UNIVERSITY OF CAPE COAST

QUANTIFYING GENOTYPIC VARIATION AND THE EFFECT OF PHOSPHORUS ON ROOT SYSTEM ARCHITECTURE, P USE EFFICIENCY, YIELD AND PHYSIOLOGICAL SEED QUALITY OF COWPEA GENOTYPES

MOHAMMED KOTOCHI CLEMENT

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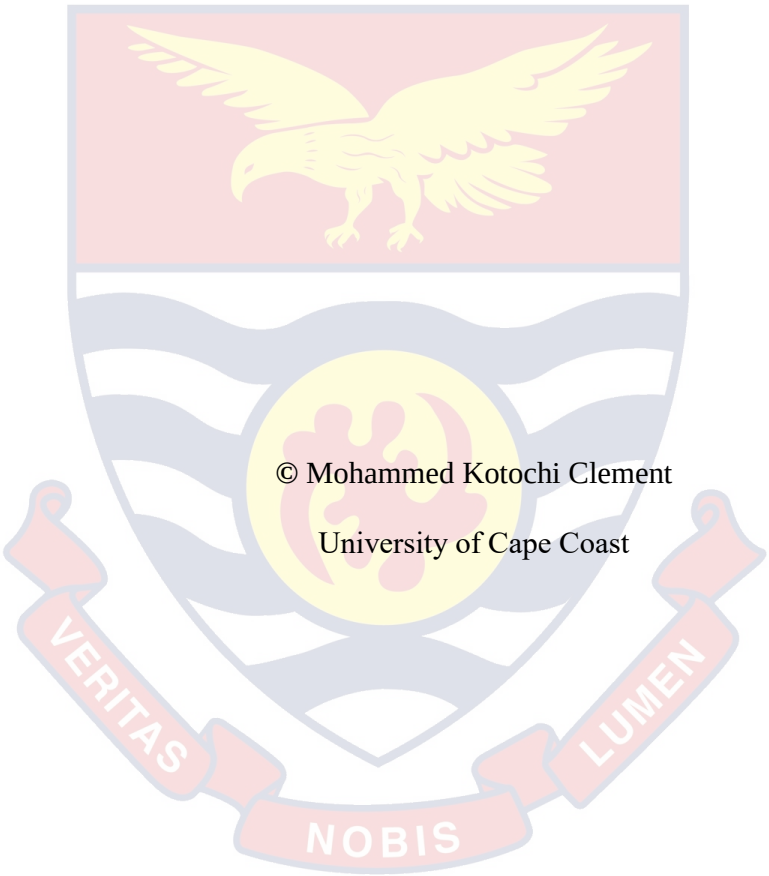

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QUANTIFYING GENOTYPIC VARIATION AND THE EFFECT OF PHOSPHORUS ON ROOT SYSTEM ARCHITECTURE, P USE EFFICIENCY, YIELD AND PHYSIOLOGICAL SEED QUALITY OF COWPEA GENOTYPES

BY

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Thesis submitted to the Department of Crop Science of the School of Agriculture, College of Agriculture and Natural Sciences, University of Cape Coast, in partial fulfillment of the requirements for the award of Master of Philosophy degree in Crop Science.

AUGUST 2020

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: ..... Date: .....

Name: ……

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature: ..... Date: .....

Name: ……

Co-Supervisor's Signature: ..... Date: .....

Name: ……

ABSTRACT

Cowpea (*Vigna unguiculata* (L) Walp) plays an important role in the livelihoods of several millions of people in the world. Despite its importance, poor soil fertility often limits the yield of cowpea in many areas, especially in the tropics, where the prevalently old and highly weathered soils have a low bioavailability of soil phosphorus (P). Plants have evolved adaptive mechanisms to low-P soils. The mechanisms include modification of root system architecture (RSA). Breeding for cowpea genotypes which use soil P efficiently and have superior RSA traits will enhance yield and ultimately promote food security and livelihoods of the millions of people who depend on the crop. The aim of this study was to evaluate genotypic variation and the effect of external P concentration ($[P]_{ext}$) on RSA, yield, and physiological seed quality among 20 cowpea genotypes under field conditions. The study also evaluated the variation in P use efficiency (PUE) parameters including agronomic P use efficiency (APE), P uptake efficiency (PUpE), and P efficiency ratio (PER). An 8 × 8 Alpha lattice design was used to screen cowpea genotypes in two seasons under 3 $[P]_{ext}$, namely 0, 10 and 45 kg P/ha. The results showed that there were significant ($P<0.05$) genotypic variations among cowpea genotypes in almost all the traits examined. For example, the stem diameter, hypocotyl root length and basal root length of genotypes Sunshine and WC35B*NE50 were greater compared to that of genotype Agyenkwa and NE15*WC35B. $[P]_{ext}$ significantly affected many traits, including yield, root growth angle, root length, tissue P concentration and germination percentage. There was increasing trend in hypocotyl root length, tissue P concentration, germination percentage and yield with increasing [P]ext. On the other hand, increasing $[P]_{ext}$ resulted in a significant ($P<0.01$) reduction in PER and PUtE. Some genotypes, including Secow3B, NE50, IT91 and WC35B*NE50 were categorized as P-efficient genotypes because they developed higher biomass weight and root length under low [P]ext. The shoot and root concentrations of P were significantly ($P<0.01$) affected by genotypes and P fertilizer application rate. The highest yielding genotypes took up more P than the low yielding ones. Differential yield response of cowpea in the field to $[P]_{ext}$ was observed. Grain yield increased with P application rate up to 45kg/ha. Days to flowering, number of branches, pod length etc. among genotypes were significantly high at 45 kgP/ha. Genotypes with longer root length such as Secow5T, WC36 had high tissue P concentration and yield confirming the role of the root system in the uptake of immobile P. The results have important implications for breeding and selection of cowpea genotypes that are adapted to a range of fertility levels. The results could be used to select for cowpea genotypes with superior RSA traits and improved PUE for use on P-poor soils and provide potential germplasm for breeding new cowpea cultivars better adapted to P-poor soils in Ghana.

KEY WORDS

Genotypic variation

Phosphorus use efficiency

Root system architecture

Seed quality

Cowpea (*Vigna unguiculata*)

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DEDICATION

I dedicate this work to my lovely and supportive wife Mrs. Cecilia Ndiago Kotochi. May this work be an emblem of my love for my sweet daughter Clementia Borechi Kotochi and my sons Caleb Borinefa Kotochi, Cresence Alela Kotochi and Ndefeso Kotochi.

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LIST OF ABBREVIATIONS

P	Phosphorus
RSA	Root System Architecture
MT	Metric Tons
N	Nitrogen
PAE	Phosphorus Acquisition Efficiency
PUE	Phosphorus Use/Utilization Efficiency
$[P]_{ext}$	External P source
CEC	Cation Exchange Capacity
RDW	Root Dry Weight
SDW	Shoot Dry Weight
NN	Nodule number
ND	Nodule diameter
SD	Stem diameter
HRL	Hypocotyl root length
HRGA	Hypocotyl root growth angle
HRD	Hypocotyl root diameter
HRN	Hypocotyl root number
BRL	Basal root length
BRGA	Basal root growth angle

BRD	Basal root diameter
BRN	Basal root number
3^{RD} BD	3^{rd} order branching density
TRD	Taproot diameter
PER	Phosphorus Efficiency Ratio
PUpE	Phosphorus Uptake Efficiency
PUtE	Phosphorus Utilization Efficiency
APE	Agronomic Phosphorus Use Efficiency
PPUE	Physiological Phosphorus Use Efficiency
DTF	Days to flowering
DTF 50%	Days to 50% flowering
NB	Number of branches
NPP	Number of pods per peduncle
NPPP	Number of pods per plant
PL	Pod length
100 SW	100-seed weight
YLD	Yield
G%	Germination percentage
GR	Germination rate
GI	Germination index

%CV	Coefficient of velocity of germination
PCA	Principal Component Analysis

CHAPTER ONE

INTRODUCTION

Background of the study

Cowpea (*Vigna unguiculata* L. Walp) is an economically essential leguminous plant in the world. The grains and leaves are an excellent source of protein for human diets, antioxidants that scavenge free radicals and reduce the risk of cancer (Widders, 2005). It provides an important and diverse source of household income for women, as it is frequently traded for multiple uses. The ability of cowpea to fix atmospheric nitrogen when grown in crop rotation with cereal crops makes it important in traditional agricultural systems (Timko *et al*., 2007). Cowpea is well suited to the increasingly challenging conditions of production including - low soil fertility, high temperatures and drought of most soils in Africa (Hiler *et al*., 1972).

Despite the importance of the crop in Africa, gap between potential and actual yield of cowpea has been reported by Adu *et al*. (2019). For instance, in Ghana, the average yield recorded in farmers' fields (0.4 - 0.6 t/ha) is less than the 1.6 - 2.5 t/ha obtained on research fields (Yirzagla *et al*., 2016). This results in the importation of about 10, 000 tonnes of cowpea annually into the country (Langyintuo *et al*., 2003; Seferiadis, 2009). Several factors such as increasing marginal soils, climate instability and low soil fertility (Wortmann, 1998; Lynch, 2007) in terms of low phosphorus (P) account for such production challenges (Sanginga *et al*., 2000).

Though P is important for plant growth and development, it has been reported that more than 40% of the world's agricultural lands are deficient in P

(Vance *et al*., 2003). The concentration in soil solution may be high, but its availability may be low for plant uptake (Clarkson & Grignon, 1991) with value ranging from 0.1 to 10 µM (Hinsinger, 2001). Low phytoavailability of P to plants reduces the yield of crops over an estimated 5.7 billion hectares (Hinsinger, 2001) especially, in cowpea production (Singh *et al*., 2011). Owing to low phytoavailability of P in the soil solution, P fertilizers are used as means of increasing crop yield (Syers *et al*., 2008).

Despite several reports on plant response to P fertilizer, the addition of industrial mineral-P fertilizer forms is often not considered economically viable (Trolove *et al*., 2003; Akhtar *et al*., 2007). Only 15 - 30% of applied fertilizer P is made available for plant uptake in the season of application (Syers *et al*., 2008) due to fixation of P-ions by Fe, Al and Ca oxides common in most tropical soils (Baligar, Fageria, & He, 2001). Loss of residual soil P through leaching, erosion and run-off are significant contributors to the eutrophication of aquatic bodies (Smil, 2000; Hart *et al*., 2004). Phosphorus reserves are expected to decline in the next century (Cordell *et al*., 2009) as a result of present production and consumption rate.

Plants have developed numerous mechanisms such as alterations of root growth and architecture and the release of exudates to enhance P use efficiency (Vance *et al*., 2003; White *et al*., 2005). Root system architecture (RSA), which is the root system's spatial configuration over time, is crucial to the acquisition of soil resources (Lynch, 2005). Root system architecture is defined as the organization, length/biomass quotient, and three-dimensional structure of the primary and lateral roots, as well as other accessory roots within the soil horizon (Lynch & Beebe, 1995; Ning *et al*., 2012; Smith & De Smet, 2012). Root system

architecture (RSA) plays a crucial role in the uptake of important soil resources such as nitrogen (N) and water (Lynch & Brown, 2001; Lynch, 2013) and essential for extremely immobile and limited resource such as P (Lynch & Beebe, 1995). Common RSA traits quantified in cowpea includes basal root growth angle (BRA), basal root whorl number (BRWN) and hypocotyl root number (HRN) (Ho *et al*., 2005; Burridge *et al*., 2016), and nodulation (Kopittke *et al*., 2007) among other traits.

Plant root adapts to the impoverished P environment by enhancing the development of basal and adventitious roots, altered root architecture (Lynch, 1995). Similarly, Miller *et al.* (2003) concluded that the development of adventitious roots in cowpea helped in the acquisition of P by enhancing foraging of plants in the most P-rich soil settings and the shallower root system were more competitive than profound root systems for topsoil P. Bean increases production of shallow basal roots in low soil P particularly in P-efficient genotypes (Miller *et al*., 2003). On the other hand, deep root systems were useful under dry circumstances (Matsui & Singh, 2003; De Barros *et al*., 2007; Agbicodo *et al*., 2009).

Common bean displays a significant genetic diversity in root system architectural features associated with growth under low P and water-limited environments (Bonser *et al*., 1996; Miller *et al*., 2003; Magalhaes *et al*., 2004; Ho *et al*., 2005; Ochoa *et al*., 2006). Lambers *et al.* (2006) reported the existence of genotypic variation among crops in their ability to obtain P from the soil. Genotypic variations in morphology of the root system offers the option of selecting and breeding plant genotypes for effective use of soil resources and enhanced agricultural yield. Developing high-yielding plant genotypes that can

effectively absorb and use P is therefore a well-thought-out measure for achieving worldwide food security.

Problem Statement

Cowpea (*Vigna unguiculata*) is an economically significant crop, and income-generating crop in many areas of the tropics and subtropics (Carlos, 2000; Tharanathan & Mahadevamma, 2003). The grains serve as an alternate protein for many households (Adu *et al*., 2019). Despite its significance, there is a gap between the actual and potential yield. In Ghana, average farm yield ranges from 0.4 - 0.6 t ha^{-1} which is below the 1.6-2.5 t ha^{-1} recorded in research fields (Yirzagla *et al*., 2016).

Several factors hinder the productivity of cowpea of which soil infertility in terms of P limitation is paramount (Wortmann, 1998; Sanginga *et al*., 2000; Lynch, 2007). Phosphorus deficiency is a phenomenon that occurs naturally and levels of bioavailable P seldomly exceeds 10 µM (Nussaume *et al*., 2011). Although lithosphere contains a considerable concentration of P-ions, it is sparsely accessible to crops (Clarkson & Grignon, 1991). Low P concentrations, therefore, restricts plant productivity in natural crop systems. In dealing with the problem of low P, approaches such as addition of P fertilizers to soil have been suggested (Vance *et al*., 2003). Nevertheless, P resources are finite in nature and world deposit is predicted to decline quickly depending on the current usage level (Cordell *et al*., 2009). In addition, P fertilizer is a significant source of soil cadmium (Cd) which is toxic substance to human health (Adu *et al*., 2014). Additionally, an average of 70 - 80% of applied P

fertilizer becomes fixed by forming complexes with Fe, Al and Ca oxides (McBeath *et al*., 2012) making it unavailable for plant uptake and utilization.

Justification

The world's population is escalating and climate change is becoming more evident. It is becoming increasingly difficult for crop production to keep up with food demand by increasing population (Lynch, 2005). Generally, food insecurity mainly in Africa and around the globe is associated with low soil nitrogen (N) and low soil P (Krasilnikoff *et al*., 2003). As a result, application of mineral fertilizer particularly P is used to improve crop yield (Kumar *et al*., 2009).

Crops have evolved extensive processes for the root adaptation in poor resource environments. Such mechanisms include modifications in root development and RSA, root exudation and soil microorganism associations (Hammond & White, 2008). Root system architecture (RSA) is particularly important because the distribution of nutrients and water in the soil on a macro scale is not uniform (Lynch & Wojciechowski, 2015). The distribution of roots in the soil column therefore determines the efficacy of a root system capturing these important soil resources. RSA is crucial in the uptake of important soil resources, including nitrogen and water (Lynch & Brown, 2001; Lynch, 2013) and principally crucial for the highly immobile and usually limiting nutrients like P (Lynch, 1995). RSA plays an important role in the absorption of soil elements such as nitrogen (N) and water (Lynch, 2013; Lynch & Brown, 2001) as well as extremely immobile and limited resource such as P (Lynch & Beebe,

1995). Root adapts to the poor P environment by enhancing the development of basal and adventitious roots, altered root architecture (Lynch, 1995).

Cowpea possess a significant genetic variation in RSA traits associated with low P and water environments (Miller *et al*., 2003; Magalhaes, 2004; Ho *et al*., 2005). Genotypic variation in the capacity to acquire P have been reported to exist within legumes such as common bean (*Phaseolus vulgaris* L.) and pigeon pea (*Cajanus Cajan L*.) (Bonser *et al*., 1996; Subbarao *et al*., 1997). Genotypic variation in RSA offers the option of selecting and breeding plants with root systems for effective acquisition and use of soil P. According to Gregory (2009), precise root system attribute measurements could be an important tool for assessing water and nutrient acquisition capacity of crops and help screen root architectural characteristics that boost sustainable agricultural production. Genotypic variation in RSA traits (BRA, BRWN and HRN) has been reported among cowpea varieties (Ho *et al*., 2005; Burridge *et al*., 2016). Exploring these genetic diversity among cowpea genotypes for these traits could serve as an important instrument for supporting breeding to improve the acquisition and P-use efficiency.

General Objective

The main objective of the study was to generate a broad knowledge on cowpea root system variation and P-use efficiency that will contribute towards the improvement of yield in cowpea in Ghana.

Specific Objectives

The specific objectives of the study were to;

1. examine the effect of external P on RSA traits among field grown cowpea genotypes.
2. evaluate genetic variation in the uptake and utilization of external P among field grown cowpea lines.
3. determine the effect of external P on yield and biomass production among field grown cowpea genotypes.
4. determine the effect of external P on some seed physiological qualities among cowpea genotypes.

Hypotheses of Research

The following hypotheses were tested in the study -

1. RSA traits among field grown cowpea genotypes is significantly influenced by external P concentration.
2. Significant variations exist among field grown cowpea genotypes in the uptake and utilization of phosphorus.
3. External phosphorus application significantly influences yield and biomass among field grown cowpea genotypes.
4. Phosphorus application significantly influences the physiological qualities of cowpea seeds produced.

CHAPTER TWO

LITERATURE REVIEW

History, origin, and domestication of cowpea

Cowpea (*Vigna unguiculata* L. Walp.) (2n=22) is a member of the Fabaceae family and of the Vigna genus (Doumbia *et al*., 2014). Several species exist within the Vigna genus including mungbean (*V. radiata*), adzuki bean (*V. angularis*), blackgram (*V. mugo*), and the Bambara groundnut (*V. subterranea*) (Timko *et al*., 2007; Timko & Singh, 2008). The four groups (*unguiculata*, biflora (or cylindrica), *sesquipedalis*, and *textilis*) are found in the *V. unguiculata* subspecies (Timko and Singh, 2008). The gene pool of the genus *V. unguiculata* subspecies primarily includes dekindtiana, stenophylla, and tenuis (Timko & Singh, 2008).

The domestication of cowpea is still debated, however, according to Coulibaly *et al*. (2002), the use of Amplified Fragment Length Polymorphism (AFLP) proved that, domestication occurred in North-East Africa. Also, Padulosi and Ng (1997) believed cowpea was domesticated only once, probably around 2000 B.C. In West Africa, the wild cowpea *V. unguiculata* var was the progenitor of the cultivated cowpea *Spontanea* (Pasquet, 1999). In Western part of Africa where most of the world's cowpea is grown, numerous weedy species are intermediate between genuinely wild forms and very small-scale cowpeas (Rawal, 1975). According to Padulosi and Ng (1997), in West Africa, the savannah region of Nigeria is the core of the greatest diversity of cultivated cowpeas and landraces.

Brief description of cowpea

Taxonomic description

Cowpea (*Vigna unguiculata* (L.) Walp.) belongs to the family Fabaceae. The genome is made up of 22 chromosomes (2n=2x =22) belonging to the division Magnoliophyte, class Magnoliopsida, order Fabales, family Leguminosae or Fabaceae and genus Vigna. The genus Vigna includes more than 80 species (Badiane *et al*., 2014) and was subdivided into six sections, namely, Vigna, Comosae, Macrodontae, Reticulatae, Liebrechtsia and Catiang (Maxted *et al*., 2004). *Vigna unguiculata* consists of 10 perennial wild subspecies and annual cowpeas (ssp. unguiculata) (Pasquet, 1993). The unguiculata subspecies includes all domesticated (var. unguiculata), wild and weedy (var. spontanea) types (Pasquet, 1993). Based on seeds and pod, domesticated cowpeas are grouped mainly into four classes. These cultivar groups include unguiculata grown as a pulse, biflora (catjang) primarily used as a forage, sesquipedalis (asparagus bean) grown as a vegetable, and textile, grown for the fibers from its lengthy floral peduncles. Coulibaly *et al*. (2002) also suggested that melanophthalmus (black-eyed pea) be classified as another cultivar group.

Morphology and Biological description

Cowpea is an annual hot season herbaceous plant with a large morphological variation. Cowpea may be prostate (trailing), non-prostate, semi-erect, erect or climbing, based not only on the genotype, but also on the photoperiod and patterns of growth (Timko *et al*., 2007). *V. unguiculata* is an

annual herbaceous, prostrate, creeping, bushy vine that grows up to 15 to 80 cm tall (Doumbia *et al*., 2014). The stems are striated and sometimes tinged with violet, soft, or mildly hairy.

Cowpea is considered a self-pollinated plant due to the cleistogamous nature of the flower and the fact that pollen is dispersed when the stigma is receptive (Ehlers & Hall, 1997). In some cases, outcrossing takes place at different rates, depending on the subspecies (Pasquet, 1996). Kouam *et al*. (2012) noted that the rates of outcrossing from is 1 to 9.5 percent.

Nevertheless, cowpea germination is known as epigeal, cotyledons do not continue and may drop as much as 90% of their dry matter as seedlings grow (Steele & Mehra, 1980). The first leaves above the cotyledons at the seedling stage are straightforward and opposite. The first leaves to form are a simple, opposite pair of true leaves followed by trifoliate leaves consisting of two smaller asymmetrical side leaflets and one bigger and broader central terminal leaflet, which is symmetrical (Ige *et al*., 2011). The leaf surface may be smooth, dull to a shiny surface, or sometimes pubescent (Pottorff *et al*., 2012). The petiole is sturdy, grooved and 5 - 25 cm long.

Cowpea flowers are arranged at the distal ends of 5 - 60 cm long peduncles in racemose or intermediate inflorescence. Colour ranges from brown, red or black to variously parti-colored with anthocyanin pigment (Steele & Mehra, 1980). Flowers are bisexual and papilionaceous with variable colours, which range from white, cream, yellow, pink to dark purple and sometimes with different combinations (Ige *et al*., 2011). The keel is boat-shaped, stamens are fused and one free, with the ovary superior. The display of brightly colored

flowers openly above the canopy on long peduncles and the presence of floral nectarines attracts insects (Timko & Singh, 2008).

Cowpea pods are smooth and cylindrical, straight or curved and may measure 10 and 110 cm (Doumbia *et al*., 2014). Wild cowpea species ' pods are straight, scabrous, slightly pubescent, black, upright or dehiscent. In the wild subspecies, the pod size varies from 4 cm to more than 1 m in subsp. Sesquipedalis (Kongjaimun *et al*., 2012). Most nursed species produce 12 - 20 cm long, non-dehiscent, fragile or smooth, bent and straight or coiled pods with about 10 - 15 seeds (Kongjaimun *et al*., 2012).

