Ano. 2009. Use of liming materials to reduce soil acidity and affect maize (*Zea mays L*) growth parameters in Umudike, Southeast Nigeria. *Journal of Production Agriculture and Technology*, 5: 386-396.

Opara-Nadi, A.O., Omenihu, A.A. and S.N. Ifemedehe. 2000. Effects of organic wastes, fertilisers and mulch on productivity of an Ultisol. In: Babalola O (ed). Proceeding of 26th Annual Conference of Soil Science Society of Nigeria held at Ibadan, 30th October-3rd November, 2000: 112-120.

Osei-Yeboah, S., Lindsay, J.I. and S.F.A. Gumb. 1983. Estimating leaf area of cowpea (*Vigna ungiculata* (L.) Walp) from linear measurement of terminal leaflets. *Tropical Agriculture*, 60:149-150.

Oyeyiola, Y.B., Omueti, J.A.I. and G.O. Kolawole. 2015. Effects of phospho-compost on acidity indices in an acidic soil in Ilesha, south-western Nigeria. In: Rahmann G, et al. (eds.), Proceeding of the 3rd African Organic Conference. Achieving Social and Economic Development through Ecological and Organic Agriculture Alternatives, Lagos, Nigeria, Africa.

Oyeyiola, Y.B., Omueti, J.A.I., Njoku, N. and E. Oyekanmi. 2014. Assessment of liming potentials of phospho-compost and synthetic fertilisers in an acidic alfisol for cowpea production. *Journal of Plant and Pest Science,* 2: 128-137.

Panda, S.K., Baluska, F. and H. Matsumoto. 2009. Aluminum stress signalling in plants. *Plant Signal Behaviour*, 4: 592-7.

Poschenrieder, C., Gunsé, B., Corrales, I. and J. Barceló. 2008. A glance into aluminum toxicity and resistance in plants. *Science of the total environment*, 400:356-368.

Pandey, S., Kumar, S., Rai, M., Mishra, U. and M. Singh. 2008. Assessment of genetic diversity in Indian ash gourd (*Benincasa hispida*) accessions using RAPD markers.1: Genetics and breeding of Cucurbitaceae, Proceedings of the IXth EUCARPIA, INRA, Avignon (France), May 21-24th, 2008.

Pimentel, L.D. Bruckner, C.H., Manfio, C.E., Motoike, S.Y. and H.E.P. Martinez. 2016. Substrate, lime, phosphorus and top-dress fertilization in macaw palm seedling production. *Revista Árvore, Viçosa-MG*, 40:235-244.

Rabie, G.H., Aboul-Nasr, M.B. and A. Al-Humiany. 2005. Increased salinity tolerance of cowpea plants by dual inoculation of an arbuscular mycorrhizal fungus *Glomus clarum* and a nitrogen-fixer *Azospirillum brasilense*. *Journal of Mycoboilogy*, 33: 51-60.

Ribeiro, M.A.Q., Almeida, A.A.F.D., Mielke, M.S., Gomes, F.P., Pires, M.V. and V.V. Baligar. 2013. Aluminum effects on growth, photosynthesis, and mineral nutrition of cacao genotypes. *Journal of Plant Nutrition,* 36: 1161-1179.

Richardson, A.E. and R.J. Simpson. 2011. Soil microorganisms mediating phosphorus availability. *Plant Physiology*. 156: 989-996.

Roberts, D., Kowal, C.L. and J.B. Sivakumar. 2005. Prediction of onset date of rainfall in the tropics. *Science*. 215: 307-410.

Ryan, P., Delhaize, E. and D. Jones. 2001. Function and mechanism of organic anion exudation from plant roots. *Annual Review of Plant Physiology and Plant Molecular Biology*, 52: 527-560.

Sancheza, P.A., Cheryl A. Palma, C.A. and S W. Buolb. 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma,* 114: 157-185.