Seeds of cowpea have various forms, texture and colours. They range between 2 and 12 mm in size, kidney-like, oblong, or cylindrical. Cowpea seeds may also be smooth or wrinkled, red, mottled, black, brown, green, buff or white as full-colored, spotted, marbled, spotted, eyed or blotched dominant (Timko *et al*., 2007). The weight of 100 seeds in some wild species varies from 1 g to 34 g in cultivars (Steele & Mehra, 1980).

Importance of cowpea production

Cowpea is generally referred to as a nutritious food source because its excellent protein and carbohydrate content (Diouf & Hilu, 2005). In many developing nations, cowpea plays a key role in people's diet. Although protein content of cowpea seeds has limited levels of methionine and cysteine, it is noted for high level of lysine and tryptophan compared to other grains (Timko & Singh, 2008). Cowpea grain also has a large content of essential mineral elements and vitamins as well as rich in folic acid (Timko & Singh, 2008). The leaves, green pods and cowpea grains serve as an excellent source of food not

only for humans but also for farm animals. An estimate of 15 percent of livestock feed is obtained from seed and waste of cowpea production (MOFA, 2012). Cowpea is used in the preparation of protein rich hay mostly used in feeding farm animals during the warm seasons where animal feed is scarce.

In Ghana, the plant is an excellent source of vegetable protein and minerals for more than 70 percent of the inhabitants (Doumbia *et al*., 2014). Cowpea is currently regarded a food safety crop in Ghana, particularly in the northern region where it is most cultivated (Armah *et al*., 2011).

Cowpea plays a vital role in most agricultural systems due to the ability to fix atmospheric nitrogen by symbiosis with beneficial bacteria and tolerance to low fertile soil conditions (Elowad & Hall, 1987). An average of 240 kg/ha of atmospheric nitrogen is fixed by cowpea and provides about 60 to 70 kg/ha of nitrogen for successive crop when cultivated in rotation (Aikins & Afuakwa, 2008). According to Baldwin and Creamer (2006), Cowpea is used as a cover for erosion control and used as green manure because of its rapid establishment speed. As a result, the crop assumes a chief role is sustainable farming systems within the arid and semi-arid regions of Sub-Saharan Africa (Mutavi, 2017).

Global cowpea production

Cowpea is widely adapted and grown worldwide (Ntombela, 2012), however, Africa predominates in its production. Cowpea is grown in around 14.5 million hectares worldwide, producing over 6.5 million tonnes (Fatokun *et al*., 2000). Zalkuwi *et al*. (2014) revealed that around 5.5 million tonnes of cowpea were grown worldwide in 2010 and Africa accounted for 94% of this figure (Langyintuo *et al*., 2003). Nigeria is the largest producer of dried grain

of cowpea (Zalkuwi *et al*., 2014). Sudanese savannah region of Nigeria accounts for the greatest centre of diversity of cultivated cowpea as well as landraces within West Africa. Nigeria has the biggest cowpea cultivation region producing 5 million ha followed by central Burkina Faso, Ghana, Togo, northern Benin and the north-western part of Cameroon (Padulosi & Ng, 1997). Among cowpea growers in Africa, majority are women engaged in subsistence cultivation of the crop (Altieri & Koohafkan, 2008).

In the southern part of USA, cowpea is cultivated on an average of 40, 000 ha which yields an amount of 45, 000 tonnes of dry cowpea seed per year most of which are frozen green cowpea (Singh *et al*., 2003). The United States exports approximately 2 000 tons of very high-quality cowpea per year (Tettey, 2017). Although Nigeria is the largest cowpea producing country, Brazil, West India, Myanmar, Sri Lanka, Australia, the United States, Bosnia and Herzegovina also produces significant quantity of cowpea (Quinn & Myers, 1999).

Cowpea production and consumption in Ghana

Cowpea is heavily consumed in Ghana and in sub-Saharan Africa and it remains an important grain legume. Consumption per capita in Ghana is estimated at 5 kg (MOFA, 2012). Most cowpea production takes place in Ghana's savannah areas, however, the crop can be grown in other ecological areas (Vijay, 2016). Guinea Savannah and transitional forest areas, including Upper West, Upper East, Northern Regions and certain districts in the Brong Ahafo region, are major cowpea producing regions in Ghana (Langyintuo *et al*., 2003). The potential yield from cowpea is up to 2.6 tons per hectare, but the

usual yield from Ghana is less than 1000 kg per hectare (Langyintuo *et al*., 2003).

The demand for cowpea is increasing in Ghana, mainly in urban areas, owing to high population growth (Vijay, 2016). In 2010, the average consumption of cowpea in the country is about 5 kilos per person per year (Vijay, 2016). Cowpea is either ground or consumed in grain and several forms for consumption. Cowpea flour has historically been a favorite of most rural households in northern Ghana because cowpea flour is less prone to damage after harvest and can be used in several different meals to boost food security between harvests. Cowpea products such as flour, cake, fritters, and chips are sold in most village markets. Ghanaian farmers typically store and sell more than 60% of their cowpeas when prices rise off-season.

Constraint of cowpea production

Numerous factors influence the expected yield of cowpea. Such constrain includes low soil fertility, insect pests and drought (Bationo *et al*., 2002). Additionally, Sabo, Bashir, Gidado, Sani and Adeniji (2014) described such limitations to include low yields due to marginal land, pests and diseases, high costs of preparing farmland, socio-economic factors, high labor costs, high costs of pesticides, poor pricing and publicity channels. Thosago (2015) categorized these limitations into abiotic and biotic factors. Therefore, cowpea production is challenged by a multitude of biotic and abiotic limiting factors that significantly reduce yields (Vassilev *et al*., 2012).

Among the abiotic constraint, low fertility status of soils and climate instability are prominent in cowpea production (Lynch, 2007). Many studies

have discovered that low soil fertility results in lower yields than rainfall in the driest parts of the Sahel and other parts of West Africa (Payne, 1997). The low P nature of agricultural soils in Africa could therefore be an important edaphic factor responsible for the observed low cowpea yield on the continent.

Biotic constrains influencing cowpea production include pests and diseases which affect crop yield and general productivity (Rusoke & Rubaihayo, 1994). Such pests include *Striga gesnerioides* and *Alectra* which are common parasitic weeds that reduce the yield of cowpea noticeably in Africa (Parker & Riches, 1993; Rugare *et al*., 2013). Up to 75% of the cowpea damage is done by these weeds before the crop emerges from the soil (Singh & Ram, 2005; Dugje *et al*., 2009). Typical example includes - cowpea wilt caused by *Fusarium osysporium*, cowpea root rust caused by a nematode (*Meloidogyne sp*), aphid-borne mosaic virus, cowpea bacterial blight caused by *Xanthomonas vignicola* and stem rot caused by *Phytophthora vignae*. Losses due to diseases can be as high as 100%.

Soil P availability status in Africa

Low concentration of P is common characteristics of most tropical soils (Osodeke, 2005; Haruna *et al*., 2011). Tropical soils are commonly described as acidic, infertile and often unable to sustain agricultural production (Sanchez & Logan, 1992). A significant proportion of the soils are highly weathered, have low nutrient reserves and therefore limited nutrient supply capacity, of which P is of paramount importance (Bekunda *et al*., 2002). Jama (1999) reported that, 80% of the smallholder land used for cultivation are P-limited. Recent analyzes of Eastern, Central, Southwestern Uganda soil samples have also shown that P

is very low (0- 8.5 mg kg^{-1}; Bray I) (Bekunda *et al*., 2002). This is due to high fixing capacity of most African soils (Kochian, 2012). One of the main factors that cause low availability of P is sorption of P by high levels of Fe, Al and Ca ions found in most tropical soils (McBeath *et al*., 2005). In addition, most African soils are classified as Ferralsols, Acrisol, and Nitisols which are mostly acidic (Sanchez *et al*., 1997) hence, influences the availability of soil P.

Effect of low P on crop production

Phosphorus is an essential component needed for crop production. Phosphorus is required in considerable amount intended for metabolism and cell division, mostly at the tips of young roots and shoots (Razaq *et al.*, 2017). It also helps in the growth of flowers, seeds and fruits (Ndakidemi & Dakora, 2007). Legumes are plants that prefer phosphorus (Sanginga *et al*., 2000). Legumes need P to grow and develop seeds, especially in the energy-driven nitrogen fixation process. Phosphorus also plays an important role in lateral root morphology and root branching (López-Bucio *et al*., 2003) and affects not only root development, but also nutrient availability (Jin *et al.,* 2005).

Phosphorus deficiency on the other hand, affects the development and growth of plant at various growth stages (Grant *et al*., 2005). Low soil P was observed to limit crop production and productivity on approximately 40% of the world's arable land (Vance, 2001). Phosphorus deficiency is the most restrictive soil fertility variables for cowpea cultivation (Bationo *et al*., 2002). Up to 60% reduction in yield have been observed in cowpea due to low soil P (Acosta-Díaz *et al*., 2009). The reduction of inorganic P in chloroplast has also been reported to reduce photosynthesis (Rubio *et al*., 2001). Without any

external supply of P, legumes rely exclusively on available soil phosphorus and other nutrients for nitrogen fixation and development, resulting in yield reduction (Singh *et al*., 2011).

Constrains associated with mineral P fertilizer use

Application of P fertilizers that provide soluble Pi to crops could alleviate the P deficiency problem. Nevertheless, owing to the current trend in consumption, global reserves of rock P are declining (Cordell *et al*., 2009). Considering the finite nature of P rock and its essential role in supplying P to the agricultural system, such possible shortage could have serious consequences for global food production and security (Heckenmüller *et al*., 2014). Furthermore, inorganic P-fertilizers are costive and difficult to reach for resource-poor farmers. The economic cost of using P fertilizers will rise in the future due to production cost of P fertilizers coupled with the non-renewable or finite nature of phosphate rock that could be exhausted at present utilization levels in the next 100 - 400 (Johnston, 2008).

When P is applied, only 15 - 30 percent is used by crops that year due to the characteristic low mobility of Pi (Syers *et al*., 2008), as phosphate (Pi). In addition, P-fertilizer can be fixed by Fe and Al oxides discovered in tropical soils in forms that are not easily accessible to crops (Sample *et al.*, 1980). Consequently, approximately 70–90 percent of P entering the soil is fixed, making it difficult for crops to uptake and use it (Hongjun *et al.*, 2004; Kou *et al*., 1999). Excessive use of P fertilizers can cause environmental issues related to eutrophication (Gaxiola *et al.*, 2011). P fertilizers have been reported to an excellent source of heavy metal noticeably cadmium which builds up in the soil

due to excessive application (van de Wiel *et al.*, 2016). Therefore, current agricultural productivity must ensure the efficiency with which P reserves are utilized for crop growth and development (Cordell *et al*., 2009).

Mechanisms for plant adaptation to low P condition in the soil

Plants have evolved an array of controlled adaptive mechanisms under low P conditions (Sarkar *et al.*, 2014) to ensure greater root soil exploration. Such mechanisms include altered root structure, association with mycorrhiza and chemical modification of rhizosphere (Raghothama, 1999; Vance *et al*., 2003; Lambers *et al*., 2006). The roots of plants obtain soil resources needed by crops for their survival hence, plants tend to change their root systems ' spatial and temporal growth or architecture in reaction to a multitude of environmental signals (López-Bucio *et al*., 2003; Hermans, 2006). Plant roots use a variety of strategies to obtain adequate P under P-deprived soils, including changes in root architecture, increased root hair density and length, cluster roots development and association with arbuscular mycorrhizal fungi (AM-fungi).

Other mechanisms of roots include symbiosis with mycorrhizal fungi, root exudation alteration of the rhizosphere, increased phosphatase output and improved P uptake rate (Shenoy & Kalagudi, 2005). Plants use certain adaptation mechanisms that include root processes, root features, mycorrhizal dependence, parameters of P absorption of kinetics, and processes of rhizosphere (Nielsen & Barber, 1978; Nye & Tinker, 1977).

Effect of phosphorus on growth and yield

Phosphorus is a major mineral element required by plants, but it is one of the least mobile and unavailable nutrients (Narang *et al.*, 2000). Phosphorus limits production on 40 percent of the world's arable soil (Vance, 2001). Phosphorus is a very important macronutrient for the development and function of legumes (Ribet & Drevon, 1996). Phosphorus is essential for yield of cowpea because it stimulates the development shoot and roots, formation of nodules and influences the effectiveness of rhizobium-legume symbiosis (Haruna & Aliyu, 2011). Leguminous crops require P for protein synthesis, energy transfer and physiological processes (Oti,, 2004).

Adequate supply of P result in enhanced production of grain, high-quality plants, enhanced stalk strength, enhanced root growth and early plant maturity (Douglas & Philip, 2002). Supply of P fertilizer to cowpea impacts cowpea yield by doubling the pod number per plant and mean weight of seeds (Owolade *et al*., 2006; Singh *et al*., 2011). Additionally, a substantial rise in seed yield was recorded when P was applied to cowpea genotypes (Nkaa *et al.*, 2014). Similar effect was recorded among cowpea genotypes in terms of 50 seed weight as well as the interactions between cowpea varieties and phosphorus treatments (Nkaa *et al*., 2014).

Phosphorus application significantly improved pod length per plant among cowpea varieties (Nkaa *et al*., 2014). Some yield characteristics such as pod fresh and dry weights, number of pods, length of pods, yield of crops and weight of 50 seeds are enhanced due to the application of phosphorus (Odundo *et al*., 2010; Haruna & Usman, 2013). According to a study by Singh *et al.*

(2011), yield parameters such as grain yield, number of pods per plant, total nitrogen and phosphorus increased as phosphorus application increased.

Effect of phosphorus on dry matter partitioning

Dry matter partitioning describes the flow of assimilates from source organs to vegetative and reproductive sinks (Marcelis, 1996). Productivity of crops depends both on dry matter accumulation and effective partitioning to the seed (Kumar *et al*., 2010). The production and distribution of dry matter is influenced by P application. Plants with P deficiencies produced more root dry matter than shoot due to higher export of photosynthates to the roots (Fageria *et al*., 2006; Oladiran *et al*., 2012). It was discovered that the entire cowpea biomass increased significantly with application of phosphorus. Singh *et al*. (2011) noted unlike dry matter production, harvest index is not influenced by P application since it is a genetic feature and is only influenced by varietal differences. Contrastingly, Malagi (2005) findings revealed a substantial difference in the harvest index due to differing levels of fertilizers with the lowest harvest index with the largest fertilizer dose (NPK). Root and shoot dry weight exhibited a significant response to P application (Okeleye & Okelana, 1997; Odundo *et al*., 2010). Using P at 30 kg / ha increases dry matter production in cowpea by 74% compared to control (Odundo *et al*., 2010).

Genotypic variation in the effect of P on cowpea nodulation (Ankomah *et al*., 1996) and yield (Jain *et al*., 1986; Tenebe *et al*., 1995; Sanginga *et al*., 2000) have been reported. Supply of phosphorus significantly enhanced dry weight of nodules, dry weight of shooting and root total biomass (Singh *et al*., 2011; Oladiran *et al*., 2012). According to Oladiran *et al*. (2012), adequate

application of external P at 40 mg P/kg soil significantly increased the number of nodules among cowpea genotypes during their study, however genotypes insignificantly affected the number of nodules recorded during the study. Similar report was presented by Agboola and Obigbesan (1977) and Luse *et al*. (1975) who concluded that, application of P causes a significant increase in the number of nodules in cowpea. This justifies the role of P in the formation of nodule in cowpea.

Effect of P on flowering of crops

Increased use of P significantly improves reproductive yields (Egle *et al*., 1999) as well floral growth and development, especially when P in natural systems is limited (Feller, 1995). In contrast, P supply limitations have resulted in a reduction in the production of floral structures (Ma *et al*., 2001). Phosphorus deficiency can delay blooming and maturity as shown by Holland *et al*. (1999). The use of P in cowpea reduced the time between planting and green pod harvesting and hastened maturity. Phosphorus was also recorded to raise the quantity of leaves and fruits per plant, flowering and early yield (Kudikeri *et al*., 1973).

Root System Architecture (RSA)

Root system architecture (RSA) refers to the arrangement, length/biomass quotient and the three-dimensional distribution of the root traits (primary and lateral roots) and other accessory roots in the rhizosphere (Lynch, 1995; Ning *et al*., 2012; Smith & De Smet, 2012). Root system architecture

(RSA) describes the shape and structure of the root system within the rhizosphere (Hodge *et al*., 2009). Root architecture refers to the root's system spatial configuration, i.e. the explicit geometric deployment of root axes (Lynch, 1995). The shape of root system describes the spatial distribution of root features (rooting depth, elongation and density of the lateral roots and root hair) occupies the soil horizon. Root structure relates to the interconnection between multitude of root system traits and parts (Hodge *et al*., 2009).

The root system incorporates three features to form its architecture; the topology, distribution, and morphology of the root system (Lynch, 1995). Topology as detailed by Fitter (1985) defines how individual roots are branched. He further described roots as a branching tree classified as a unit by links or internodes with the links or internodes. These links include - External link (E) - a root between a meristem and secondary root and internal connection (I)-a root between two secondary root axes or between an axis and a stem (Fitter, 1986).

The root characteristics of the connections include lengths and diameters, number of node roots, root insertion angles, magnitude (Glimskär, 2000). Root distribution is derived from characteristics such as biomass and length and is expressed as a function of soil depth or arrangement in rhizosphere. Destructive sampling could be used to estimate the distribution of the root system, and this is often measured to quantify the fraction of soil resources available to roots (Votrubová, 2002). Root morphology, on the other hand, refers to the external characteristics of a root axis or organ and may include root hair properties, root diameter and secondary root development pattern (Fitter, 1986).

Importance of root system architecture

Mostly under field conditions where water and nutrients are heterogeneously distributed in the soil, RSA plays a vital role via the uptake of these resources (Lynch, 1995), since RSA significantly determine exploration of distinct spatial domains in the soil (Lynch, 1995). Plant root systems perform many essential functions including water and nutrient absorption, soil anchorage and rhizosphere biotic interactions (López-Bucio *et al*., 2003; Lynch, 2013; Lynch & Brown, 2001)

Root architecture is essential for the acquisition of vital soil resources such as nitrogen and P is immobile and limiting (Lynch, 1995). Absorption of phosphorus is mostly increased by greater length and density of root hair (Lynch, 2011; Miguel *et al*., 2015). Numerous studies have identified the importance of a deep root system in crops such as rice, millet and sorghum to absorb water from deeper soil layers in water-stressed environments (Reynolds *et al*., 2006; Hammer *et al*., 2009). The tap roots of most desert plants are capable of storing large amounts of water (Graham & Nobel, 1999).

Roots also host many soil microbes whose proliferation inside or outside the root surface is inadvertently catalyzed by the release of C from the root cells into the rhizosphere (Gregory, 2006; Lambers *et al*., 2009). Increased rhizodeposition may in effect stimulate N mineralization from the pools of recalcitrant organic soil (De Graaff *et al*., 2009).

Coarse or tap roots anchor plants and establish root system architecture, control root system depth and thus determine the ability of a plant to grow under a compact soil profile (Henry *et al*., 2011). Roots also anchor the plant to prevent wind, water or other mechanical disturbances from dislocating it (Sitte

et al., 2002). According to Smucker (1993), root systems function in photosynthesis, respiration and ensure a balance between the biomass below and above the soil. In epiphytic orchids and mangrove aerial roots, root respiration is particularly common.

Factors that influence the development of root system

A variety of biotic and abiotic factors affect the growth, development, and penetration of root system in the rhizosphere (López-Bucio *et al*., 2003; Malamy, 2005). The root system is therefore a highly plastic feature, which means that genotypically identical plants can differ greatly depending on their macro- and micro-environment (Osmont *et al*., 2007). These factors include water content of soil, soil properties, nutrient accessibility (Nibau *et al*., 2008).

The physical and chemical properties of soil have significant impact on root elongation in cereals (Rogers *et al*., 2016). Soil compaction causes general irregular root growth (shorter, thicker), shape (bell, tortuous), and distribution in the agroforestry, agronomic and horticultural plants (Alameda & Villar, 2009; Grzesiak *et al*., 2013; Tracy *et al*., 2013). Moderate bulk density on the other hand, improves root growth in the nutrient-rich loamy soils (Tracy *et al*., 2013). Likewise, soil texture also affects root phenes by regulating oxygen, water, and nutrients supply to the roots (Tracy *et al*., 2013; Rogers *et al*., 2016).

The growth and development of root system has been noted to be affected by macro- and micro-nutrient status of the soil (Saleem *et al*., 2018). For instance, lateral rather than primary roots are more sensitive to nitrogen supply in the soil (Tian *et al*., 2014). Exposure to high nitrate leads to decline

in lateral root growth just before lateral root meristem activation (Zhang & Forde, 1998). Nitrate itself has also been shown to boost this increased growth of the lateral root (Zhang *et al*., 1999). Phosphate is a significant plant nutrient that has been shown to affect the development of the root system among various crop species (López-Bucio *et al*., 2002). Low P levels result in decreased primary root growth, increased lateral root numbers, and lateral root growth closer to the primary root tip (López-Bucio *et al*., 2002). Under sulfate deficient condition, the root system of *Arabidopsis* developed profuse branching root (López-Bucio *et al*., 2002).

Abiotic factors such as drought, temperature, rainfall, greenhouse gasses (i.e., CO_2) and climate change also affect the growth of the root system (Saleem *et al*., 2018). Soil biodiversity (i.e., nematodes, protists, bacteria, fungi, phages) and its ecological interactions with plants may influence the root system and its characteristics (Yang *et al*., 2015).

Effect of P on RSA traits

Soil nutrients are essential to the growth and productivity of plants. The bioavailability of these nutrients in the soil solution influences root growth, root proliferation and unique functional responses depending on the plant's prevailing nutrient status (López-Bucio *et al*., 2002). Among soil nutrient reported to regulate post-embryonic root developmental processes are N, P, iron (Fe) and sulfur (S) (López-Bucio *et al*., 2002) of which P is prominent (Giehl & von Wirén, 2014). Plants respond to phosphate availability by altering RSA to enhance soil exploration and uptake capacity (Ingram & Malamy, 2010).

According to López-Bucio *et al*. (2002), root system processes influenced by soil P status include - primary root growth, lateral root number and lateral roots density. Soil available P ions modifies the root system characteristics by influencing the development processes that regulate lateral root primordium initiation and emergence, primary and lateral root growth, lateral root angle and root hair density and elongation rate (López-Bucio *et al*., 2003, 2002).

Root Growth

Lateral roots emerge from branching of a primary root in legumes however, they are primarily made of adventitious roots in cereals (Sarkar *et al*., 2014). Lateral roots boost the acquisition of root P by increasing soil exploration, the root system's absorptive surface and P solubilization (Sarkar *et al*., 2014). The supply of P affects lateral roots ' growth and proliferation. *Arabidopsis* research showed that low P increases lateral root growth by decreasing primary root elongation and increasing lateral root elongation and density (Williamson *et al*., 2001). López-Bucio *et al*. (2002) suggested that, low P conditions reduces the rate of cell division as well as inhibits cell growth in the root elongation zone of primary root tip. Phosphorus deficiency results in to shallow root system with longer lateral roots (Péret *et al*., 2011). With increasing phosphate supply in *Arabidopsis*, the lateral root density decreased dramatically. High nitrate and high phosphate availability suppress lateral root elongation (Linkohr *et al*., 2002). Under low phosphorus conditions, the initiation of lateral roots and lateral-root density are reduced (Borch *et al*., 1999).

Primary root growth is reduced under P-limiting medium. This is due to reduced cell differentiation in the primary root meristem and cell proliferation inhibition in the root elongation zone (Ticconi *et al*., 2004). Several studies indicated that P deficiency in plants such as *Arabidopsis* resulted in a significant reduction in primary root growth (Williamson *et al*., 2001; Jain *et al*., 2007). Reduced growth of primary root systems is beneficial in the development of a shallow root system to ensure more efficient acquisition of topsoil resources in a P-limiting environment (Sarkar *et al*., 2014).

Root length

The length of the root specifies the length of the root per unit of root mass. In response to P supply, plants are also known to change their specific root length - an increased specific root length under low P conditions is observed (Schroeder & Janos, 2005). Similarly, Bates and Lynch (1996) found that, Root hair elongation, lateral roots and density of root hair increased but total root length decreased under P stress conditions in *Arabidopsis thaliana*. Zhu, Kaeppler and Lynch (2005) also observed that P deficiency in the top soil of P-efficient corn cultivars enhanced the total root length and specific root length. In a research with soybean, sunflower and maize, Fernández *et al*. (2009) noted an increase in the specific root length with a decline in P supply. In maize, some genotypes respond to low P by increasing the number and length of lateral roots, while others have the opposite effect (Bayuelo-Jiménez *et al*., 2013). In low-P soils, three-whorl cowpea genotypes produced nearly twice the biomass of the shoot, greater total root length and greater area of the leaf compared to two-whorl genotypes. (Miguel *et al*., 2013). Studies in the Col-0 accession of

Arabidopsis, however, found that low phosphorus reduces the primary root length (Linkohr *et al*., 2002; Reymond *et al*., 2006; Williamson *et al*., 2001).

Root branching

A reduced gravitropic trajectory of basal roots, adventitious rooting and altered dispersion of lateral roots enable topsoil foraging in response to low P availability (Miguel *et al*., 2015). Studies in *Arabidopsis thaliana* and other rape cultivars showed that when crops were cultivated under low P soil, there was an increased branching with reduced primary root and an increased number of lateral roots in the root system (Akhtar *et al*., 2008; Pérez-Torres *et al*., 2008). Low P levels influence the angle of the basal roots to expand outward rather than downward, leading to a shallower and wider root system as seen in common beans (Lynch, 2007; Ramaekers *et al*., 2010). For maize, however, plants grow fibrous root systems that are typically more widespread than the basal roots of the soybean tap-root system (Sarkar *et al*., 2014). Liao *et al*. (2001) research on common fruit revealed that, availability of P altered the shallowness of the basal root and found that P deficiency produced shallow root system. The growth of primary and basal root axes in beans is increased under low P conditions (Borch *et al*., 1999). Shallow basal roots, increased adventitious rooting and increased lateral branching from the basal roots have been reported as root system traits associated with topsoil foraging in cowpea (Lynch, 2007; Ramaekers *et al*., 2010). This implies basal root angle changes outward than growing downward when crops are cultivated under low p conditions leading to shallower and wider root system. This argument is supported by the correlation found between the capacity of bean cultivars to decrease root angle in low-P and yield in poor P soils (Bonser *et al*., 1996). A

shallow root system efficiently exploits top-soil resources that are useful in low-P soils. This may, however, inadvertently result to lower water absorption (Sanders & Markhart III, 1992). In common beans, (Lynch, 2011) noted that the top whorls produce basal roots with a shallower growth angle, while the bottom whorls produce gradually steeper angle roots.

Root number and diameter

Low phosphate availability results in increasing lateral root number and developing lateral roots closer to the primary root tip (López-Bucio *et al*., 2002). Studies with *Arabidopsis thaliana* and other rape cultivars showed that when crops were cultivated under low P soil, there was reduced primary root and an increase number of lateral roots in the root system (Akhtar *et al*., 2008; Pérez-Torres *et al*., 2008). Cowpea alters the number and diameter of lateral roots in a more gradual manner along the hypocotyl and radical (Burridge *et al*., 2016). Comparisons of basal and hypocotyl roots show genetic variation for growth angle but angles of basal roots vary less in cowpea than in common bean (Burridge *et al*., 2016).

Methods of quantifying Root System Architecture (RSA)

Root system architecture have been defined in varying ways ranging from mathematical concepts (e.g. fractals) to comprehensive 3D structures. Duhamel du Monceau is credited as pioneer for the concept of RSA because he studied root systems of trees from 1764-1765 (Kramer & Boyer, 1995). The study of RSA previously consisted mainly of digging roots and measuring their

weight and length manually. To study root systems, many others also cultivated plants in containers (Bates, 1937). This included observing, sketching or tracing and quantifying crop root systems in the field or in pots (Bates, 1937; Hiltner, 1904; Kutschera, 1960). The most popular and easiest technique of investigating roots in the field is to excavate and wash from the soil to assess their length and architecture. Other classical root study methods entail destructive soil sampling techniques including core, monolith, and profile (Zhu *et al*., 2011). It is also possible to use trench profiles to assess root spatial shape and more importantly, the root system. Although, trench profiles provide quantitative information about the root system, it however provides measurement for only limited fraction of the rot system as a result of significant soil destruction (Pierret *et al*., 2003).

Nutrient use efficiency (NUE)

Nutrient efficiency (uptake and utilization) have been outlined in many respects. Variations in the definition of nutrient uptake and nutrient efficiency calculation methods make it hard to compare the results of distinct research. Efficiency can be defined in simple terms as the proportion of output (economic output) to input (fertilizer) for a process or complex system. (Crop Science Society of America, 1992). Variations among crop species and genotypes of the same species in nutrient absorption and utilization have been reported (Baligar *et al*., 2001; Epstein & Bloom, 2005). Crop nutrient efficiency can be distinguished between absorption efficiency (P-acquisition efficiency, PAE) and efficiency of inner use (P-use efficiency, PUE) (Veneklaas *et al*., 2012).

Phosphorus use efficiency (PUE)

Phosphorus use/utilization efficiency is referred to as dry matter or yield per unit of P acquired or supplied (Hammond *et al*., 2009). There are numerous measures of PUE as suggested by White *et al*. (2005) and White and Hammond (2008). A common measure of PUE is the increase in yield per unit of added P fertilizer (g DM g^{-1} P_f), often referred to as the agronomic P use efficiency (APE) in the literature. Literally, this corresponds to P uptake efficiency (PUpE) (product of the increase in plant P content per unit of added P fertilizer (g P g^{-1} P_f) and P utilization efficiency (PUtE) (the increase in yield per unit increase in plant P content (g DM g^{-1} P) (Hammond *et al*., 2009).

Table 1 - Definitions of phosphorus use efficiency (PUE)

Name	Calculation	Units
Agronomic P use efficiency	$(Y_{high}–Y_{low}) / \Delta Papp$	g DM g^{-1} P_f
P uptake efficiency	$[(Y_{high} \times Y_{low}) – (Y_{low} \times Y_{low})] / \Delta Papp$	g P g^{-1} P_f
P utilization efficiency	$(Y_{high}–Y_{low}) / [(Y_{high} \times Y_{high}) – (Y_{low} \times Y_{low})]$	g DM g^{-1} P_f
Physiological P use efficiency	Y_{high} / Y_{high} or Y_{low} / P_{low}	g^2 DM g^{-1} P_f
P efficiency ratio	$Y_{high} / (P_{high} \times Y_{high})$ or $Y_{low} / (P_{low} \times Y_{low})$	g DM g^{-1} P_f

(Hammond *et al*., 2009).

Y_{high} = yield on a high P/fertilized soil; Y_{low} = yield on a low P/unfertilized soil; Y_{high} = tissue P concentration on a high P/fertilized soil; Y_{low} = tissue P concentration on a low P/unfertilized soil; ΔPapp = difference in amount of P applied as fertilizer between high and low P treatments; DM = dry matter; P_f = fertilizer P.

Phosphorus use/utilization efficiency covers a wide range of physiological, structural, and developmental characteristics as they regulate the use of P at the tissue level and the allocation and reallocation of P between

different functions and efficiencies of plant parts. Better allocation of nutrients in plant parts (root, shoot and grain) represents their use efficiency. Genotypes with high PUE either produce comparable yields with reduced inputs of inorganic Pi fertilizers or have reduced physiological P requirements and tissue P concentrations (Hammond *et al*., 2009). Higher concentration of grain N and P improves production, leading to higher efficiency in the use of these nutrients (Fageria *et al*., 2006).

Phosphorus acquisition efficiency (PAE)

One of the mechanisms responsible for efficient plant uptake is the capacity within species of certain plant or genotypes to absorb nutrients at a higher rate at small and/or high concentrations of medium nutrients. While PUE seeks to generate more biomass at lower P expenses, P acquisition efficiency (PAE) is defined in terms of the capacity to improve soil P uptake, particularly from unavailable soil P conditions (Hammond *et al*., 2009). Most scientists generally describe PAE as the relative difference in low and high availability of P (Vandamme *et al*., 2013; Seguel *et al*., 2015). Phosphorus acquisition efficiency describes the ratio of shoot Pi content under Pi-deficient conditions and Pi shoot content under a normal Pi supply (Lopez-Arredondo *et al*., 2014).

Phosphorus acquisition efficiency is influenced by root system traits that enhances Pi availability in the soil solution, including the type and rate of efflux of organic acids (OAs) and phosphatases from the root into the rhizosphere (Lopez-Arredondo *et al*., 2014). Plant uptake of available soil P is determined by activities of numerous Pi transporters and is significantly influenced by the

root exploration capacity; the Pi uptake and scavenging capacity, which is influenced primarily by RSA (Lopez-Arredondo *et al*., 2014).

CHAPTER THREE

MATERIALS AND METHODS

Study area

The study was carried out at the Teaching and Research Farm of School of Agriculture (A.G Carson technology area), University of Cape Coast (UCC; 5.1155 ° N, 1.2909 ° W). Usually, temperature and relative humidity of the area ranges between 24 ° C - 32 ° C and 60 percent to 80 percent respectively (Abbey & Oppong-Konadu, 1997)). Day length of the area ranged from 11.30 to 12.40 hours with atmospheric radiation ranging from 3151 KJ cm^{-2} day^{-1} to 3804 KJ cm^{-2} day^{-1} (Adu *et al*., 2017). The area experiences a bi-modal rainfall pattern (May to June and from August to October) with an annual rainfall of 750 to 1000 mm from (Asare-Bediako *et al*., 2014).

The soil was a haplic acrisol with a sandy loam textural class, composed of 30.2, 56.3 and 13.5% clay, sand, and silt, respectively and was typical of arable soils of the coastal savannah agro-ecological zone of the Central region of Ghana. Screening of cowpea genotypes was carried under rain-fed condition between June - September 2018 (major season) and November - February 2019 (minor season).

Genetic materials

Twenty (20) cowpea genotypes were used for the study (Table 2). The genotypes comprised of improved local cowpea varieties, introduced inbred lines of cowpea and landraces. The genotypes of cowpea were obtained from

the Council for Scientific and Industrial Research (CSIR-Fumesua), Uganda and the International Institute of Tropical Agriculture (IITA) (Table 2).

Table 2 - Genetic characteristics and source of cowpea genotypes used for the study

Genotype	Cultivar type	Source	Seed colour	Growth habit
Soronko	Improved	Ghana	Red	Semi-erect
Asontem	Improved	Ghana	Red	Semi-erect
Agyenkwa	Improved	Ghana	white	Semi-erect
Songotra	Improved	Ghana	white	Erect
NE 15*WC 35B	Inbred line	Uganda	Brown	Semi-erect
Nketewadea	Improved	Ghana	white	Semi-erect
Secow 5T	Improved	Uganda	Brown	Semi-erect
WC 36	Landrace	Uganda	Brown	Semi-erect
IT91	Inbred line	IITA	Brown	Semi-erect
MU9	Landrace	Uganda	Brown	Semi-erect
Alegi*Secow 5T	Inbred line	Uganda	Brown	Semi-erect
NE 48*WC 10	Inbred line	Uganda	Brown	Semi-erect
WC 35B*NE 50	Inbred line	Uganda	Brown	Semi-erect
NE 15*Sunshine	Inbred line	Uganda	Brown	Semi-erect
Alegi*Sunshine	Inbred line	Uganda	Brown	Semi-erect
WC 10*WC 36	Inbred line	Uganda	Brown	Semi-erect
Sunshine	Landrace	Uganda	Brown	Semi-erect
Secow 3B	improved	Uganda	Brown	Semi-erect
NE 50	Landrace	Uganda	White	Semi-erect
NE 51*NE 50	Inbred line	Uganda	Brown	Semi-erect

Research design

An 8 × 8 alpha lattice design with four replications was used for screening the cowpea genotypes in the field. Field screening of cowpea genotypes was carried out in both major and minor season. Each replication consisted of 60 subplots (2.8 m × 1.8 m) on which treatments were randomized.

Treatments

Treatments used for the study were twenty (20) cowpea genotypes (Table 2) and concentration of external phosphorus. Three (3) rates of P (0, 10 and 45 kg P/ha) based on initial soil analysis and recommended application rate was used for the study. Triple super phosphate (TSP) was P-fertilizer used for the study. Zero (0) kg P/ha TSP served as the control treatment for the experiment. At 10 kg P/ha, 0.85 g of TSP was applied and 3.82 g TSP per plant was applied for treatment 45 kg P/ha which was estimated as shown in (Appendix 4). Same field and randomization were used for evaluating cowpea genotypes in the major and minor conditions.

Field Preparation

Ploughing and laying out the field

Experimental field was slashed after which debris were gathered and collected from the planting area. The field was ploughed and harrowed at a depth of approximately 30cm. A total of 1332.6 m^2 plot size was used for the study during each growing season. Main field was demarcated into four replications or blocks of size 302.4 m^2. Each replication or block was further divided into 60 subplots (2.8 m × 1.8 m). Subplots were spaced 1 meter apart and replications/blocks were spaced 1.5 meters apart.

Analysis of chemical and physical characteristics of the soil

Analysis was carried out on the following initial soil physicochemical properties of the experimental site (soil pH, total nitrogen (N), total phosphorus

(P), magnesium concentration (Mg), calcium (Ca) and exchangeable K (potassium). This was carried out in order to be informed about the current status of the experimental field since these physicochemical properties influence the yield of crops (Table 3). Maize had previously been cropped on the site but had been lying fallow for seven (7) months before the current experiment.

Table 3 - Initial physical and chemical characteristics of experimental field

PARAMETER	**VALUE**			
Chemical properties	**BLOCKS**			
	B1	**B2**	**B3**	**B4**
Nitrogen (N) %	0.12	0.16	0.13	0.13
Phosphorus (P) µP	36.4	35.23	27.44	34.01
Potassium (K) cmol/kg	0.06	0.08	0.09	0.08
Calcium (Ca) cmol/kg	10.55	13.54	10.44	9.08
Magnesium (Mn) cmol/kg	0.71	0.99	0.43	0.60
Physical properties	**B1**	**B2**	**B3**	**B4**
pH	7.34	7.11	7.40	7.15
CEC (cmol/kg)	1.70	2.41	1.80	1.38
Bulk Density (g/cm3)	1.41	1.37	1.40	1.44
Particle Density (g/cm3)	2.70	2.73	2.67	2.47

Source - (Field data, 2018)

Planting and Cultural practices

Cowpea genotypes were planted in rows of 5 with each row having 6 plants. A planting distance of 70 cm between rows and 30 cm within row was used. A total population of 30 plants were obtained within each subplot.

Healthy seeds of cowpea genotypes were planted manually using a hand dibber. Seeds were sown at a depth of 2-3cm below soil surface. Germinated

seedlings were thinned to 1 plant per stand a week after germination. Application of TSP ($[P]_{ext}$) was carried out two (2) weeks after germination using ring method of fertilizer application.

Weeds were controlled by manual hoeing on the 3rd and 6th weeks after germination. Field was mainly under rainfed conditions but irrigation of experimental field was carried out as and when needed using a sprinkler irrigation system connected to a tap water. Pests were controlled with Dursban with active ingredient chlorpyrifos. The first pesticide spraying was carried out before flowering and the second spraying done during pod formation at a rate of 30 ml/15 litters of knapsack sprayer.

Experiment 1 - Screening for genetic variation and effect of $[P]_{ext}$ on RSA traits among cowpea genotypes

Excavation of cowpea genotypes

Excavation of crops for root analysis was done at anthesis. Four (4) representative plants was selected for excavation and root system analysis. Selection was carried out randomly but only fully bordered plants were selected. Excavation was done manually early in the morning to avoid excessive loss of moisture from excavated plant materials. Research field was irrigated to field capacity three (3) days prior to excavation in order to loosen soil for ease of - excavation and reduction in root damage. Selected data plants were tagged. To excavate, a standard spade was forced gently into the soil 30 cm away from stem of the plants and 30 cm deep into the soil in order to get root ball from the soil. Root ball was gently removed from the soil and soaked in a basin containing

water and washed free of soil lumps to remove root crown. Shoot were then separated from the roots, carefully packed in a well labelled envelope for drying. Roots were then placed in a basin filled with water to avoid loss of moisture.

Data Collection

Data on RSA parameters were collected manually from excavated roots. The evaluation of the RSA traits was based on the protocol described by Adu *et al*. (2019) and Burridge *et al*. (2016).

Evaluation of root system architectural traits

Root system architecture was manually scored on the following traits - stem diameter (SD), hypocotyl root length (HRL), hypocotyl root diameter (HRD), hypocotyl root number (HRN), hypocotyl root angle (HRA), number of basal root (BRN), length of basal root (BRL), basal root angle (BRA), taproot diameter at 5cm (TRD), 3rd order branching density within 10cm (3rd BD), nodule diameter (ND) and nodule number (NN) (Appendix I).

Stem diameter of excavated root was measured using digital hand-held calipers. Measurement was taken around the collar region (section between stem and point of first root development) of the plant (Appendix I).

Hypocotyl root length (HRL) - Hypocotyl root length was an average of three (3) randomly chosen representative root and measured using a meter rule. The number of roots forming the first crown was counted to represent the hypocotyl root number.

Average diameter of three (3) randomly selected hypocotyl roots was used to represent the diameter of hypocotyl root. Diameter was measured using

a per of hand-held digital calipers (Moore and Wright) at 2cm from origin of the representative root.

A standard shovelomics scoreboard (*http -//roots.psu.edu*) was used for measuring the branching angle of hypocotyl roots at within 5 and 10cm on the standard board. The tap root was placed on the 90^0 line on the board from which both hypocotyl and basal root growth angles were traced and recorded**.**

In this study, basal root was considered as the next set of root crown after the hypocotyl root crown (Appendix I). Basal root length was an average of three (3) randomly chosen representative root and measured using a meter rule.

Basal root diameter was the mean diameter of three (3) basal roots that were randomly selected. Diameter was measured using a pair of hand-held digital calipers (Moore and Wright) at 2cm from origin of the representative root. Basal root angle was measured using a standard shovelomics scoreboard (*http -//roots.psu.edu*) within the 5 and 10 cm on the standard board.

Diameter of three (3) randomly selected nodules were measured using a digital caliper along the widest nodule point if the nodule was not symmetrical. Mean of diameter was calculated to represent nodule diameter for each treatment combination. Nodule number was visually counted and recorded.

Third order branching density was visually counted within 10 cm on representative lateral roots. Third order branching in this study was considered as the number of root branching from the main lateral root (Appendix I).

Assessing genotype variation in the uptake and utilization of external P among field grown cowpea lines.

Data collection

Data was collected on the tissue P content and concentration of cowpea genotypes. Shoot and root samples were blended after which three (3) replicates from each treatment combination was used for tissue P concentration analysis for both roots and shoots.

Tissue phosphorus analysis

Phosphorus concentration in shoot and root samples were determined using spectrophotometric protocol as described by Heffernan (1985). Five (5) mL of 18 M H_2SO_4 digestion mixture was used to digest 1g of milled samples at 360 °C for 2 hours. Digested samples were then diluted to 100 ml of distilled water. One (1) ml of the diluted solution was pipetted into 25 ml beaker and 4ml of reagent B (ascorbic acid mixture) was added and was topped to 25ml mark with distilled water. A set of standard P solutions containing 0, 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 ppm P was prepared. The set up was allowed to stand for 15 minutes for blue colour to develop and thereafter phosphorus content determined using a spectrophotometer. Absorbance of each sample was recorded upon reading (Heffernan, 1985).

Estimating P uptake and use efficiency

Parameters on phosphorus uptake and use efficiencies was estimated using formulas as described by Hammond *et al*. (2009).

Agronomic P use efficiency

Agronomic phosphorus use efficiency (APE) was calculated by the Equation 1;

$$APE = (Y_{high} – Y_{low}) / \Delta Papp \quad \text{Eqn (1)}$$

Where; Y_{high} = Yield on P amended soil; Y_{low} = Yield on unamended soil and ΔPapp = difference in amount of P applied as fertilizer between P amended and unamended soil treatment.

Phosphorus uptake efficiency

Phosphorus uptake efficiency (PUpE) was calculated by Equation 2

$$PUpE = [(Y_{high} \times Y_{low}) – (Y_{low} \times Y_{low})] / \Delta Papp \quad \text{Eqn (2)}$$

Where; Y_{high} = Yield on P amended soil; Y_{low} = Yield on unamended soil and ΔPapp = difference in amount of P applied as fertilizer between P amended and unamended soil treatment.