Sanginga, N., Okogun, J.A., Vanlauwe, B and K. Dashiell .2002. The contribution of nitrogen by promiscuous soybeans to maize based cropping in the moist savanna of Nigeria. *Plant Soil,* 241: 223-231.

Samac, D.A. and M. Tesfaye. 2003. Plant improvement for tolerance to aluminium in acid soil-a review. *Plant cell, Tissue and organ Culture*, 75:189-207.

Samaee, S.M., Shobbar, Z.S., Ashrafi, H. and M. Hosseini-Mazinani. 2003. Molecular characterization of olive germplasm in Iran by use of random amplified polymorphic DNA (RAPD): Correlation with phenotypic studies. *Acta Horticulturae,* 623: 169-175.

Saria, J.E. 2010. Enhancing cowpea (*Vigna unguiculata [L.] Walp*.) production through insect pest resistant line in East Africa. PhD Thesis, University of Copenhagen, Denmark, 99 pp. http://curis.ku. dk/ws/files/32439416/. Accessed 16 September 2016.

Schönfeldt, H.C. and B. Pretorius. 2011. The nutrient content of five traditional South African dark green leafy vegetables-a preliminary study. *Journal of Food Compound. and Analysis*. 24: 1141-1146.

Schrick, K. and T. Laux. 2001. Zygotic embryogenesis: developmental genetics. In Current trends in the embryology of angiosperms .Springer. Netherlands. pp. 249-277.

Sebetha, E. T., Ayodele, V. I., Kutu, F. R. and I.K. Mariga. 2010. Yields and protein content of two cowpea varieties grown under different production practices in Limpopo Province, South Africa. *African Journal of Biotechnology*. 9: 628-634.

Sheahan, C.M. 2012. Plant guide for cowpea (*Vigna unguiculata* (L.) Walp). USDA-Natural Resources Conservation Services, Cape May, Plant Materials Center, Cape May, NJ.

Shiringani, R.P. and H.A. Shimelis. 2011. Yield response and stability among cowpea genotypes at three planting dates and test environments. *African Journal of Agricultural Researc*h, 6: 3259-3263.

Shishkova, S., Rost, T. L. and J. G. Dubrovsky. 2008. Determinate root growth and meristem maintenance in angiosperms. Annals of Botany, 101: 319-340.

Shujie, M., and Q. Yunfa. 2011. Effects of phosphorus concentration on adaptive mechanisms of high- and low-P eficiency soybean genotypes when grown in solution. *Plant, Soil and Environment,* 57:61-66.

Silva, W.A., Bonatto, S.L., Holanda, A.J., Ribeiro-dos-Santos, AK., Paixão, B.M., Goldman, G.H., Abe-Sandes, K., Rodriguez-Delfin, L., Barbosa, M., Paçó-Larson., M.L, Petzl-Erler, M.L., Valente, V., Santos, S.E.B. and M.A. Zago .2003. Correction: mitochondrial DNA variation in Amerindians. *American Journal of Human Genetics,* 72:1346-1348.

Simpson, M.G. 2010. Plant Systematics. 2nd edition. San Diego, California: Elsevier Inc. pp. 740-850.

Singh, B.B. 2002. Recent genetic studies in cowpea. Challenges and opportunities for enhancing sustainable cowpea production. International Institute of Tropical Agriculture, Ibadan, pp. 3-13.

Singh, A., Baoule, A.L., Ahmed, H.G., Dikko, A.U., Aliyu, U., Sokoto, M.B., Alhassan, J., Musa, M. and B.Haliru. 2011. Influence of phosphorus on the performance of cowpea (Vigna unguiculata (L) Walp.) varieties in the Sudan Savanna of Nigeria. *Journal of Agricultural Sciences*, 2: 313-317.

Singh, B.B. and H.A. Ajeigbe. 2002. Improving cowpea-cereal based systems in the dry Savannas of West Africa. In: Fatokun, C.A., Tarawali, S.A., Singh, B.B., Kormawa, P.M. and M. Tamo. (eds). Challenges and opportunities for enhancing sustainable cowpea production. Proceedings of the World Cowpea Conference III held at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, 4-8 September 2002. IITA, Ibadan Nigeria. pp. 278-286.