Phosphorus efficiency ratio

Phosphorus efficiency ratio (PER) was calculated by Equation 3

$$PER = Y_{high} / (P_{high} \times Y_{high}) \text{ or } Y_{low} / (P_{low} \times Y_{low}) \quad \text{Eqn (3)}$$

Where; Y_{high} = Yield on P amended soil; Y_{low} = Yield on unamended soil, P_{high} = tissue P concentration on P amended soil treatment; P_{low} = tissue P concentration on unamended soil treatment and ΔPapp = difference in amount of P applied as fertilizer between P amended and unamended soil treatment.

Phosphorus utilization efficiency

Phosphorus utilization efficiency (PUtE) was calculated by Equation 4.

$$PUtE = (Y_{high} - Y_{low}) / [(P_{high} \times Y_{high}) - (P_{low} \times Y_{low})] \quad \text{Eqn (4)}$$

Where; Y_{high} = Yield on P amended soil; Y_{low} = Yield on unamended soil, P_{high} = tissue P concentration on P amended soil treatment; P_{low} = tissue P concentration on unamended soil treatment and $\Delta Papp$ = difference in amount of P applied as fertilizer between P amended and unamended soil treatment.

Physiological P use efficiency

Physiological P use efficiency (PPUE) was calculated by Equation 5.

$$Y_{high} / P_{high} \text{ or } Y_{low} / P_{low} \quad \text{Eqn (5)}$$

Where; Y_{high} = Yield on P amended soil; Y_{low} = Yield on unamended soil, P_{high} = tissue P concentration on P amended soil treatment and P_{low} = tissue P concentration on unamended soil treatment.

Effect of $[P]_{ext}$ on yield and biomass production among field grown cowpea genotypes

Harvesting of pods

Pods were harvested at physiological maturity when the leaves turned pale green to yellow and dropped off the stem and at weekly intervals when the pods turned brown. Harvested pods were collected in viva poly bags, labelled for easy identification then sun-dried to ensure smooth threshing and bagging. The total area/plot of data plants was estimated which was used for the various yield calculation.

Data collection

Yield parameter

Five (5) randomly selected middle row crops were used for collecting data on yield. Yield data included - number of days to first flowering, number of days to 50% flowering, number of branches per plant, number of pods per peduncle, number of pods per plant, pod length (cm), number of seeds per pod, and 100 grams of seed weight. Grain yield (t ha^{-1}) was estimated for yield per plot.

The number of days to the first flowering of each cowpea genotype was estimated by the total number of days from planting to flowering. The number of days from sowing to 50 percent flowering of crops on each plot was estimated for each treatment. The pods of each data plant were separated and counted to obtain the number of pods per plant**.** Total number of pods per peduncle for each tagged plant was manually counted at physiological maturity. The length (cm) of fifteen (15) randomly selected pods from each data plant was measured using a meter rule. The mean length was calculated to represent the pod length per genotype. Hundred seeds from each data plant were randomly counted and weighed. The weight obtained represented the weight of 100 seeds per plant. Seeds of five (5) randomly selected pods on each data plant was counted. Mean value was calculated to obtain number of seeds per pod for each plant as follows -

$$\text{Number of seeds per pod} = \frac{\text{Number of seeds counted}}{\text{Number of pods counted}} \qquad \text{Eqn} \quad (6)$$

Grain yield was determined from a plot of 0.7 m x 1.2 m (0.84 m^2) measured

within two middle rows of each plot. The grain yield computed from this area was used to calculate the yield per hectare.

Data on biomass

The fresh weight of both the root and shoot samples was determined by weighing with electronic balance. The fresh weight of roots and shoots were recorded after excavation. After extracting RSA traits, roots and shoots were oven dried at 80 ^{0}C for approximately 3 days to constant weight and weighed with electronic scale to obtain dry weight of shoots.

Experiment 2 - Effect of $[P]_{ext}$ on physiological seed quality of cowpea genotypes.

Seed sample

Fifty (50) healthy seeds were randomly counted from the well-mixed pure seeds harvested from each of the treatments from the field trial (ISTA, 2013). Replicates of 10 seeds were used for seed testing, spaced enough to minimize the impact of neighboring plants on the growth of seedlings.

Preparation of seed testing soil (germination medium)

Sand collected from seashore was treated and used as germination medium. The collected sand was screened through a sieve to obtain a more uniform medium and isolate foreign debris from the soil sample (ISTA, 2013). Jute sacks were used to pack the sand and washed under running tap water for

5-6 hrs to flash out the salt content of the soil. Soil sample was sterilized at a temperature of 150 ^{0}C for four (4) hours. Sterilization was to destroy pathogens and keep the soil medium sterile. The pH of the sand was determined using a pH meter and the value obtained was 8.5.

Sowing of seeds

Seed trays for the experiment were disinfected using 70 % bleach and arranged on laboratory table. Sterile soil was then moistened with distilled water after which trays were filled to about 2/3 the depth leaving space above. The seeds were then sowed into the medium. This was followed by covering the seed tray (medium) with transparent poly bags to help retain the moisture within the medium for the entire duration of the test, thus, reducing evaporation of moisture from the medium. The trays were then arranged on a working bench in the laboratory using a Completely Randomized Design since a uniform condition was expected to prevail in the laboratory.

Data on physiological seed quality

Laboratory experiment for investigating physiological quality of cowpea seeds was based on protocol as described by ISTA (2013). The experiment lasted for a period of 14 days after which final computations were made. Data on physiological quality was collected from day 1 until the 14th day after sowing of seeds. Any seed which germinated each day within this period was counted and recorded on daily basis.

Below are formulae for estimating various parameters taken**;**

$$\text{Germination Percentage} = \frac{\text{Number of seeds germinated}}{\text{Total number of seed sown}} \times 100 \quad \text{Eqn (7)}$$

The value of germination was calculated using the suggested formula (Hartmann, Kester, Davies, & Geneve, 1997)

$$\text{Germination Value} = \text{(Final) MDG} \times \text{PV MDG} \quad \text{Eqn (8)}$$

Where -

Final MDG = Final Mean daily germination

PV MDG = Peak value mean daily germination

The rate of germination was calculated using the suggested formulae (Ghorbani, Seel, & Leifert, 1999), as follows -

$$\text{Germination Rate} = \frac{\text{Number of germination from } n-1}{n} \quad \text{Eqn (9)}$$

Where;

n = Days after sowing

The coefficient of germination speed was also determined using the formulas established by Hartmann, Kester, Davies and Geneve (1997).

$$\text{Coefficient of velocity of germination } (GV) = \frac{1}{\textbf{Mean days}} \times 100$$

Eqn (10)

Where

$$\text{Mean days} = \frac{(N1T1+N2T2+\cdots NXTX)}{\text{Total number of seed germinaton}} \times 100 \quad \text{Eqn (11)}$$

Where;

N = number of germinations

T = Days after sowing

Statistical Analysis

Analysis of Variance (ANOVA)

Data from both major and minor season were combined to determine descriptive statistics, including mean ($\overline{x}$), standard deviation (σ) and the coefficient of variation (CV). Residual maximum likelihood (REML) procedures were used to estimate variance components for all the traits and ANOVA was used to determine variation between genotypes, phosphorus, trials, and selected interaction effects depending on the experiment. All factors were categorized as random factors in REML so that the proportional contribution of genotype to overall variation in traits could be determined (Adu *et al*., 2018). Analysis of experimental data was based on the following model.

$$y_{ik} = \mu + g_i + p_k + gp_{ik} + \varepsilon_{ik} \qquad \text{Eqn (12)}$$

where - y_{ijk} = observation from the ik^{th} genotype and phosphorus level, μ = overall mean, gi = effect of the i^{th} genotype, p_k = effect of the k^{th} phosphorus level, gp_{ik} = interactive effect of the i^{th} genotype with the k^{th} phosphorus level, gp_{ik} = interactive effect of the i^{th} genotype with k^{th} phosphorus level and ε_{ik} = experimental error.

Principal components analysis (PCA) was carried out. The correlation matrix was the basis for PCA, while the number of major components was estimated on the basis of the Kaiser criterion, retaining any component with a uniqueness of more than one (Kaiser, 1960; Tabachnick & Fidell, 1996).

Broad heritability (H^2) was estimated as the quotient of the estimated genotypic variance and the characteristic's full phenotype variance (π^2_g/π^2_p)

(Adu-Asare & Aboagye, 2014). The phenotypic variance was calculated using the applied equation (Kumar *et al.,* 2012).

$$\sigma_p^2 = \sigma_g^2 + \frac{\sigma_{g \times t}^2}{n} + \frac{\sigma_\varepsilon^2}{rn} \qquad \text{Eqn (13)}$$

where - r is the number of replicates, n is the number of trials and $\sigma_g^2 \times t$ is the genotype x trial variance.

CHAPTER FOUR

RESULTS

Genotypic variation and effect of $[P]_{ext}$ on vegetative parameters of cowpea genotypes

Root dry weight

Genotypes screened during major and minor season exhibited significant ($P < 0.001$) variation in root dry weight (RDW) (Figure 1A). RDW ranged from 2.78 - 3.68 g and 3.10 - 4.07 g for major and minor season respectively. Genotypes Alegi*Secow5T, Soronko, NE51*NE50 and Sunshine were superior in of root dry weight in both growing seasons. However, genotypes WC10*WC36 and Songotra were among the genotypes with least RDW in both seasons (Figure 1A).

Varying $[P]_{ext}$ concentration significantly ($P < 0.001$) affected RDW in both growing seasons (Figure 1B). In the major season, 45% more RDW was obtained at soil amended with 45 kg P/ha compared to 0 kg P/ha. Application of P resulted in 22% more RDW at 10 kg P/ha compared to the control treatment in the minor season (Figure 1B).

The interaction of genotype and $[P]_{ext}$ was insignificant for RDW in the major ($P = 0.834$) and minor season ($P = 0.971$) (Figure 1C and 1D). All genotypes screened increased RDW production in response to phosphorus application (Figure 1C). For example, Soronko, Agyenkwa, WC 36 had high RDW at amended soil treatment compared to control treatment (Figure 1D).

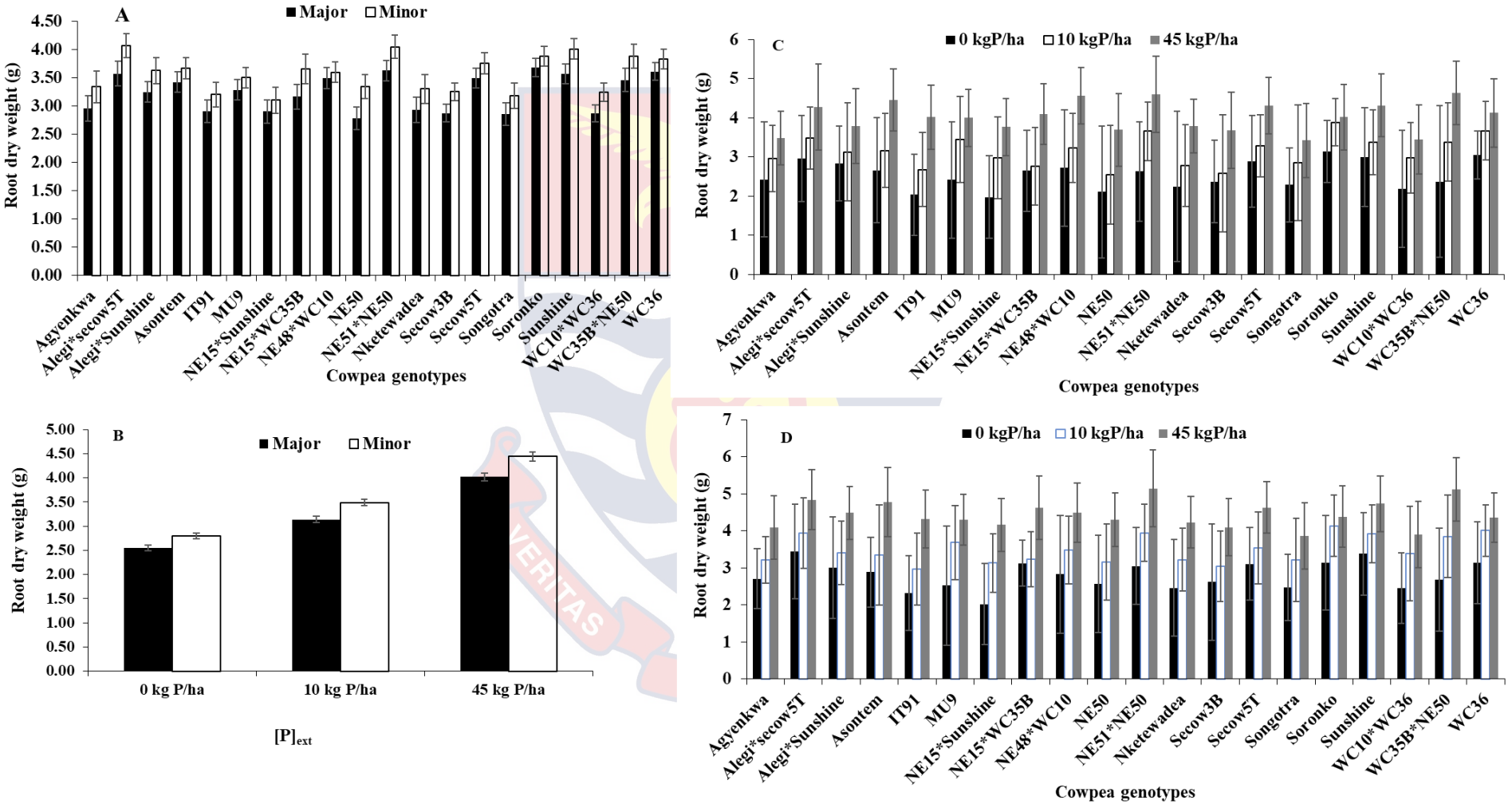

Figure 1 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on RDW. Interaction of genotype and $[P]_{ext}$ on RDW in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Shoot dry weight

Genotypic effect was insignificant for shoot dry weight (SDW) in the major ($P = 0.415$) and minor ($P = 0.943$) season (Figure 2A).

The effect of $[P]_{ext}$ on SDW was significant in the major ($P = 0.030$) and minor ($P = 0.022$) season (Figure 2B). Soil amended with 45 kg P/ha obtained the highest SDW of 26.17 g compared to treatment 10 and 0 kg P/ha (Figure 2B) which was significantly different from SDW recorded on the soil amended with 0 kg P/ha. In the minor season, genotypes planted under 45 kgP/ha obtained 42.67% more SDW than 0 kgP/ha (Figure 2B).

Two-way interaction between genotypes and $[P]_{ext}$ was significant ($P = 0.038$) for SDW in the major season (Figure 2C) and minor ($P = 0.038$) growing season (Figure 2D). Generally, majority of the genotypes increased SDW with increasing $[P]_{ext}$ concentration however, in the major season, genotypes Agyenkwa (30.73 g), Asontem (26.08 g), MU9 (23.45 g) and WC36 (24.48 g) obtained more SDW at 10 kg P/ha (Figure 2C). Genotypes Alegi*Secow5T and WC10*WC36 recorded high SDW at control treatment in the major season (Figure 2C). In the minor season, SDW was high at 10 kg P/ha for genotypes Agyenkwa, Asontem, IT91, MU9 and WC10*WC36 (Figure 2C). Genotypes Alegi*Secow5T and Secow5T had greater SDW on the control treatment compared to 45 and 10 kg P/ha soil (Figure 2D).

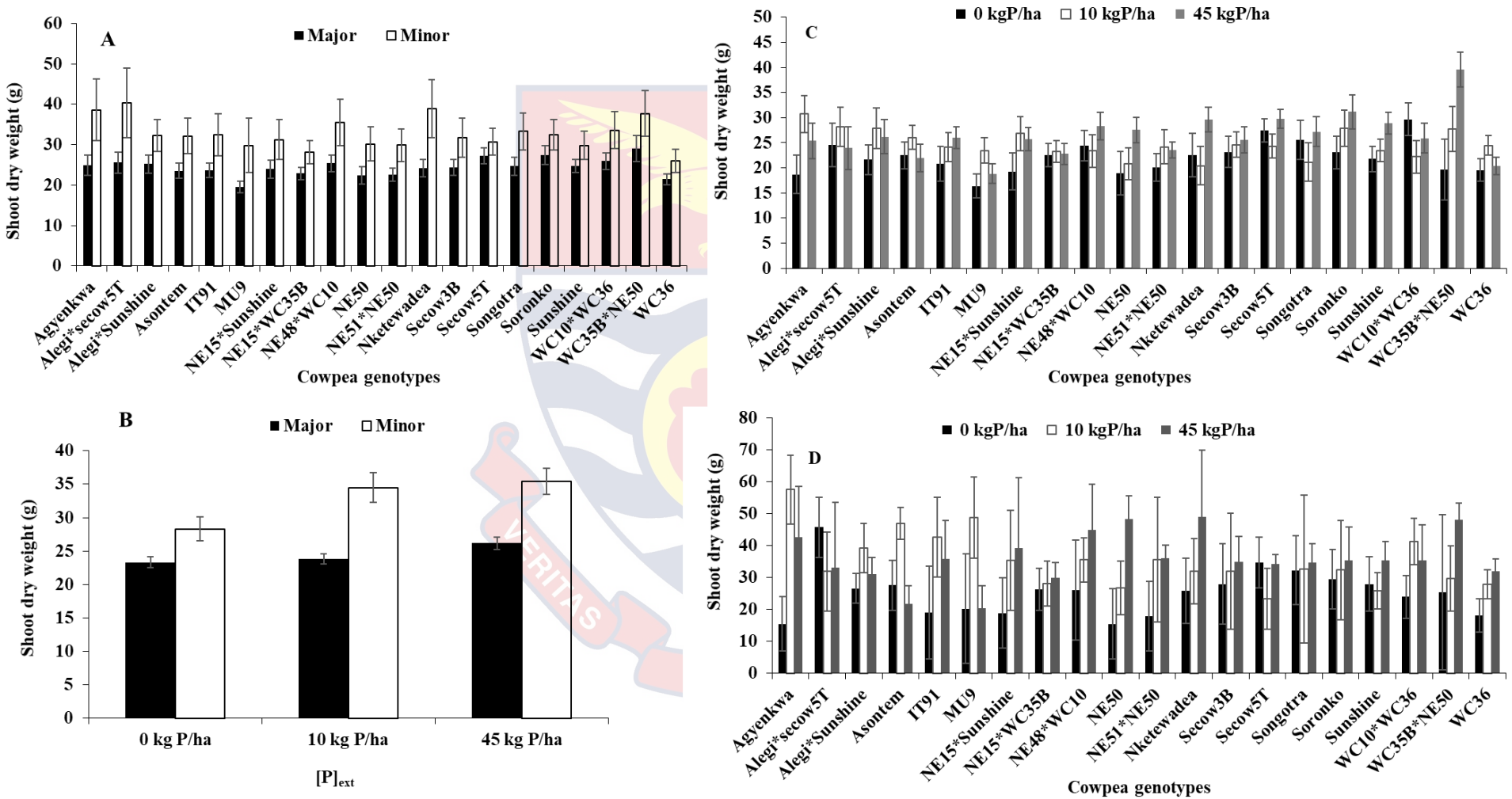

Figure 2 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on SDW. Interaction of genotype and $[P]_{ext}$ on SDW in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Genotypic variation and the effect of $[P]_{ext}$ on RSA traits among cowpea genotypes

Stem diameter

Genotypes differed significantly ($P < 0.001$) for stem diameter (SD) during the major season (Figure 3A). Genotype WC35B*NE50 (16.84 mm), Sunshine (16.61 mm) and NE51*NE50 (16.43 mm) were superior in SD in the major season whilst Nketewadea (15.62 mm), Soronko (15.42 mm) and Sunshine (14.83 mm) had the highest SD in the minor season (Figure 3A).

Stem diameter was significantly affected by varying $[P]_{ext}$ concentration in both major ($P = 0.011$) and minor ($P < 0.001$) seasons (Figure 3B). Stem diameter was higher for treatment 45 kg P/ha in the major and minor season with 27% more SD obtained in the minor season under P amended soils compared to the control treatment (Figure 3B).

Generally, the interaction of $[P]_{ext}$ and genotypes was significant ($P < 0.001$) for SD in the major season (Figure 3C). Variations in response of genotypes to P existed in more than two folds. Genotypes Alegi*Sunshine, Nketewadea, Secow3B, Soronko, WC10*WC36 and WC36 obtained highest SD at 0 kg P/ha whilst IT91, Asontem, Agyenkwa and WC35B*NE50 had higher SD at 10 kg P/ha in the major season (Figure 3C). An insignificant ($P = 0.057$) interaction of genotype and $[P]_{ext}$ for SD was observed in the minor season (Figure 3D). Genotypes screened under varying P conditions increased SD with increasing concentration of P (Figure 3D)

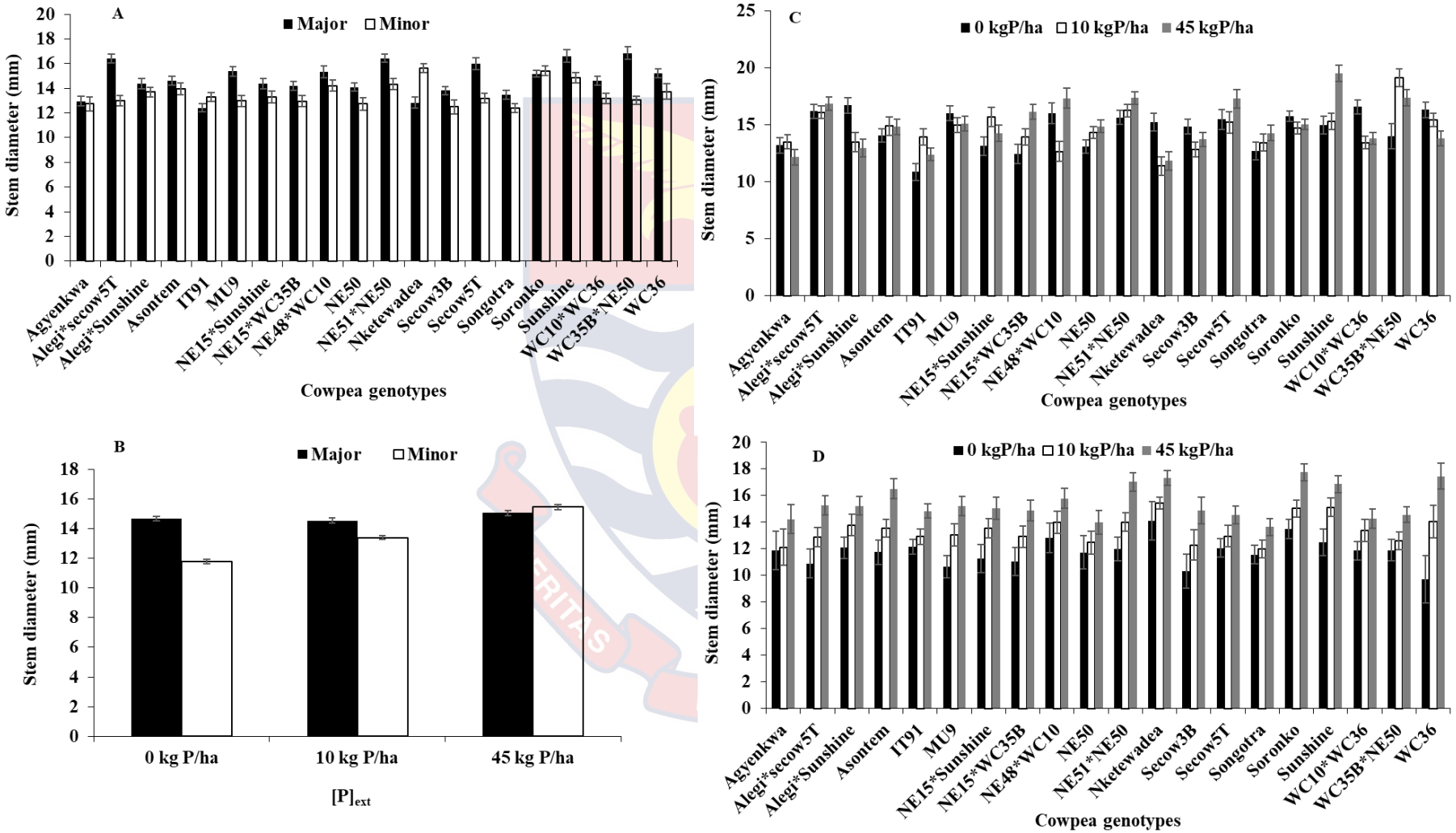

Figure 3 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on SD. Interaction of genotype and $[P]_{ext}$ on SD in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Hypocotyl root length

Hypocotyl root length (HRL) varied significantly ($P < 0.001$) among cowpea genotypes in the major and minor season (Figure 4A). Hypocotyl root was longer in genotypes WC35B*NE50 (14.74 cm), Sunshine (13.17 cm), Agyenkwa (12.44 cm), Songotra (12.38 cm) and NE48*WC10 (12.26 cm) in the major season. However, genotype Agyenkwa (9.42 cm) was among the last four (4) with shorter HRL in the minor season with genotype Asontem (16.02 cm) obtaining the highest value of HRL in the minor season (Figure 4A).

There was a significant ($P < 0.001$) effect of $[P]_{ext}$ on HRL in the minor season with soil amended with 45 kg P/ha producing twenty-seven per cent (27%) more HRL compared to 10 and 0 kg P/ha soil treatment (Figure 4B). However, in the major season $[P]_{ext}$ had an insignificant ($P = 0.675$) effect on HRL (Figure 4B). Compared to 0 and 10 kg P/ha, treatment 45 kg P/ha (10.77 cm) had the highest mean HRL in the major season (Figure 4B).

Significant interaction of genotype and $[P]_{ext}$ was observed for HRL in both growing seasons (Figure 4C and 4D). In the major season, genotypes Sunshine, WC10*WC36 and NE15*Sunshine had higher HRL at 0 kg P/ha (Figure 4C). However, genotype IT91 and MU9 obtained high HRL at 10 kg P/ha in both minor and major growing season (Figure 4C). Genotypes Secow5T, Asontem, Alegi*Sunshine and Nketewadea increased HRL with increasing concentration of $[P]_{ext}$ in both growing seasons (Figure 4D).

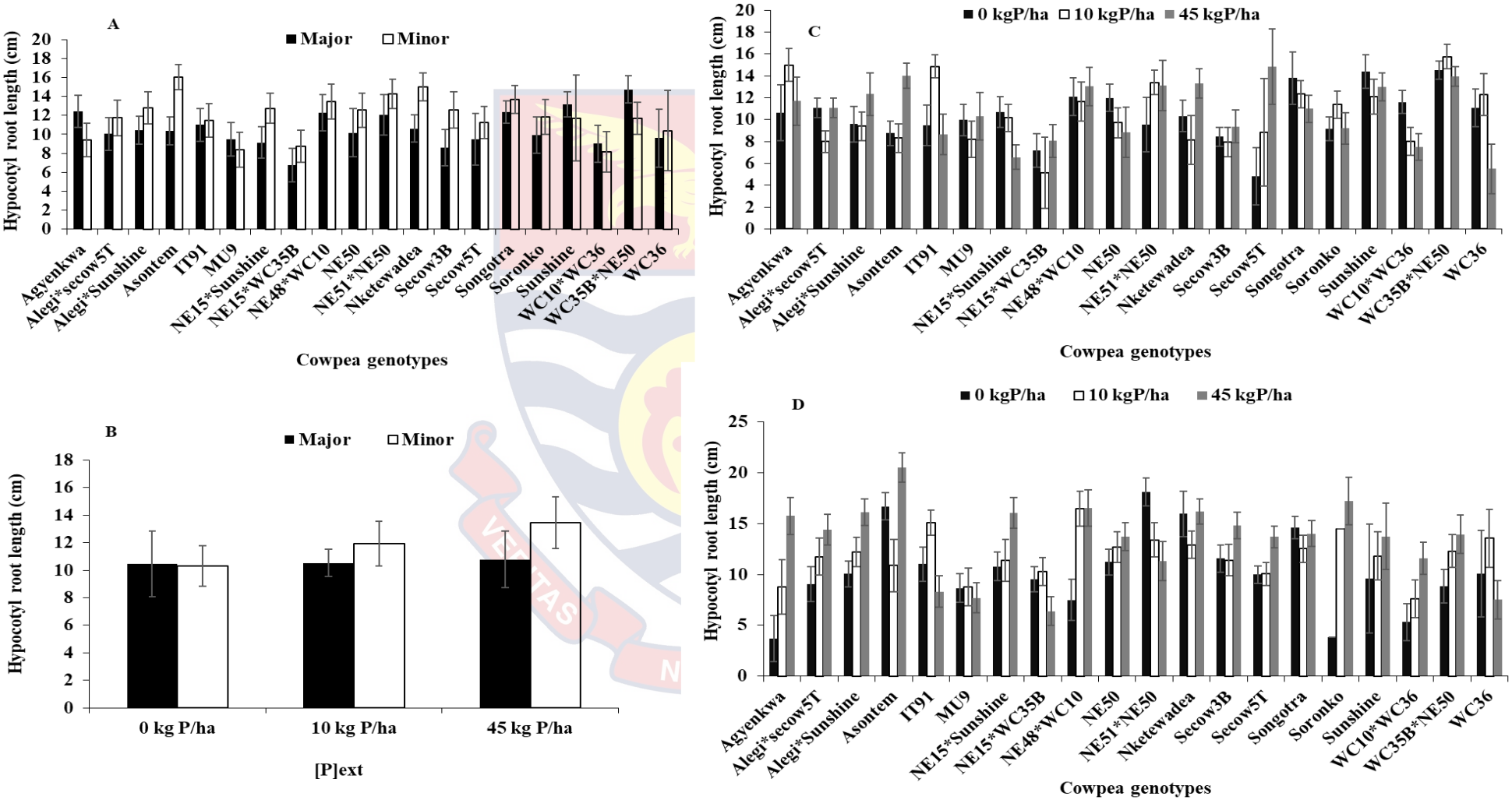

Figure 4 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on HRL. Interaction of genotype and $[P]_{ext}$ on HRL in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Hypocotyl root diameter

Cowpea genotypes evaluated at flowering stage exhibited significant ($P < 0.001$) variation in hypocotyl root diameter (HRD) during the major and minor season (Figure 5A). Hypocotyl root diameter ranged from 0.39 - 0.91 mm and 0.41 - 0.86 mm for the major and minor season respectively (Figure 5A). Genotype WC35B*NE50 (0.91 mm) had the highest HRD in the major season with Alegi*Sunshine - 0.40 mm and NE15*WC35B - 0.39 mm recording the least HRD (Figure 5A). Genotype Nketewadea, WC36 and Alegi*Sunshine were the top three (3) genotypes with high HRD in the minor season (Figure 5A).

The application of $[P]_{ext}$ had a significant ($P < 0.001$) influence on HRD in the major as well as the minor season (Figure 5B). It was observed that, HRD of cowpea genotypes increased with increasing $[P]_{ext}$ application with, 15% increase in diameter obtained at 10 kgP/ha compared with HRD obtained at 0 kgP/ha in the major season (Figure 5B).

Interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for HRD in the major and minor season (Figure 5C and 5D). Although P application increased HRD among majority of the genotypes however, genotypes MU9 and NE50 obtained high HRD among genotypes cultivated under 0 kg P/ha compared to 10 and 45 kg P/ha in the major season (Figure 5C). In the minor season, genotypes Alegi*Sunshine, Secow3B and MU9 recorded significantly high HRD at 0 kg P/ha compared to the remaining treatments (Figure 5D). Genotype Secow5T and WC35B*NE50 obtained high HRD at 10 kg P/ha during the minor season (Figure 5D).

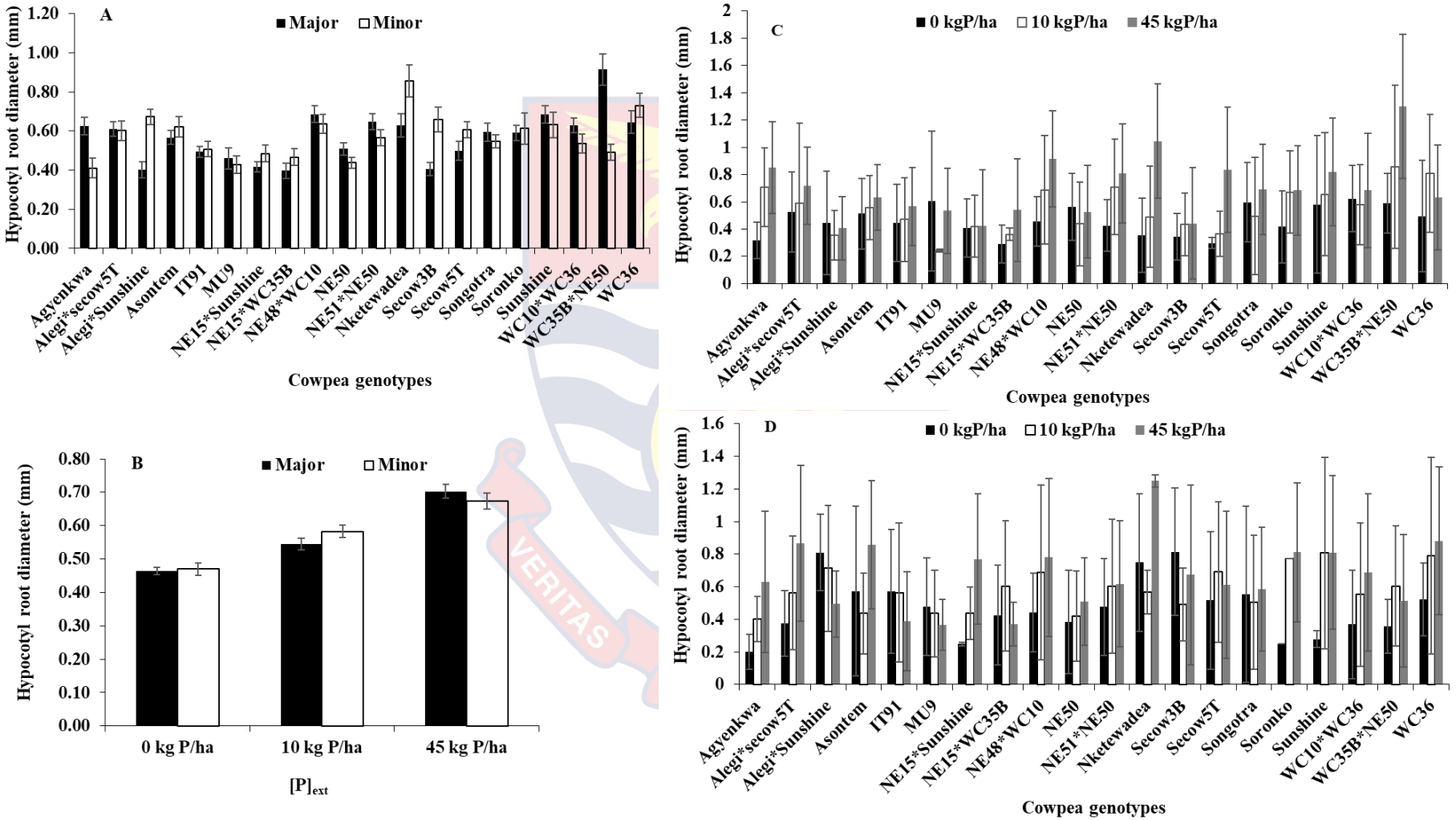

Figure 5 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on HRD. Interaction of genotype and $[P]_{ext}$ on HRD in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Hypocotyl root number

Hypocotyl root number (HRN) varied significantly ($P < 0.001$) among genotypes in the major and minor season (Figure 6A). Hypocotyl root was high for genotypes WC10*WC36 (5.77) and Alegi*Sunshine (4.62) in the major and minor season respectively (Figure 6A). Genotype Soronko, WC10*WC36 and Agyenkwa were the three (3) genotypes with least mean HRN of 2.65 in the minor season (Figure 6A).

A significant ($P < 0.001$) increasing trend in HRN was observed with increasing $[P]_{ext}$ during the major season, with 45 kg P/ha (4.66) obtaining the highest HRN followed by 10 kg P/ha (4.50) and 0 kg P/ha (3.99) (Figure 6B). Similarly, HRN was significantly ($P < 0.001$) different among varying $[P]_{ext}$ concentration in the minor season (Figure 6B). The results indicated that, treatment 10 kg P/ha produced 20.69% more HRN compared to the control treatment in the minor season (Figure 6B).

Two-way interaction between cowpea genotype and $[P]_{ext}$ was significant ($P < 0.001$) for HRN in the major and minor growing season (Figure 6C and 6D) respectively. Results in the major season revealed that, genotype NE48*WC10, MU9, Sunshine and WC10*WC36 obtained high HRN at 0 kg P/ha while Agyenkwa and NE15*Sunshine had high HRN at 10 kg P/ha (Figure 6C). In the minor season, IT91 obtained high HRN at control treatment whilst genotype Sunshine, MU9, NE15*Sunshine and NE15*WC35B had high HRN at 10 kg P/ha compare to 0 and 45 kg P/ha (Figure 6D). Genotype Nketewadea and Asontem recorded high HRN at 0 kg P/ha in both major and minor growing season (Figure 6C and 6D).

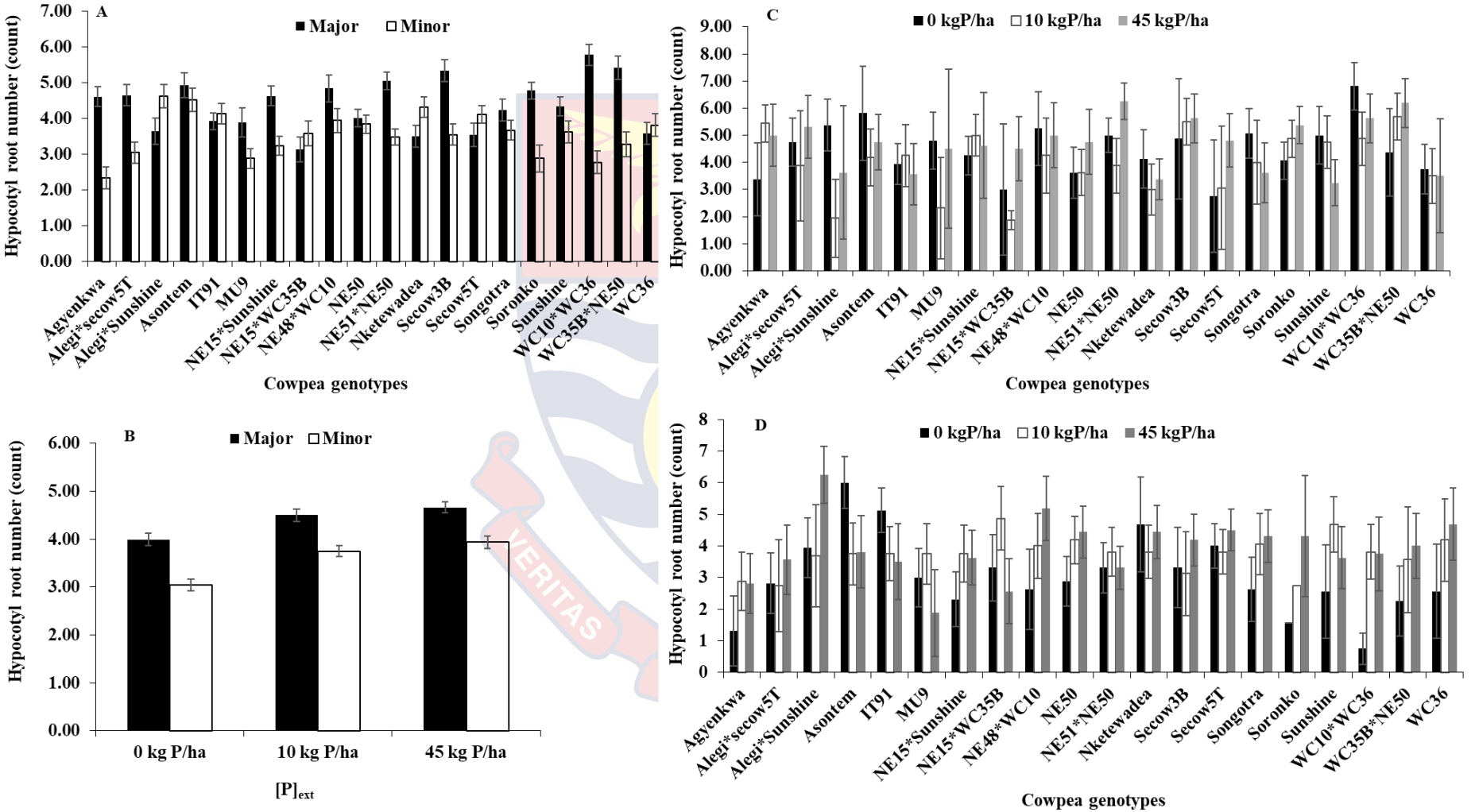

Figure 6 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on HRN. Interaction of genotype and $[P]_{ext}$ on HRN in; **(C)** Major season and **(D)** Minor season Error bars representing the s.e.m.

Basal root length

There was a significant ($P < 0.001$) difference in basal root length (BRL) among cowpea genotypes in the major and minor growing season (Figure 7A). Basal root length was longer in genotypes Sunshine, Alegi*Sunshine and IT91 and least for WC10*WC36 in the major season (Figure 7A). However, the topmost four (4) genotypes with high BRL in the minor season were Nketewadea (20.02 cm) followed by WC36 (18 cm), WC10*WC36 (18.33 cm) and Alegi*Secow5T (17.98 cm) (Figure 7A).

Basal root length obtained under varying concentration of $[P]_{ext}$ was different however, these differences were insignificant in both major ($P = 0.213$) and minor ($P = 0.732$) seasons (Figure 7B).

Interaction effect of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for BRL obtained by cowpea genotypes screened at flowering stage in both seasons (Figure 7C and 7D). Longer BRL was recorded by genotypes Alegi*Secow5T, Asontem, NE51*WC35B, Secow5T, Sunshine, WC36 and WC10*WC36 at treatment 0 kg P/ha while NE15*NE50, Secow3B, IT91 and Alegi*Sunshine increased BRL at 10 kg P/ha in the major season (Figure 7C). During the minor season, Agyenkwa, Alegi*Sunshine, Asontem, NE51*NE50, Secow3B, Sunshine and WC10*WC36) developed longer BRL under 0 kgP/ha treatment compared to the other levels of phosphorus concentration (Figure 7D).

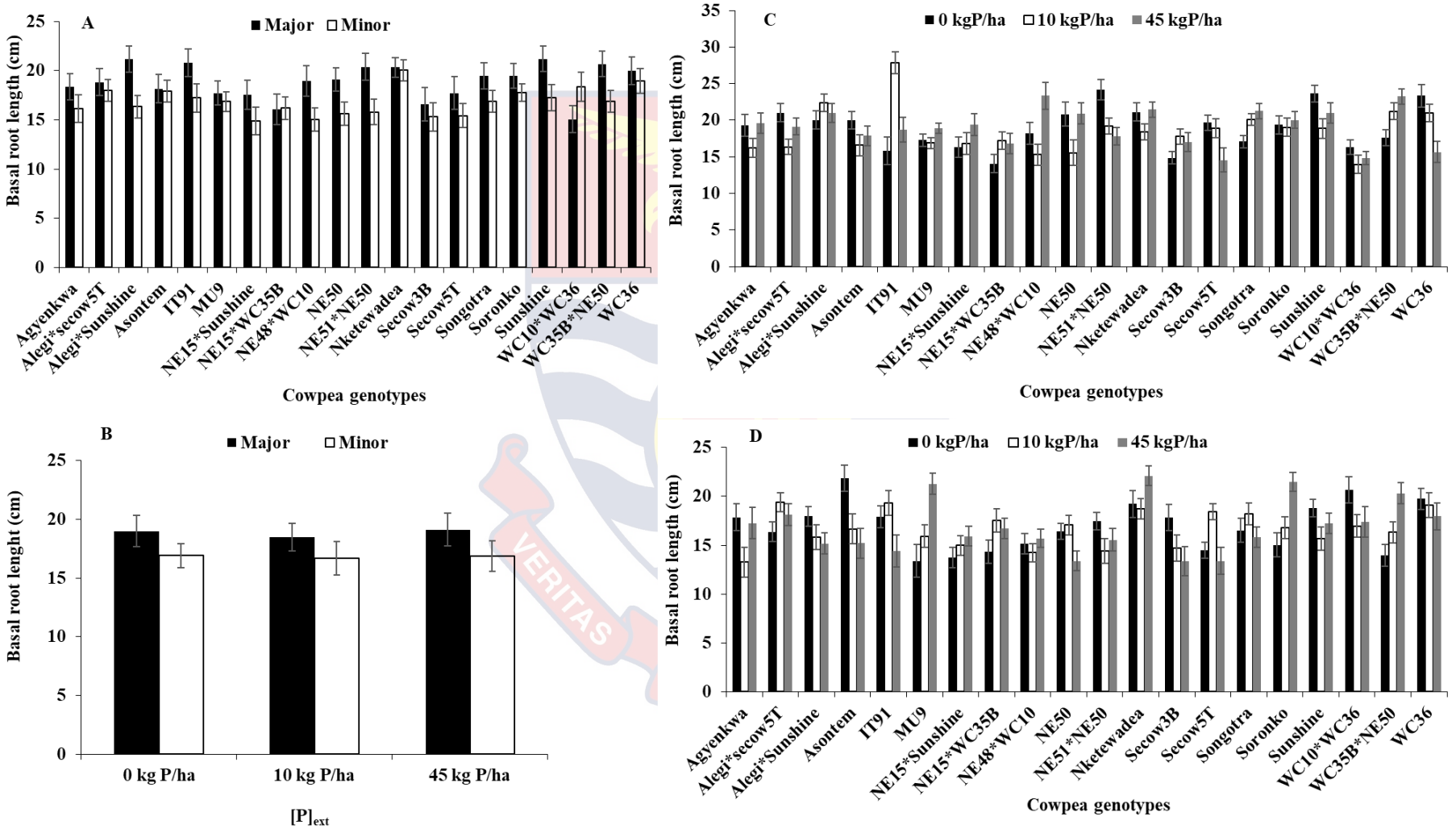

Figure 7 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on BRL. Interaction of genotype and $[P]_{ext}$ on BRL in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Basal root diameter

The basal root diameter (BRD) of cowpea genotypes in the major and minor growing season was significantly ($P < 0.001$) influenced by genotype (Figure 8A). Basal root diameter ranged from 0.77 - 1.46 mm. Mean BRD for topmost two (2) genotypes WC35B*NE50 and WC36 was 1.37 mm (Figure 8A). However, in the minor season, genotype NE50 (1.22 mm) had the highest BRD compared to WC35*NE50 (0.66 mm) which had the least BRD (Figure 8A).