Singh, B.B. and H.A. Ajeigbe. 2001. Breeding improved cowpea varieties for different cropping systems and Agro-ecologies in West Africa. *African Crop Science Conference Proceedings*, 5: 35-41.

Smith S.E., and D.J, Read. 2008. Mycorrhizal Symbiosis, Edition 3. Academic Press and Elsevier London.

Soil Association of United Kingdom (SAUK). 2010. A rock and a hard place: peak phosphorus and the threat to our food security. Soil Association, (Bristol). pp. 23.

Sydenham, S. 2015. The importance of aluminium tolerance for production. *Wheat Focus*, 1: 16-19.

Tairo, E.V. and P. A. Ndakidemi. 2013. *Bradyrhizobium japonicum* Inoculation and phosphorus supplementation on growth and chlorophyll accumulation in soybean (*Glycine max* L.). *American Journal of Plant Sciences*, 4: 2281-2289.

Thomson, I.S.I. 2014. Anu Rahal, Mahima, Amit Kumar Verma, Amit Kumar, Ruchi Tiwari, Sanjay Kapoor, Sandip Chakraborty and Kuldeep Dhama. *Journal of Biological Sciences*, 14:1-19.

Thomas Jefferson Agricultural Institute (TJAI). 2010. Cowpea: A versatile legume for hot, dry conditions. Columbia, MO. http://www.jeffersoninstitute.org/pubs/cowpea.shtml. Accessed 02/08/2016.

Timko, M. P. and B.B. Singh. 2008. Cowpea, a multifunctional legume. In: P.H. Moore, R. Ming (eds.), Genomics of tropical crop plants. Springer New York, pp. 227-258.

Timko, M.P., Ehlers, J.D. and P.A. Roberts. 2007. Cowpea: In genome mapping and molecular breeding in plants, Volume 3 Pulses, Sugar and Tuber Crops C. Kole (ed) *Springe-Verlag Berlin Heidelberg.*

Tisdale, L.S., Nelson, L.W. and .D.J. Beaton. 1990. Soil fertility and Fertilizes. 4th Edition. Maxwell Macmillan International Editors, pp. 189-349.

Trachsel, S, Kaeppler, S.M., Brown, K.M., and J.P., Lynch. 2010. Shovelomics: high throughput phenotyping of maize (*Zea mays L.*) root architecture in the field. *Plant Soil* 341: 75–87.

Tripathi, D.K., Singh, S., Singh, S., Mishra, S., Chauhan, D.K. and N.K. Dubey. 2015. Micronutrients and their diverse role in agricultural crops: advances and future prospective. *Acta Physiologiae Plantarum,* 37: 1-14.

Trindade, R.D., and A.P. Araújo. 2014. Variability of root traits in common bean genotypes at different levels of phosphorus supply and ontogenetic stages. *Brazilian Journal of Soil Science*, 38: 1170-1180.

TSO. 2010. Fertiliser manual (8th ed.). Department for Environment, Food and Rural Affairs. United Kingdom (UK).

Tsubo, M., Walker, S. and E.Mukhala. 2001. Comparisons of radiation use efficiency of mono-/inter-cropping system with different row orientations. *Field Crops Research*, 71: 17-29.

Uchida, R. 2000. Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In: Silva, J.A. and Uchida, R., Eds., Plant Nutrient Management in Hawaii’s Soils, Approaches for Tropical and Subtropical Agriculture, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu, 31-55.

Van der Merwe, A.J., Johnson, J.C. and L.S.K. Ras. 1984. An $NH_4HCO_3^-$, NH_4F, $(NH_4)_2$ EDTA method for the determination of extractable P, K, Ca, Mg, Cu, Fe, Mn & Zn in soils. Soil and irrigation Research Institute (SIRI) info. Bull. B2/2. Soil and irrigation Research Institute, Pretoria.