Phosphorus application signifcantly ($P < 0.001$) affected BRD of cowpea genotypes screened in the major and minor season (Figure 8B). An increasing trend in BRD was observed with increasing $[P]_{ext}$ concnetration with 45 kg P/ha soil treatment producing 11% more BRD compared to soil amended with 0 kg P/ha in the major season (Figure 8B). Basal root diameter obtained at P amended soil treatment was 16.87% greater compared to that of 0 kgP/ha in the minor season (Figure 8B).

Significantt ($P < 0.001$) interaction of genotype and $[P]_{ext}$ was observed for BRD in both seasons (Figure 8C and 8D). It was observed that values of BRD was higher for genotypes IT91 and Secow3B at 10 kg P/ha but genotype MU9, NE15*Sunshine, WC10*WC36 and WC36 had high BRD at 0 kg P/ha (Figure 8C). Genotypes Sunshine and Agyenkwa recorded high BRD at control treatment during the minor season compared to IT91, Soronko and WC35B*NE50 which had high BRD at 10 kg P/ha in the minor season (Figure 8D). The remaining genotypes increased BRD in response to increasing $[P]_{ext}$ concnetration.

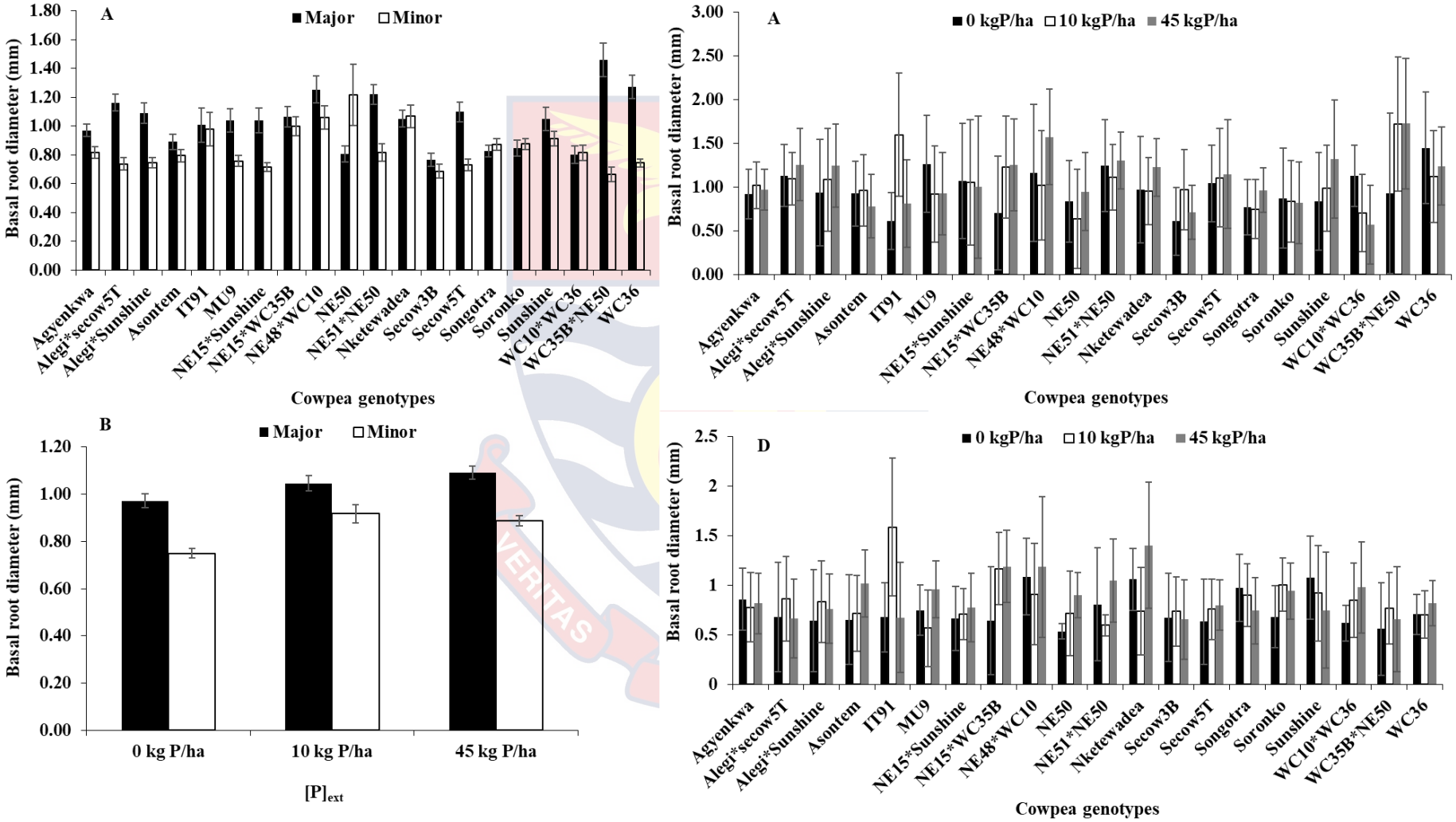

Figure 8 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on BRD. Interaction of genotype and $[P]_{ext}$ on BRD in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Basal root number

Genotypes varied significantly ($P < 0.001$) in basal root number (BRN) in the major and minor growing season (Figure 9A). Among the twenty (20) genotypes screened in the major season, genotype Asontem had the highest number of basal root (8.06) compared to genotypes Agyenkwa (5.31), MU9 (5.21) and Secow5T (5.17) which recorded the least BRN (Figure 9A). In the minor season, BRN ranged from 4.60 - 658 with genotype WC36 (6.58) recording the highest BRN and Secow3B obtaining the least (Figure 9A).

Analysis of variance indicated that $[P]_{ext}$ signifcantly ($P = 0.027$) affected BRN in the major season (Figure 9B). Generally, increasing $[P]_{ext}$ resulted in a decrease in BRN (Figure 9B). Application of P resulted in 6.15% reduction in BRN among cowpea genotypes in the major season (Figure 9B). In the minor season, a signifcant ($P = 0.047$) effect of $[P]_{ext}$ on BRN was observed (Figure 9B). BRN recorded at 0 kgP/ha was 5.31% greater than BRN obtained at 45 kgP/ha amended soil (Figure 9B).

There was signifcant interaction of genotype and $[P]_{ext}$ ($P < 0.001$) for BRN both seasons (Figure 9C and 9D). Genotypes Asontem, NE15*WC35B, NE51*NE50 and Nketewadea had high BRN at 45 kg P/ha in the major season (Figure 9C). In the minor season, genotypes IT91, MU9, NE15*Sunshine, NE50, Songotra, Soronko and Sunshine produced high BRN at 45 kg P/ha compraed to Nketewadea, Alegi*Sunshine, Agyenkwa, Asontem and WC35B*NE50 which had more BRN among genotypes cultivated under the control soil treatment (Figure 9D).

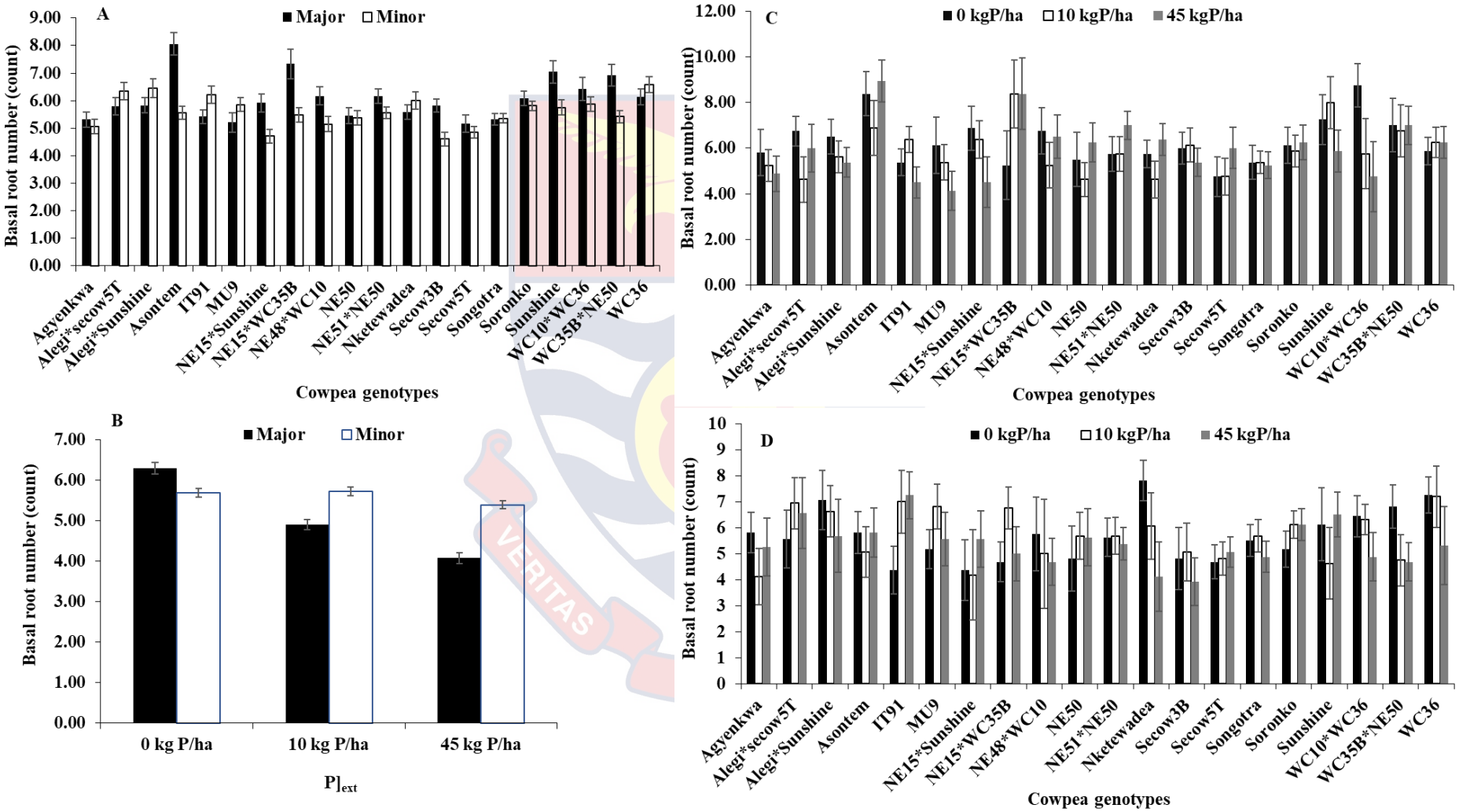

Figure 9 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on BRN. Interaction of genotype and $[P]_{ext}$ on BRN in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Results on additional root system architectural traits

Basal root growth angle (BRGA) was significantly ($P < 0.001$) affected by genotypic effect in both the major and minor growing seasons (Table 4). Basal root growth angle was greater for genotypes Agyenkwa (47.81), Secow3B (46.47), Songotra (46.36) and Soronko (46.35) in the major season (Table 4). However, genotype NE48*WC10 (41.56), MU9 (41.46) and NE15*WC35B (40.52) constituted the distribution with lower BRGA in the major season (Table 4). In the minor season, genotype Asontem (42.60) recorded the highest BRGA and WC36 (33.75) obtained the lowest BRGA (Table 4). The effect of $[P]_{ext}$ on BRGA was insignificant ($P = 0.216$) on BRGA in the major season as well as the minor season ($P = 0.311$) (Table 5). Interaction between cowpea genotypes and $[P]_{ext}$ was significant ($P < 0.001$) for BRGA in both seasons (Table 6 and 7) respectively. In general, genotype Agyenkwa (49.38) and WC35B*NE50 (48.44) obtained highest angles at 0 kg P/ha amended soil whilst, Agyenkwa (50.31), WC36 (49.38), Asontem (48.75) and Nketewadea (47.19) were superior in BRGA among genotypes cultivated at 10 kg P/ha in the major season (Table 6). In the minor season, genotypes Alegi*Secow5T (39.06), Alegi*Sunshine (39.81), MU9 (44.38), NE50 (41.56), NE51*NE50 (42.81), Soronko (44.41) and WC36 (38.12) obtained highest BRGA among genotypes cultivated on 0 kg P/ha (Table 7).

Hypocotyl root growth angle (HRGA) varied significantly ($P < 0.001$) among cowpea genotypes cultivated in the major and minor season (Table 4). Genotype Asontem (37) obtained highest HRGA which was significantly greater than value obtained by genotype MU9 (25) in the major season (Table 4). Genotypes Alegi*Secow5T, Asontem, Secow5T, NE51*NE50 and

NE48*WC10 were the topmost five (5) genotypes with high HRGA ranging from 28.54 - 33.85^0 in the minor season (Table 4). Hypocotyl root growth varied significantly ($P < 0.001$) among various $[P]_{ext}$ concentrations in both seasons (Table 5). Generally, an increasing trend was observed in HRGA in relation to increasing $[P]_{ext}$ concentration, with 3.41% and 22.38% greater HRGA obtained at 10 and 45 kg P/ha compared to 0 kg P/ha in the major and minor season respectively (Table 5). The interaction of genotypes and $[P]_{ext}$ was significant ($P < 0.001$) for HRGA in the major and minor season (Table 6 and 7) respectively. Genotype WC10*WC36, Songotra, Agyenkwa, MU9, NE51*NE50 and Alegi*Sunshine recorded higher HRGA among genotypes cultivated on soil amended with 0 kg P/ha in the major season (Table 6). However, higher HRGA was obtained by Asontem, WC36, IT91 and NE48*WC10 at 10 kg P/ha amended soil compared to genotypes cultivated on soil amended with 0 and 45 kg P/ha in the major season (Table 6). In the minor season, genotypes Agyenkwa, NE15*WC 35B, WC 36, IT91, Sunshine obtained high HRGA at 10 kg P/ha (Table 7).

Genotypes differed significantly ($P < 0.001$) in nodule diameter (ND) in the major and minor seasons (Table 4). Higher ND was recorded among genotype WC35B*NE50 (0.78 mm), Asontem (0.78 mm) and Secow5T (0.77 mm) which was significantly different from ND recorded by genotype Nketewadea (0.26 mm), Soronko (0.244 mm) and IT91 (0.15 mm) (Table 4). Genotypes Asontem, NE15*Sunshine, NE48*WC10 and Alegi*Sunshine were superior in the ND in the minor season (Table 4). Variation existed in ND obtained by various $[P]_{ext}$ treatments however, these variations was statistically insignificant ($P = 0.339$) in the major season (Table 5). However, effect of $[P]_{ext}$

on ND was significant ($P < 0.001$) in the minor season (Table 5). Higher ND was recorded at 45 kg P/ha (1.33 mm) followed by 0 kg P/ha (1.27 mm) and 10 kg P/ha (1.01 mm) in the minor season (Table 5). The interaction effect of cowpea genotypes and $[P]_{ext}$ on ND was significant ($P < 0.001$) in both seasons (Table 6 and 7). Nodule diameter was high at 0 kg P/ha for genotype Alegi*Secow5T (1.25 mm), NE15*Sunshine (1.00 mm), WC10*WC36 (0.76 mm), NE15*WC35B (0.46 mm) and NE50 (0.51 mm) (Table 6). Genotype Secow5T (1.25 mm), WC35B*NE50 (1.01 mm), Songotra (0.51 mm), NE51*NE50 (0.62 mm) and NE48*WC10 (0.54 mm) obtained greater ND among genotypes cultivated under 45 kg P/ha soil treatment in the major season (Table 6). Genotypes Alegi*Sunshine, Asontem, MU9 and WC36 obtained high ND at treatment 0 kg P/ha compared to IT91, NE15*WC35B, Secow5T and Songotra which had high ND at 10 kg P/ha in the minor season (Table 7).

Nodule number (NN) varied significantly ($P = 0.007$) among field grown cowpea genotypes evaluated at flowering stage (Table 4). In the major season, NN was greater for genotype Alegi*Secow5T, WC35B*NE50, Sunshine, NE51*NE50 and Agyenkwa which constituted the topmost five (5) genotypes with greater NN (Table 4). In the minor season, Asontem (16.40), Alegi*Sunshine (14.35), NE48*WC10 (12.77) and NE15*Sunshine (11.63) produced high NN compared to WC36 (4.46) and NE15*WC35B (3.04) which produced the least NN in the minor season (Table 4). Application of P had an insignificant ($P = 0.421$) effect on NN in the major season but was significant ($P < 0.001$) in the minor season (Table 5). Phosphorus application resulted in 6.62% more nodules compared to unamended soil treatment in the major season but resulted in 13.61% increase at 45 kg P/ha compared to 0 kg P/ha in the minor

season (Table 5). The interaction of genotypes and $[P]_{ext}$ was significant ($P < 0.001$) for NN obtained by genotypes in both seasons (Table 6 and 7). In all, genotype Alegi*Secow5T, NE15*Sunshine, NE50, NE15*WC35B, Soronko, Sunshine, NE51*NE50 and WC10*WC36 produced more NN at 0 kg P/ha in the major season (Table 6). Among genotypes cultivated at 10 kg P/ha soil Agyenkwa, Secow3B and Alegi*Sunshine produced greater NN compared to other treatments in the major season (Table 6). Number of nodules obtained in the minor season was high for genotypes NE51*NE50, Secow3B, Sunshine and WC10*WC36 among genotypes cultivated at 0 kg P/ha (Table 7)

A significant ($P < 0.001$) genotypic effect was observed for taproot diameter (TRD) among genotypes in both seasons (Table 4). Taproot diameter ranged from 7.96 - 11.43 mm (Table 4). In all, the topmost two (2) genotypes (WC35B*NE50 and Sunshine) obtained a mean diameter of 11.31 mm which was significantly different from the mean TRD of 8.24 mm obtained by the last four genotypes Secow3B, Alegi*Sunshine, IT91 and Songotra with least TRD in the major season (Table 4). The topmost three genotypes with high TRD in the minor season were Sunshine, WC36 and Nketewadea (Table 4). The effect of $[P]_{ext}$ significantly ($P < 0.001$) affected TRD in both seasons (Table 5). Soil amended with 45 kgP/ha recorded the highest TRD of 10.00 mm. TRD increased with it increasing $[P]_{ext}$ concentration with 8.69% greater diameter recorded at 45 kgP/ha than at 0 kgP/ha in the major season (Table 5). However, in the minor season, 10.23% more TRD was observed at 45 kg P/ha compared to 0 kg P/ha (Table 5). A significant interaction ($P < 0.001$) of genotype and $[P]_{ext}$ was observed for TRD in both seasons (Table 6 and 7). Majority of cowpea genotypes produced higher TRD in response to increasing P levels. However,

genotype NE15*Sunshine (9.57 mm), Nketewadea (10.19 mm) and Secow3B (9.60 mm) recorded higher TRD on soil amended with 0 kg P/ha in the major season (Table 6). In the minor season, Alegi*Secow5T, Alegi*Sunshine, NE15*Sunshine, Sunshine and WC36 recorded high TRD at 10 kg P/ha (Table 6). However, TRD was high at 0 kg P/ha for genotypes Agyenkwa, IT91, Songotra and WC10*WC36 in the minor season (Table 7)

Third order branching density (3rd BD) among the twenty (20) cowpea genotypes exhibited significant ($P < 0.001$) variation in both seasons (Table 4). Third order branching density was significantly higher for genotype Sunshine (19.18), IT91 (18.99), WC35B*NE50 (18.06) and Alegi*Secow5T (17.60) compared to NE50 (14.76) and WC10*WC36 (14.56) which had the least 3rd BD in the major season (Table 4). In the minor season, Asontem, MU9, Alegi*Secow5T and Secow5T were superior in production of branching density (Table 4). Varying rates of $[P]_{ext}$ significantly ($P = 0.009$) affected 3rd BD in the major season and minor season ($P < 0.001$) (Table 5). Generally, 3rd BD increased with increasing rate of $[P]_{ext}$ with soil amended with 45 kg P/ha obtaining highest branching density of 17.18 and 18.13 in the major and minor season respectively (Table 5). Two-way interaction between genotype and $[P]_{ext}$ was significant ($P < 0.001$) for 3rd BD among genotypes (Table 6 and 7). Genotype MU9, Sunshine, Agyenkwa and NE48*WC10 obtained the highest 3rd BD at 0 kg P/ha in the major season (Table 6). Genotype Alegi*Sunshine, IT91, NE15*WC35B, Secow5T and Soronko obtained high 3rd BD at soil amended with 10 kg P/ha while Sunshine, NE50 and Secow3B recorded high mean 3rd BD at 0 kg P/ha in the minor season (Table 7

Table 4 - Genotypic effect on additional RSA traits for field grown cowpea genotypes during the major and minor season

	Measurements											
	BRGA		HRGA		ND		NN		3RD BD		TRD	
Genotypes	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**
Agyenkwa	47.81	41.04	33.23	22.81	0.54	0.72	4.54	8.56	16.61	15.27	9.40	8.20
Alegi*secow5T	41.87	38.02	33.85	33.85	0.70	1.40	5.52	8.17	16.97	18.83	11.07	8.05
Alegi*Sunshine	44.17	38.48	26.46	28.54	0.34	1.62	3.52	14.35	17.60	17.66	8.42	7.78
Asontem	45.62	42.6	37.00	31.35	0.78	2.00	3.44	16.40	15.86	21.06	10.54	8.51
IT91	42.83	36.15	31.46	26.88	0.15	0.89	1.65	10.79	18.99	16.15	8.24	8.46
MU9	41.46	39.69	25.19	21.52	0.26	1.53	3.94	10.02	16.60	19.29	9.93	7.90
NE15*Sunshine	44.79	42.4	31.19	23.13	0.41	1.93	2.63	11.63	15.29	17.31	9.14	6.69
NE15*WC35B	40.52	38.23	26.75	24.58	0.38	0.35	2.77	3.04	16.85	14.92	8.51	8.75
NE48*WC10	41.56	42.19	31.04	28.54	0.26	1.84	3.42	12.77	16.98	17.8	9.27	7.93
NE50	44.37	38.54	33.12	27.29	0.40	1.41	3.52	7.88	14.76	14.67	8.75	8.21
NE51*NE50	43.75	41.46	33.94	28.65	0.38	0.61	4.56	5.67	17.15	15.04	10.58	8.59
Nketewadea	45.83	34.1	28.65	22.29	0.26	1.08	4.15	8.65	16.67	16.53	9.05	9.62
Secow3B	46.87	39.9	29.38	27.71	0.43	1.24	3.33	11.17	16.96	16.68	8.50	7.30
Secow5T	43.44	34.9	31.15	29.17	0.77	1.52	4.42	11.10	16.72	18.6	9.33	7.57
Songotra	46.46	41.15	32.19	27.08	0.30	1.17	3.02	6.31	15.43	18.15	7.96	7.61
Soronko	46.35	40.94	29.90	17.08	0.24	1.25	3.60	8.67	16.83	18.44	9.82	9.16
Sunshine	42.29	39.48	29.69	23.54	0.42	0.62	4.58	7.54	19.18	17.77	11.18	10.98
WC10*WC36	43.75	36.46	35.73	22.6	0.44	0.89	3.46	7.58	14.56	14.47	9.44	7.77
WC35B*NE50	42.60	39.27	34.48	23.75	0.78	1.45	5.10	7.60	18.06	17.87	11.43	7.07
WC36	45.83	33.75	32.40	27.08	0.36	0.53	1.81	4.46	16.72	16.51	9.99	9.86
ANOVA												
LSD	*3.547*	*2.56*	*3.305*	*3.953*	*0.27*	*0.2107*	*1.963*	*3.368*	*1.264*	*1.77*	*0.8751*	*0.7258*
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.007*	*<0.001*	*<0.001*	*<0.001*	*0.002*	*<0.001*
Cv	*20.1*	*16.4*	*26.3*	*38.1*	*15.6*	*85.9*	*24.2*	*92.2*	*18.8*	*25.7*	*22.9*	*21.8*

Where HRGA: hypocotyl root growth angle, BRGA: basal root growth angle, 3rd BD: 3rd order branching density, TRD: taproot diameter, NN: number of nodules ND; nodule diameter

Table 5 - Effect of $[P]_{ext}$ on additional RSA traits for field grown cowpea genotypes during the major and minor season

	Measurements											
	BRGA		**HRGA**		**ND**		**NN**		**3RD BD**		**TRD**	
$[P]_{ext}$	Major	Minor	Major	Minor	Major	Minor	Major	Minor	Major	Minor	Major	Minor
0 kg P/ha	43.47	38.57	30.03	22.06	0.43	1.268	3.90	8.37	16.49	16.13	9.17	7.838
10 kg P/ha	44.69	39.34	31.61	27.94	0.47	1.007	3.65	8.89	16.55	17.2	9.41	8.43
45 kgP/ha	44.17	38.89	32.38	27.62	0.39	1.331	3.39	10.1	17.18	18.13	10.00	8.631
ANOVA												
LSD	*1.374*	*0.991*	*1.28*	*1.531*	*0.1046*	*0.0816*	*0.76*	*1.304*	*0.489*	*0.685*	*0.3389*	*0.2811*
p-value	*0.216*	*0.311*	*0.001*	*<0.001*	*0.339*	*<0.001*	*0.421*	*0.029*	*0.009*	*<0.001*	*<0.001*	*<0.001*
Cv	*20.1*	*16.4*	*26.3*	*38.1*	*15*	*85.9*	*24.2*	*92.2*	*18.8*	*25.7*	*22.9*	*21.8*

Where HRGA: hypocotyl root growth angle, BRGA: basal root growth angle, 3rd BD: 3rd order branching density, TRD: taproot diameter, NN: number of nodules ND; nodule diameter

Table 6 - Interaction of genotype and $[P]_{ext}$ on additional RSA traits for field grown cowpea genotypes during the major season

Genotypes	Measurements																	
	BRGA (^{0})			HRGA (^{0})			NN (count)			ND (mm)			TRD (mm)			3rd BD (count)		
	0	10	45	0	10	45	0	10	45	0	10	45	0	10	45	0	10	45
Agyenkwa	49.38	50.31	43.75	36.56	34.06	29.06	4.25	8.56	0.81	0.39	1.14	0.07	8.94	11.00	8.27	18.33	15.58	15.92
Alegi*secow5T	42.50	40.63	42.50	27.50	31.56	42.50	6.06	4.50	6.00	1.25	0.27	0.57	10.56	11.41	11.26	16.73	14.79	19.37
Alegi*Sunshine	43.13	44.38	45.00	29.38	24.38	25.62	2.94	5.50	2.12	0.25	0.64	0.12	10.05	8.23	6.99	16.50	17.67	18.63
Asontem	45.31	48.75	42.81	33.75	42.56	34.69	3.19	5.25	1.87	0.79	1.48	0.08	10.26	11.23	10.14	17.04	14.58	15.96
IT91	35.63	44.75	48.13	26.25	37.50	30.63	0.44	3.06	1.44	0.01	0.23	0.21	6.92	8.72	9.08	16.50	23.17	17.31
MU9	42.50	41.88	40.00	29.00	18.44	28.12	3.81	3.94	4.06	0.14	0.36	0.29	10.15	9.15	10.48	19.73	16.00	14.08
NE15*Sunshine	40.00	44.38	50.00	30.62	33.75	29.19	3.19	3.06	1.62	1.00	0.19	0.03	9.57	9.43	8.44	13.65	16.31	15.92
NE15*WC35B	38.13	37.81	45.62	18.75	30.62	30.88	3.25	2.81	2.25	0.46	0.39	0.28	7.01	9.41	9.12	13.50	19.62	17.42
NE48*WC10	36.88	46.56	41.25	23.75	35.00	34.38	3.44	2.06	4.75	0.11	0.12	0.54	9.58	6.70	11.52	18.29	13.15	19.50
NE50	43.75	43.13	46.25	35.62	30.62	33.12	6.50	1.38	2.69	0.51	0.25	0.46	8.02	8.87	9.35	15.27	13.33	15.69
NE51*NE50	45.63	43.13	42.50	29.62	33.75	38.44	5.62	2.75	5.31	0.19	0.34	0.62	8.68	11.39	11.68	15.46	15.85	20.12
Nketewadea	45.63	47.19	44.69	29.38	26.25	30.31	4.25	3.00	5.19	0.14	0.23	0.41	10.19	7.70	9.26	16.71	14.31	19.00
Secow3B	50.63	45.00	45.00	29.06	25.94	33.12	1.62	5.50	2.88	0.32	0.35	0.64	9.60	6.83	9.07	16.29	17.79	16.79
Secow5T	42.19	43.13	45.00	28.75	28.44	36.25	2.38	3.44	7.44	0.49	0.58	1.25	9.09	8.95	9.91	16.77	16.35	17.04
Songotra	45.00	49.38	45.00	35.00	30.62	30.94	2.88	2.25	3.94	0.21	0.20	0.51	8.03	7.54	8.31	15.92	14.83	15.54
Soronko	45.00	47.19	46.88	30.94	33.44	25.31	5.25	2.31	3.25	0.23	0.40	0.10	9.96	9.09	10.40	16.96	17.38	16.17
Sunshine	40.62	41.88	44.38	25.00	32.81	31.25	7.38	4.44	1.94	0.63	0.47	0.16	10.19	11.00	12.37	19.25	18.88	19.42
WC10*WC36	43.75	44.38	43.12	39.38	34.06	33.75	6.38	2.12	1.88	0.77	0.33	0.22	9.66	9.09	9.56	14.87	15.96	12.83
WC35B*NE50	48.44	40.63	38.75	29.38	33.44	40.62	4.56	3.94	6.81	0.54	0.81	1.01	8.97	10.75	14.56	14.17	17.96	22.04
WC36	45.31	49.38	42.81	32.81	35.00	29.38	0.69	3.12	1.62	0.10	0.68	0.31	7.99	11.72	10.26	17.83	17.46	14.88
ANOVA																		
l.s.d.	*6.113*			*5.72*			*3.400*			*0.105*			*1.516*			*2.189*		
p - value	*<.001*			*<.001*			*<.001*			*<.001*			*< .001*			*<.001*		
Cv %	*20.1*			*26.3*			*34.2*			*31.2*			*22.9*			*18.8*		

Where HRGA: hypocotyl root growth angle, BRGA: basal root growth angle, 3rd BD: 3rd order branching density, TRD: taproot diameter, NN: number of nodules ND; nodule diameter

Table 7 - Interaction of genotype and $[P]_{ext}$ on additional RSA traits for field grown cowpea genotypes during the minor season

Genotypes	Measurements																	
	BRGA (^{0})			HRGA (^{0})			NN (count)			ND (mm)			TRD (mm)			3rd BD (count)		
	0	10	45	0	10	45	0	10	45	0	10	45	0	10	45	0	10	45
Agyenkwa	40.31	40.00	42.81	8.75	32.81	26.88	5.44	7.00	13.25	0.52	0.74	0.91	7.94	7.53	9.14	17	11.6	17.22
Alegi*secow5T	39.06	36.25	38.75	30.00	32.81	38.75	6.50	3.50	14.50	1.34	0.77	2.09	7.08	9.10	7.97	18.4	18.96	19.13
Alegi*Sunshine	39.81	39.06	36.56	31.56	27.19	26.88	10.44	23.25	9.38	2.00	1.80	1.06	6.67	8.88	7.80	17.44	19.35	16.19
Asontem	43.12	43.12	41.56	33.75	27.81	32.50	17.62	11.06	20.50	2.57	1.41	2.01	8.40	7.42	9.70	20.37	19.9	22.92
IT91	30.62	38.75	39.06	21.25	30.63	28.75	5.31	15.81	11.25	0.15	1.97	0.54	9.31	7.86	8.22	16.12	18.17	14.17
MU9	44.38	39.06	35.62	24.56	24.06	15.94	10.12	6.44	13.50	2.07	0.69	1.84	8.02	6.78	8.89	19.4	17.42	21.06
NE15*Sunshine	42.50	44.06	40.62	13.13	28.13	28.13	9.69	12.62	12.56	2.02	1.05	2.71	6.59	7.40	6.10	12.44	19.69	19.79
NE15*WC35B	32.81	37.81	44.06	20.62	39.06	14.06	3.56	3.00	2.56	0.34	0.40	0.31	7.14	9.79	9.32	10.81	19.58	14.35
NE48*WC10	42.81	42.81	40.94	20.31	34.06	31.25	15.50	5.44	17.37	2.08	1.33	2.10	7.41	7.23	9.15	17.42	14.98	21.00
NE50	41.56	34.06	40.00	26.25	24.06	31.56	8.06	5.12	10.44	1.52	0.84	1.88	6.66	9.74	8.24	17.37	10.31	16.33
NE51*NE50	42.81	40.94	40.62	27.50	31.25	27.19	9.69	4.75	2.56	0.69	0.42	0.72	6.88	8.94	9.94	12.81	14.56	17.75
Nketewadea	33.56	39.37	29.37	20.63	21.25	25.00	2.56	4.69	18.69	0.20	0.33	2.72	9.50	9.14	10.22	14.37	15.67	19.56
Secow3B	37.81	39.06	42.81	27.81	18.44	36.88	16.25	13.06	4.19	1.67	1.67	0.39	6.90	7.15	7.85	19.08	14.95	16.02
Secow5T	34.38	35.94	34.38	28.44	30.00	29.06	9.12	17.56	6.62	1.59	2.16	0.79	7.21	7.56	7.94	14.79	22.5	18.5
Songotra	36.56	44.06	42.81	26.56	26.88	27.81	6.94	8.62	3.37	1.55	1.58	0.39	8.31	7.37	7.16	17.71	18.4	18.33
Soronko	44.37	36.87	41.56	10.94	16.56	23.75	7.37	2.25	16.38	1.05	0.16	2.54	8.81	8.71	9.96	13.42	21.81	20.08
Sunshine	36.56	40.31	41.56	18.13	29.06	23.44	13.62	4.50	4.50	0.74	0.60	0.53	9.54	12.29	11.13	19.25	16.19	17.87
WC10*WC36	33.75	40.31	35.31	10.63	25.63	31.56	11.44	6.25	5.06	1.42	0.71	0.71	9.06	7.13	7.10	15.48	15.5	12.44
WC35B*NE50	36.56	37.19	44.06	14.38	27.19	29.69	4.56	9.94	8.31	1.24	1.02	2.08	7.97	7.30	5.92	14.27	19.38	19.96
WC36	38.12	37.81	25.31	25.94	31.88	23.44	3.94	2.50	6.94	0.63	0.48	0.48	7.39	11.30	10.89	14.71	15	19.83
ANOVA																		
l.s.d.	*4.434*			*6.847*			*5.834*			*0.717*			*1.257*			*1.682*		
p - value	*<.001*			*<.001*			*<.001*			*<.001*			*<.001*			*<.001*		
Cv %	*16.4*			*38.1*			*92.2*			*85.9*			*21.8*			*29.4*		

Where HRGA: hypocotyl root growth angle, BRGA: basal root growth angle, 3rd BD: 3rd order branching density, TRD: taproot diameter, NN: number of nodules ND; nodule diameter

Effect of $[P]_{ext}$ on agronomic parameters of cowpea genotypes

Genotypes varied significantly ($P < 0.001$) in days to flowering (DTF) in the major and minor season (Table 8). In general, genotypes WC36, Secow3B and Secow5T recording the earliest DTF compared to Agyenkwa which recorded approximately 41 days to flowering in both seasons (Table 8). The effect of $[P]_{ext}$ was significant ($P < 0.001$) for DTF during both seasons (Table 9). In the major season, soil amended with 45 kg P/ha took 36.98 days to reach anthesis compared to 0 kg P/ha which took 37.34 days to flower (Table 9). In the minor season, DTF decreased with increasing $[P]_{ext}$ level (Table 9). Plants cultivated at 10 and 45 kgP/ha took approximately 36.96 and 36.80 days to reach flowering stage compared to 0 kgP/ha which took 37.15 DTF (Table 9). The interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for DTF in both screening periods (Table 10 and 11). In the major season, genotypes Soronko and Asontem flowered early in response to increasing $[P]_{ext}$ rates compared to the remaining genotypes which had the same DTF irrespective of P levels (Table 10). In the minor season, genotypes Secow3B, Agyenkwa, NE51*NE50 and Sunshine recorded the same DTF despite variation in $[P]_{ext}$ concentration whilst, Soronko, Asontem and Alegi*Sunshine had reduced DTF with increasing P rates (Table 11).

Days to 50% flowering among genotypes was significantly ($P < 0.001$) affected by genotype in the major and minor season (Table 8). Genotypes NE15*WC35B, NE15*Sunshine, MU9 and IT91 took a mean of 45 days to obtain 50% flowering compared to WC36 (34) which recorded the least days to 50% flowering in the major season (Table 8). Similarly, in the minor season, genotype WC36 (34 days) topped the group with early days to 50% flowering

followed by Secow3B (35.75 days) and Secow5T (37.75 days) (Table 8). The effect of $[P]_{ext}$ on days to 50% flowering observed was statistically insignificant ($P = 1.000$) in both seasons (Table 9). Similarly, in both seasons, the interaction of genotypes and $[P]_{ext}$ was insignificant for days to 50% flowering among cowpea genotypes (Table 10 and 11).

Number of branches (NB) varied ($P < 0.001$) among cowpea genotypes in both growing seasons (Table 8). In both season, genotypes Alegi*Sunshine, MU9 and Songotra were the topmost three (3) genotypes with high NB compared to NE50 and WC35B*NE50 which recorded the least value for NB (Table 8). Effect of $[P]_{ext}$ on NB in the major and minor season was significant ($P < 0.001$) (Table 9). In the major season, soil amended with 45 kg P/ha produced 47.74% more NB compared to the control treatment (Table 9). However, in the minor season NB obtained at treatment 45 kgP/ha was 9.69% greater compared to plants grown on 0 kgP/ha (Table 9). Significant ($P < 0.001$) interaction of genotype and $[P]_{ext}$ was observed for NB in both season (Table 10 and 11). In general, majority of genotypes increased NB in response to increasing $[P]_{ext}$ in the major season. A typical example includes genotype Asontem, Agyenkwa, Songotra, NE15*WC35B, Nketewadea and Secow5T (Table 10). However, genotypes MU9, WC10*WC36 and WC35B*NE50 had high NB on unamended soil in the minor season (Table 11) Effect of genotype on number of pods per peduncle (NPP) was significant ($P < 0.001$) in the major season but insignificant ($P = 0.576$) in the minor season (Table 8). The topmost two (2) genotypes with high NPP were Secow3B (2.98) and Sunshine (2.88) which was significantly higher than values obtained by genotype NE15*WC35B (2.40) and NE15*Sunshine (2.23) (Table 8). Number of pods

per peduncle was significantly ($P < 0.001$) affected by $[P]_{ext}$ in both seasons (Table 9). In the major season, NPP at 45 kgP/ha was 86.88% greater compared to 0 kgP/ha (Table 9). Similarly, treatment 45 kg P/ha had the highest NPP of 3.19 in the minor season (Table 9). Interaction of genotypes and $[P]_{ext}$ was significant ($P < 0.001$) for NPP in the major season (Table 10) but insignificant ($P = 0.991$) in the minor season (Table 11). In general, NPP increased with increasing P concentration among genotypes in the major season (Table 10). Example is observed in genotype Agyenkwa, WC36 and IT91. In the minor season, genotype IT91, NE15*WC35B and WC36 obtained high NPP at 10 kg P/ha compared to 45 and 0 kg P/ha (Table 11).

Number of pods per plant (NPPP) varied significantly ($P < 0.001$) among genotypes in the major season but insignificantly ($P = 0.231$) in the minor season (Table 8). In the major season, genotype Secow3B - 107.75, Sunshine - 98.65 and Soronko - 97.42 were within distribution with superior NPPP compared to NE15*WC35B with least NPPP (Table 8). Significant effect ($P < 0.001$) of $[P]_{ext}$ was observed for NPPP in both major and minor season (Table 9). External P application resulted in an increase in NPPP. Percentage increase of 77 and 39.44 in NPPP was observed at 45 kg P/ha compared to 0 kg P/ha in the major and minor season respectively (Table 9). Interaction effect was significant ($P = 0.018$) in the major season (Table 10) but insignificant ($P = 0.804$) in the minor season for NPPP (Table 11). In the minor season, genotypes WC36, WC10*WC36, NE15*WC35B and Soronko had high NPPP at treatment 10 kg P/ha (Table 11).

Number of seeds per pod (NSP) observed in both seasons was significantly ($P < 0.001$) affected by genotypes (Table 8). Number of seeds per

pod ranged from 15.50 - 20.17 (count) in the major season of which genotype IT91 obtained the highest and WC35B*NE50 obtained the least (Table 8). In the minor season, genotype IT91 (18.81), WC10*WC36 (17.73) and Asontem (17.56) recorded the highest value of NSP compared to WC35B*NE50 which recorded the least (Table 8). Number of seeds per pod was significantly ($P < 0.001$) affected by $[P]_{ext}$ concentration in both seasons (Table 9). In the major season, NSP obtained under P amended soil was 40.78% greater than number of seeds obtained by plants grown on unamended soil treatment (Table 9). Number of seed per pods recorded on P amended soil was 18.49% greater than NSP obtained under unamended soil treatment in the minor season (Table 9). Interaction effect was significant ($P < 0.001$) in both seasons for NSP (Table 10 and 11). An increasing trend in NSP was observed among majority of cowpea genotypes in response to P application. However, genotype MU9, Nketewadea, Songotra, Al*Secow5T and NE15*Sunshine produced greater number of NSP in response to $[P]_{ext}$ rate to a point where it begun to decline in the major season (Table 10). Similarly, in the minor season genotype Nketewadea, Songotra, Al*Secow5T, NE51*NE50 and NE15*Sunshine produced greater NSP at 10 kgP/ha compared to 45 kgP/ha in the minor season (Table 11).

Genotypes significantly ($P < 0.001$) differed in pod length (PL) in both seasons (Table 8). Genotype IT91 and Nketewadea was superior in producing longer PL in both major and minor season relative to Alegi*Sunshine which produced least PL in both season (Table 8). Pod length varied significantly ($P < 0.001$) under varying $[P]_{ext}$ in the major and minor season (Table 9). Compared to 0 kg P/ha treatment, longer PL was recorded at soil amended with

45 kg P/ha (20.73 cm) in the major season. Plants cultivated at 45 kg P/ha recorded 42.86% more PL in the minor season compared to P unamended soil (Table 9). Variation ($P < 0.001$) was observed for PL for the interaction of genotype and $[P]_{ext}$ in both seasons (Table 10 and 11). An increasing trend in PL of evaluated genotypes was observed with increasing $[P]_{EXT}$ application. With certain genotypes, PL increased at 10 kgP/ha after which it begun to decline. Example includes genotype Songotra, Alegi*Secow5T, NE15*Sunshine etc. in both seasons (Table 10 and 11).