Vance, C.P., Uhde-Stone, C., and D.L. Allan. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a non-renewable resource. *New Phytologist*, 157: 423-447.

Venter, A., Herselman, J.E., Van der Merwe, G.M.E., Steyn, C. and D.J. Beukes. 2001. Developing soil acidity map for South Africa. *In*. Plant Soil Interaction at Low pH: 5th International Symposium Abstracts, pp. 21.

Von Uexküll, H.R. and E. Mutert. 1995. Global extent, development and economic impact of acid soils. *Plant and Soil*, 171: 1-15.

Waisel, T., Eshel, A, Beeckman, T. and U. Kafkafi. 2002. Plant roots: the hidden half, 3rd edition. New York/Basel: Marcel Dekker, Inc.

Walker, N.J. and R.E. Schulze. 2008. Climate change impacts on agro-ecosystem sustainability across three climate regions in the maize belt of South Africa. Agriculture. *Ecosystems and Environment*, 124: 114-124.

Walkley, A. and I.A. Black. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Journal Soil Science*, 37: 29-38.

Wang, X. 2009. Phosphorus acquisition characteristics of cotton (*Gossypium hirsutum* L.) compared with other crop species. PhD thesis (Agriculture), La Trobe University, Bundoora, Victoria 3086: Australia.

Ward, C.L., Kleinert, A., Scortecci, K.C., Benedito, V.A. and A.J. Valentine. 2011. Phosphorus-deficiency reduces aluminium toxicity by altering uptake and metabolism of root zone carbon dioxide. *Journal of Plant Physiology*, 168: 459-465.

Weinberger, K. and J. Msuya. 2004. Indigenous vegetables in Tanzania significance and prospects. AVRDC. The world vegetable center, Technical Bulletin Series No 31, Taiwan.

White, P.J., George, T.S., Gregory, P.J., Bengough, A.G., Hallett, P.D. and B.M. McKenzie. 2013. Matching roots to their environment. *Annals of botany,* 112: 207-222.

White P.J. and M.R. Broadley. 2009: Biofortification of crops with seven mineral elements often lacking in human diets iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytologis*t, 182: 49-84.

Wijanarko, A. and A. Taufiq. 2016. Effect of lime application on soil properties and soybean yield on Tidal land. *Agrivita Journal of Agricultural Science,* 38: 1305-1315.

XiaoJun, Z., Jin Song, Y., YongChao, L., YunSheng, L. and Y. XiaoYing. 2004. Effects of exogenous calcium on photosynthesis and its related physiological characteristics of rice seedlings under salt stress. *Journal of Science and. Agriculture,* 37: 1497-1503.

Yakubu, H., Kwari, J. D. and M.K. Sandabe. 2010. Effect of phosphorus fertiliser on nitrogen fixation by some grain legume varieties in Sudano-Sahelian zone of North Eastern Nigeria. *Nigerian Journal of Basic and Applied Science,* 18: 19-26.

Yang, Y., Hu, C. and M.M. Abu-Omar. 2012. Conversion of glucose into furans in the presence of $AlCl_3$ in an ethanol–water solvent system. *Bio-resource technology,* 116: 190-194.

Yorst, R.S. and A. Ares. 2007. Phosphorus and lime requirements of tree crops in tropical acid soils: a review. *Journal of Tropical Forest Science*, 19: 176-185.

Zhao, D., Reddy, K.R., Kakani, V.G., Read, J.J. and G.A. Carter. 2003. Corn (*Zea mays L.*) growth leaf pigment concentration, photosynthesis and leaf hyper-spectral reflectance properties as affected my nitrogen supply. *Plant Soil,* 257: 205-217.

Zhou, X., Huang, J., Zhou. Y., and W. Shi. 2012. Genotypic variation of rape in phosphorus uptake from sparingly soluble phosphate and its active mechanism. *African Journal of Biotechnology*, 11: 3061-3069.

Zhu, J.M. and J.P. Lynch. 2004. The contribution of lateral rooting to phosphorus acquisition efficiency in maize (*Zea mays L*.) seedlings. *Functional Plant Biolog*y, 31: 949-958.

APPENDIX

Appendix 1 Mean sum of square for phenological data during 2014/15 planting

Source of variance	Degree of freedom	Trial 1			Trial 2		
		Emergence 1	Emergence 2	50% flowering	50% podding	100% flowering	100% podding
Lime rates, L	3	1.89ns	4.68ns	342.18***	371.68***	288.48***	277.55***
P rates	4	1.12ns	3.52ns	122.61***	123.01***	74.05***	61.83***
L*P interaction	12	2.76*	7.28*	70.10***	70.29***	49.19***	35.94***

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 2: Mean sum of square for soil chemical properties after harvest

Source of variance	Degree of freedom	pH (H_2O)	pH (KCl)	Phosphorus (P)	EC (µs cm)	EC (mS cm)	NH_4N (µg/kg)	(TOC)	(OM)
Lime rates, L	3	4.97***	3.81***	0.56ns	1251222***	1.25***	0.02ns	1.39***	4.12***
P rates	4	0.04ns	0.01ns	5.11***	185087***	0.18***	0.02ns	0.15***	0.43***
L*P interaction	12	0.20ns	0.09*	0.23ns	197411***	0.20***	0.04ns	0.04*	0.12**

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 3a: Mean sum of square for yield parameters during 2013/14 planting

Source of variance	Degree of freedom	1ST PLANTING SEASON			
		FPB	OPB	FRB	ORB
Lime rates, L	3	2.51***	0.20***	0.01ns	0.24*
P rates	4	3.83***	0.12***	0.01ns	0.75*
L*P interaction	12	0.62ns	0.04*	0.01ns	0.70**

*, **, *** *connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant*

Appendix 3b: Mean sum of square for yield parameters during 2014/15 planting

Source of variance	Degree of freedom	2ND PLANTING SEASON							
		FPB	OPB	FRB	ORB	NOPP	WOPP	WSPP	NOSPP
Lime rates, L	3	46.20***	35.28***	4.97***	0.42***	2.26*	0.32ns	31.39ns	89.96***
P rates	4	154.40***	35.88***	2.97**	0.22***	8.65**	0.37*	32.51ns	95.18***
L*P interaction	12	11.072*	4.63***	1.28*	0.29***	0.55ns	0.20ns	40.77ns	213.51ns

*, **, *** *connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant*

Appendix 4a: Mean sum of square for growth parameters during 2013/14 planting

Source of variance	Degree of freedom	Week 3						Week 6					
		PL	**SD**	**NT**	**LT**	**WT**	**AT**	**PL**	**SD**	**NT**	**LT**	**WT**	**AT**
Lime rates, L	3	137.36***	1.21***	1.16***	63.82***	20.79***	1074.06***	442.06***	0.96**	2.48***	52.85***	17.31***	3475.84***
P rates	4	9.16ns	0.49ns	0.24ns	10.02*	5.42**	249.30**	156.98***	0.62*	2.66****	11.35*	1.50ns	290.68ns
L*P interaction	12	28.46***	0.67***	0.40**	13.67***	5.28***	208.59**	86.21***	0.80***	1.66***	20.07***	5.73***	666.43**
Error	217	7.97	0.18	0.13	3.44	1.50	67.34	20.28	0.22	0.43	4.95	1.49	221.87

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 4b: Mean sum of square for growth parameters during 2013/14 planting

Source of variance	Degree of freedom	Week 9						Week 10					
		PL	**SD**	**NT**	**LT**	**WT**	**AT**	**PL**	**SD**	**NT**	**LT**	**WT**	**AT**
Lime rates, L	3	528.10***	1.53**	1.16***	63.82***	20.79***	1074.06***	198.93***	2.57**	3.31**	42.46***	4.27ns	1280.09**
P rates	4	198.47***	0.92**	0.24ns	10.02*	5.42**	249.30**	138.13***	0.50ns	2.31**	15.46*	11.14**	1189.92**
L*P interaction	12	59.51**	1.11*	0.40**	13.67***	5.28***	208.59**	50.32**	0.346ns	0.89ns	5.40ns	2.56ns	221.92ns

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 5a: Mean sum of square for growth parameters during 2014/15 planting

Source of variance	Degree of freedom	Plant number 1						Plant number 2					
		PL	SD	NT	LT	WT	AT	PL	SD	NT	LT	WT	AT
Lime rates, L	3	66.83***	2.71***	0.43*	28.93**	2.50ns	4078.1ns	84.27***	2.98***	1.24*	10.00*	5.00ns	8546.8*
P rates	4	332.80***	1.33**	9.49***	49.97***	68.18***	26428.2***	426.49***	1.55***	0.71ns	23.14***	16.25**	20175.1**
L*P interaction	12	14.62*	0.46*	0.15ns	5.99ns	6.06ns	2361.7ns	16.05ns	0.45ns	0.41ns	6.49**	1.78ns	3039.3ns

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 5b: Mean sum of square for growth parameters during 2014/15 planting

Source of variance	Degree of freedom	plant number 3					
		PL	SD	NT	LT	WT	AT
Lime rates, L	3	56.57***	1.97***	4.48***	8.01*	3.63ns	2600.3ns
P rates	4	240.23***	1.61***	2.03**	19.22***	16.75*	18312.7***
L*P interaction	12	16.48**	0.39ns	0.71ns	6.30**	2.10ns	3387.4ns

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 6: Mean sum of square for root parameters during 2013/14 planting

Source of variance	DF	ABR	NBR	AAD	SD	TRD 5cm	TRD 10cm	TRD 15cm	TRD 20cm	3rd BRD	1.5 mm BRD 5cm	1.5 mm BRD 10cm	DS	SS	NOND
Lime rates, L	3	590.82**	16.52**	319.29ns	2.58**	0.32ns	1.87ns	0.01ns	1.172E-04ns	46.68***	27.05*	112.52***	8.25***	1.79*	2.69***
P rates	4	105.83ns	5.16ns	253.58ns	0.34ns	0.16ns	4.05**	0.01ns	1.420E-04ns	5.62ns	12.01ns	42.37*	3.10*	0.81ns	1.15*
L*P interaction	12	180.92ns	5.12ns	587.7ns	0.68ns	0.33ns	2.85**	0.01ns	2.319E-04ns	2.85ns	14.95ns	22.30ns	2.41*	0.57ns	1.47**

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 7: Mean sum of square for root parameters during 2014/15 planting season

Source of variance	DF	ABR	NBR	AAD	SD	TRD 5cm	TRD 10cm	TRD 15cm	TRD 20cm	3rd BRD	1.5 mm BRD 5cm	1.5 mm BRD 10cm	DS	SS	NOND
Lime rates, L	3	877.45*	40.22*	139.29ns	0.27ns	1.38ns	0.55ns	0.48ns	1.955E-03ns	23.8***	42.17ns	94.36***	0.79ns	2.77ns	931.03***
P rates	4	285.00ns	16.09ns	173.58ns	0.94*	0.34ns	0.58ns	0.39ns	3.612E-03ns	14.65**	35.99ns	10.92ns	2.49ns	2.61*	113.39*
L*P interaction	12	180.92ns	10.43ns	2767.7ns	0.32ns	0.32ns	0.30ns	1.19ns	4.951E-03ns	2.85ns	31.08ns	23.34**	15.56ns	23.33*	59.70ns

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant

Appendix 8: Mean sum of square for chlorophyll content during 2014/15 planting

Source of variance	**Degree of freedom**	**Flower formation**	**Pod formation**
Lime rates, L	3	3870.49***	3779.88***
P rates	4	347.26ns	341.88ns
L*P interaction	12	1341.32***	1329.49***

*, **, *** connotes 5%, 1% and 0.1% probability level, respectively while ns implies not significant