Genotypic effect was significant ($P < 0.001$) for hundred seed weight (100-SW) among genotypes (Table 8). Genotype Secow3B obtained the highest SW of 17.23 g in the major season compared to NE50 which obtained the least (Table 8). Genotype Secow3B - 16.16, NE15*WC35B - 15.99, Asontem - 15.73 and Sunshine - 15.62 were superior in SW during the major season (Table 8). Seed weight was significantly ($P < 0.001$) affected by $[P]_{ext}$ in both seasons (Table 9). In all, SW increased with increasing concentration of external P. In the major season, $[P]_{ext}$ application resulted in 33.54 percent increase in SW compared to control treatment (Table 9). Hundred (100) SW of genotypes cultivated on amended soil was 15.38% greater compared to genotypes grown on unamended soil treatment in the minor season (Table 9). Interaction effect was significant ($P < 0.001$) for SW (Table 10 and 11). Majority of cowpea genotypes screened under varying P conditions increased with increasing P concentration in both seasons. For example, genotypes Soronko, Asontem, Agyenkwa, NE50 and Sunshine recorded high SW at high phosphorus levels compared to low phosphorus conditions (Table 10 and 11).

Yield in both major and minor season was significantly ($P < 0.001$) affected by genotype (Table 8). In both seasons, genotypes Secow3B, Sunshine and Songotra recorded the highest yield whilst MU9 and Alegi*Sunshine were genotypes with least yield (Table 8). Application of $[P]_{ext}$ significantly ($P < 0.001$) affected yield of cowpea genotypes (Table 9). Yield obtained at 45 kgP/ha was greater and significantly different from yield values obtained under 10 and 0 kgP/ha in the major season. In the minor season, yield obtained at 45 kgP/ha was greater 31.09% and 48.19% significantly different form yield values obtained under 10 and 0 kgP/ha (Table 9). Interaction of genotype and $[P]_{ext}$ was significant ($P = 0.010$) in the major season as well as the minor season ($P < 0.001$) (Table 10 and 11). An increasing trend in yield of evaluated genotypes was observed with increasing P application. Example, Soronko, Asontem, NE 50, MU9 and WC36 are among genotypes that recorded high yield at high phosphorus level compared to low phosphorus levels (Table 10 and 11) respectively.

Table 8 - Genotypic effect on agronomic parameters among field grown cowpea genotypes during the major and minor season

	Measurements																	
	DTF		50%DF		NB		NPP		NPPP		NSP		PL		100-SW		Yield	
Genotypes	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**
Agyenkwa	40.94	40.75	44.81	44.75	7.00	6.44	2.71	2.98	86.73	85.77	17.58	16.23	17.45	16.31	16.67	15.58	959.20	986.30
Alegi*secow5T	39.94	39.75	44.81	44.75	7.00	6.44	2.63	3.04	86.27	89.60	16.00	14.65	18.79	17.65	15.08	13.92	890.40	923.40
Alegi*Sunshine	39.94	39.75	44.81	44.75	5.67	5.10	2.50	2.90	79.17	84.02	15.83	14.48	16.41	15.27	15.80	14.85	793.30	815.80
Asontem	38.27	38.08	44.81	44.75	7.00	6.44	2.52	3.02	89.08	93.04	18.92	17.56	18.57	17.44	16.73	15.73	1013.30	1004.30
IT91	39.94	39.75	44.81	44.75	6.00	5.44	2.60	2.83	82.67	80.21	20.17	18.81	19.64	18.50	15.42	14.36	930.30	914.00
MU9	39.94	39.75	44.81	44.75	5.67	5.10	2.75	2.92	82.44	78.87	17.67	16.31	18.29	17.15	15.76	14.56	842.20	869.40
NE15*Sunshine	39.94	39.75	44.81	44.75	6.00	5.44	2.23	2.94	77.27	90.83	17.75	16.40	18.51	17.37	15.79	14.98	967.40	1000.70
NE15*WC35B	39.94	39.75	44.81	44.75	6.67	6.10	2.40	3.50	73.35	92.79	17.92	16.56	17.26	16.12	16.79	15.99	980.40	1032.30
NE48*WC10	37.94	37.75	39.81	39.75	6.67	6.10	2.58	2.81	87.35	86.00	16.33	14.98	16.59	15.45	14.84	13.85	862.80	920.40
NE50	37.94	37.75	39.81	39.75	7.33	6.77	2.63	2.96	90.58	92.25	17.33	15.98	17.20	16.06	12.71	11.82	949.20	1004.50
NE51*NE50	37.94	37.75	39.81	39.75	7.00	6.44	2.52	2.73	79.73	76.37	18.00	16.65	18.47	17.34	14.59	13.49	859.80	873.20
Nketewadea	37.94	37.75	39.81	39.75	6.00	5.44	2.60	2.94	86.08	85.79	17.83	16.48	19.62	18.49	15.46	14.52	997.80	1019.90
Secow3B	33.94	33.75	35.81	35.75	6.00	5.44	2.98	3.19	107.75	102.29	18.11	16.75	19.28	18.15	17.23	16.16	1149.60	1200.40
Secow5T	33.94	33.75	37.81	37.75	6.67	6.10	2.65	3.13	83.12	88.17	18.50	17.15	18.72	17.59	14.65	13.68	1000.70	1071.60
Songotra	33.94	33.75	37.81	37.75	5.67	5.10	2.48	3.15	74.06	83.81	18.83	17.48	18.21	17.07	14.10	13.34	1045.20	1074.50
Soronko	36.10	35.92	37.81	37.75	7.10	6.46	2.58	2.85	97.42	96.44	16.67	15.31	17.30	16.06	14.07	13.12	968.30	995.70
Sunshine	33.94	33.75	37.81	37.75	6.00	5.44	2.88	3.06	98.65	94.52	17.75	16.40	17.77	16.64	16.50	15.62	1060.40	1086.30
WC10*WC36	33.94	33.75	37.81	37.75	7.00	6.44	2.65	2.85	93.21	93.40	19.08	17.73	18.61	17.47	14.43	13.72	1037.50	1077.10
WC35B*NE50	33.94	33.75	37.81	37.75	7.33	6.77	2.50	2.92	80.75	82.73	15.50	14.15	17.26	16.12	14.66	13.65	807.00	896.30
WC36	32.94	32.75	33.81	33.75	6.67	6.10	2.69	3.17	84.21	90.85	16.42	15.06	18.22	17.09	14.90	13.94	905.80	943.10
ANOVA																		
LSD	*0.302*	*0.287*	*0.252*	*0.283*	*0.793*	*0.619*	*0.208*	*0.505*	*11.733*	*16.12*	*1.404*	*1.241*	*1.147*	*0.990*	*0.8713*	*0.7129*	*66.61*	*101.47*
p-value	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*0.576*	*<0.001*	*0.231*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Cv	*2*	*1.9*	*1.5*	*1.7*	*30.2*	*25.9*	*19.9*	*42.1*	*34*	*45.5*	*19.9*	*19.1*	*15.8*	*14.6*	*14.2*	*12.4*	*26.1*	*25.7*

Table 9 - Effect of $[P]_{ext}$ on agronomic parameters among field grown cowpea genotypes during the major and minor season

	Measurements																	
	DTF		50%DF		NB		NPP		NPPP		NSP		PL		100-SW		Yield	
$[P]_{ext}$	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**	**Major**	**Minor**
0 kg P/ha	37.34	37.15	40.71	40.65	5.00	5.68	1.98	2.73	48.68	71.80	13.47	14.29	14.86	15.89	12.29	13.09	686.10	738.50
10 kg P/ha	37.16	36.98	40.71	40.65	6.25	5.94	2.62	3.06	85.85	94.00	18.98	17.04	18.73	17.00	16.39	14.93	950.70	1010.40
45 kgP/ha	36.99	36.80	40.71	40.65	8.32	6.25	3.21	3.19	123.46	99.40	20.37	17.44	20.73	18.01	17.25	15.01	1216.30	1207.40
ANOVA																		
LSD	*0.117*	*0.111*	*0.098*	*0.110*	*0.307*	*0.240*	*0.080*	*0.196*	*4.544*	*6.240*	*0.544*	*0.481*	*0.444*	*0.384*	*0.338*	*0.276*	*38.580*	*39.300*
p-value	*<0.001*	*<0.001*	*1.00*	*1.00*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Cv	*2..2*	*1.9*	*1.5*	*1.7*	*30.3*	*25.9*	*19.9*	*42.1*	*34*	*45.5*	*19.9*	*19.1*	*15.8*	*14.6*	*14.2*	*12.4*	*26.1*	*25.7*

Traits in matrix are YLD: yield, DTF: days to flowering, DT50%: days to 50% flowering, NB: number of branches: NPP: number of pods per peduncle, NPPP: number of pods per plant, NSP: number of seeds per plant, PL: pod length, SW: 100 seeds weight and YLD: yield per plot.

Table 10 - Interaction of genotype and $[P]_{ext}$ on agronomic parameters of field grown cowpea genotypes measured in the major season

	Measurements																									
	DTF			50%DF			NB			NPP			NPPP			NSP			PL			100-SW			Yield		
Genotypes	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**
Agyenkwa	40.94	40.94	40.94	44.81	44.81	44.81	5.75	6.80	8.50	2.00	2.69	3.44	44.19	83.81	132.19	13.75	18.25	20.75	14.21	17.76	20.38	13.73	17.76	18.53	673.00	920.50	1284.10
Alegi*secow5T	39.94	39.94	39.94	44.81	44.81	44.81	4.75	6.80	9.50	1.88	2.75	3.25	39.38	83.19	136.25	9.75	20.00	18.25	16.78	20.91	18.68	11.20	16.68	17.36	554.90	970.90	1145.60
Alegi*Sunshine	39.94	39.94	39.94	44.81	44.81	44.81	3.75	6.80	6.50	2.13	2.38	3.00	54.75	72.88	109.88	11.75	17.75	18.00	12.78	16.76	19.68	13.70	16.55	17.14	638.70	765.10	976.10
Asontem	39.94	37.94	36.94	44.81	44.81	44.81	4.75	6.80	9.50	1.81	2.56	3.19	41.00	91.25	135.00	15.50	20.00	21.25	15.58	18.63	21.51	13.74	17.62	18.82	665.90	1024.50	1349.60
IT91	39.94	39.94	39.94	44.81	44.81	44.81	4.75	5.80	7.50	1.81	2.75	3.25	38.00	84.38	125.62	17.25	21.00	22.25	16.33	19.63	22.96	12.96	15.95	17.35	814.70	911.40	1064.70
MU9	39.94	39.94	39.94	44.81	44.81	44.81	4.75	5.80	6.50	2.13	2.75	3.38	43.50	80.31	123.50	13.75	18.50	20.75	15.41	18.36	21.11	13.94	16.41	16.94	579.90	881.10	1065.70
NE15*Sunshine	39.94	39.94	39.94	44.81	44.81	44.81	3.75	6.80	7.50	1.50	2.13	3.06	40.81	71.50	119.50	13.75	20.00	19.50	15.78	20.08	19.66	13.87	16.14	17.36	640.80	958.50	1302.80
NE15*WC35B	39.94	39.94	39.94	44.81	44.81	44.81	3.75	6.80	9.50	1.63	2.38	3.19	37.50	73.38	109.19	14.50	16.25	23.00	13.38	15.03	23.36	14.08	18.37	17.92	763.90	962.00	1215.40
NE48*WC10	37.94	37.94	37.94	39.81	39.81	39.81	5.75	5.80	8.50	2.13	2.63	3.00	57.88	89.06	115.12	12.75	18.00	18.25	11.58	18.01	20.18	10.29	16.95	17.28	616.50	848.20	1123.80
NE50	37.94	37.94	37.94	39.81	39.81	39.81	5.75	6.80	9.50	2.19	2.88	2.81	67.25	91.69	112.81	14.25	18.25	19.50	14.51	17.68	19.41	9.97	13.50	14.68	811.10	915.70	1120.90
NE51*NE50	37.94	37.94	37.94	39.81	39.81	39.81	5.75	6.80	8.50	2.00	2.56	3.00	52.75	79.31	107.12	13.75	20.25	20.00	16.08	18.61	20.73	9.76	16.58	17.44	654.70	816.50	1108.20
Nketewadea	37.94	37.94	37.94	39.81	39.81	39.81	3.75	5.80	8.50	2.00	2.63	3.19	44.75	92.94	120.56	12.25	21.75	19.50	16.03	21.38	21.46	12.22	16.58	17.59	670.30	966.30	1356.90
Secow3B	33.94	33.94	33.94	35.81	35.81	35.81	4.75	5.80	7.50	2.38	3.00	3.56	57.31	108.06	157.88	15.00	19.32	20.00	16.53	20.66	20.66	14.15	18.06	19.47	918.00	1196.20	1334.60
Secow5T	33.94	33.94	33.94	37.81	37.81	37.81	5.75	5.80	8.50	2.13	2.69	3.13	53.62	81.56	114.19	13.75	20.50	21.25	15.91	19.46	20.81	11.29	15.75	16.92	706.70	1012.50	1282.90
Songotra	33.94	33.94	33.94	37.81	37.81	37.81	3.75	6.80	7.50	2.13	2.19	3.13	39.31	66.19	116.69	15.00	22.00	19.50	14.38	20.36	19.88	12.65	13.65	16.00	661.10	1112.10	1362.40
Soronko	37.94	36.44	33.94	37.81	37.81	37.81	5.75	6.80	8.80	1.88	2.56	3.31	46.94	104.69	140.62	13.75	16.75	19.50	14.23	17.76	19.91	10.50	15.33	16.37	677.10	991.40	1236.30
Sunshine	33.94	33.94	33.94	37.81	37.81	37.81	4.75	5.80	7.50	2.06	2.88	3.69	60.19	100.69	135.06	11.00	20.75	21.50	12.53	19.38	21.41	12.50	18.54	18.47	652.00	1149.50	1319.80
WC10*WC36	33.94	33.94	33.94	37.81	37.81	37.81	6.75	5.80	8.50	2.00	2.50	3.44	58.75	91.38	129.50	14.25	19.00	24.00	15.13	18.13	22.56	11.82	15.32	16.15	779.50	1007.70	1325.30
WC35B*NE50	33.94	33.94	33.94	37.81	37.81	37.81	6.75	5.80	9.50	1.81	2.56	3.13	47.25	76.56	118.44	11.00	14.75	20.75	14.51	17.66	19.61	11.53	15.53	16.92	608.70	684.20	1128.20
WC36	32.94	32.94	32.94	33.81	33.81	33.81	4.75	6.80	8.50	2.00	3.00	3.06	48.38	94.12	110.12	12.75	16.50	20.00	15.61	18.41	20.66	11.97	16.50	16.23	633.90	919.80	1163.60
ANOVA																											
LSD		*0.523*			*0.252*			*1.373*			*0.359*			*20.32*			*2.432*			*1.985*			*1.509*			*172.52*	
p-value		*<.001*			*1.00*			*<.001*			*<.001*			*0.047*			*<.001*			*<.001*			*<.001*			*0.010*	
Cv		*2.0*			*1.5*			*30.3*			*19.9*			*34.0*			*19.9*			*15.8*			*14.2*			*26.1*	

Traits in matrix are YLD: yield, DTF: days to flowering, DT50%: days to 50% flowering, NB: number of branches: NPP: number of pods per peduncle, NPPP: number of pods per plant, NSP: number of seeds per plant, PL: pod length, SW: 100 seeds weight and YLD: yield per plot.

Table 11 - Interaction of genotype and $[P]_{ext}$ on agronomic parameters of field grown cowpea genotypes measured in the minor season

	Measurements																								
Genotypes	**DTF**			**50%DF**			**NB**			**NPP**			**NPPP**			**NSP**			**PL**			**100-SW**			**Yield**		
	0	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**	**0**	**10**	**45**
Agyenkwa	40.75	40.75	40.75	44.75	44.75	44.75	6.44	6.44	6.44	2.81	2.75	3.38	68.00	82.70	106.60	14.56	16.31	17.81	15.24	16.04	17.66	14.74	15.97	16.04	735.60	959.60	1263.60
Alegi*secow5T	39.75	39.75	39.75	44.75	44.75	44.75	5.44	6.44	7.44	2.94	3.00	3.19	72.60	85.20	110.90	10.56	18.06	15.31	17.81	19.19	15.96	11.85	15.11	14.80	602.60	942.00	1225.60
Alegi*Sunshine	39.75	37.75	36.75	44.75	44.75	44.75	4.44	6.44	4.44	2.63	2.81	3.25	73.10	80.70	98.30	12.56	15.81	15.06	13.81	15.04	16.96	14.61	14.93	15.00	674.90	864.30	908.40
Asontem	39.75	37.75	36.75	44.75	44.75	44.75	5.44	6.44	7.44	2.69	3.13	3.25	64.40	104.60	110.10	16.31	18.06	18.31	16.69	16.84	18.79	14.65	16.04	16.51	725.00	978.80	1308.90
IT91	39.75	39.75	36.75	44.75	44.75	44.75	5.44	5.44	5.44	2.81	2.94	2.75	68.10	86.90	85.60	18.06	19.06	19.31	17.36	17.91	20.24	13.52	14.70	14.87	733.60	945.80	1062.60
MU9	39.75	39.75	39.75	44.75	44.75	44.75	5.44	5.44	4.44	2.69	3.19	2.88	60.70	88.70	87.10	14.56	16.56	17.81	16.44	16.64	18.39	14.26	14.39	15.02	627.50	916.80	1063.80
NE15*Sunshine	39.75	39.75	39.75	44.75	44.75	44.75	4.44	6.44	5.44	2.38	2.88	3.56	67.30	93.30	111.90	14.56	18.06	16.56	16.81	18.36	16.94	14.05	15.36	15.53	642.60	1031.20	1328.20
NE15*WC35B	39.75	39.75	39.75	44.75	44.75	44.75	4.44	6.44	7.44	3.25	3.88	3.38	80.10	107.80	90.40	15.31	14.31	20.06	14.41	13.31	20.64	15.18	16.93	15.85	829.90	1026.30	1240.70
NE48*WC10	37.75	37.75	37.75	39.75	39.75	39.75	6.44	5.44	6.44	2.38	2.75	3.31	67.50	87.20	103.20	13.56	16.06	15.31	12.61	16.29	17.46	11.28	15.33	14.94	664.10	933.00	1164.00
NE50	37.75	37.75	37.75	39.75	39.75	39.75	6.44	6.44	7.44	2.69	3.13	3.06	86.60	96.70	93.40	15.06	16.31	16.56	15.54	15.96	16.69	10.60	12.24	12.63	961.80	986.10	1065.60
NE51*NE50	37.75	37.75	37.75	39.75	39.75	39.75	6.44	6.44	6.44	2.38	2.56	3.25	67.30	71.10	90.70	14.56	18.31	17.06	17.11	16.89	18.01	10.44	15.04	14.97	716.30	886.80	1016.40
Nketewadea	38.75	37.75	36.75	39.75	39.75	39.75	4.44	5.44	6.44	2.88	3.00	2.94	68.70	99.40	89.20	13.06	19.81	16.56	17.06	19.66	18.74	13.05	15.15	15.37	717.90	1089.30	1252.50
Secow3B	33.75	33.75	33.75	35.75	35.75	35.75	5.44	5.44	5.44	3.06	3.25	3.25	83.60	108.90	114.30	15.81	17.39	17.06	17.56	18.94	17.94	15.02	16.58	16.87	1000.00	1258.30	1342.80
Secow5T	33.75	33.75	33.75	35.75	35.75	35.75	6.44	5.44	6.44	2.75	3.25	3.38	73.70	91.40	99.40	14.56	18.56	18.31	16.94	17.74	18.09	12.04	14.31	14.69	754.30	1152.30	1308.30
Songotra	33.75	33.75	33.75	35.75	35.75	35.75	4.44	5.44	5.44	2.88	3.00	3.56	59.50	82.40	109.50	15.81	20.06	16.56	15.41	18.64	17.16	13.74	12.48	13.79	708.80	1138.40	1376.20
Soronko	37.75	36.25	33.75	37.75	37.75	37.75	6.19	6.44	6.75	2.63	3.00	2.94	66.90	116.30	106.10	14.56	14.81	16.56	15.09	15.91	17.19	11.26	14.03	14.09	747.00	1026.20	1213.90
Sunshine	33.75	33.75	33.75	35.75	35.75	35.75	5.44	5.44	5.44	2.63	3.00	3.56	79.90	99.20	104.40	11.81	18.81	18.56	13.56	17.66	18.69	13.59	17.15	16.12	699.60	1154.20	1405.10
WC10*WC36	33.75	33.75	33.75	35.75	35.75	35.75	7.44	5.44	6.44	2.50	3.13	2.94	77.60	107.70	94.90	15.06	12.81	17.81	16.16	16.41	19.84	12.66	14.16	14.34	827.10	1133.10	1271.20
WC35B*NE50	33.75	33.75	33.75	35.75	35.75	35.75	7.44	5.44	7.44	2.75	3.00	3.00	75.00	81.80	91.40	11.81	12.81	17.81	15.54	15.94	16.89	12.36	14.02	14.58	720.60	780.40	1187.80
WC36	32.75	32.75	32.75	33.75	33.75	33.75	5.44	6.44	6.44	2.81	3.63	3.06	74.70	106.90	91.00	13.56	14.56	17.06	16.64	16.69	17.94	12.86	14.72	14.25	681.50	1006.10	1141.80
ANOVA																											
LSD	*0.496*			*0.491*			*1.071*			*0.874*			*27.92*			*2.150*			*1.715*			*1.235*			*175.7*		
p-value	*<.001*			*1.00*			*<.001*			*0.991*			*0.804*			*<.001*			*<.001*			*<.001*			*<.001*		
Cv	*1.9*			*1.7*			*25.9*			*42.1*			*45.5*			*19.1*			*14.6*			*12.4*			*25.7*		

Traits in matrix are YLD: yield, DTF: days to flowering, DT50%: days to 50% flowering, NB: number of branches: NPP: number of pods per peduncle, NPPP: number of pods per plant, NSP: number of seeds per plant, PL: pod length, SW: 100 seeds weight and YLD: yield per plot.

Variation in phosphorus uptake and use efficiency among cowpea genotypes

Shoot P concentration

Shoot P concentration in both major and minor season were significantly ($P < 0.001$) influenced by genotype (Figure 10A). Genotype IT91 97714 µg/g), WC10*WC36 (7637 µg/g) and WC36 (7190 µg/g) had high shoot P concentration in the major season (Figure 10A). Shoot P concentration was high for genotype Secow3B (8110 µg/g), MU9 (8049 µg/g) and WC35B*NE50 (8048 µg/g) whilst genotype Soronko (6632 µg/g) and Nketewadea (6199 µg/g) had the least shoot P concentration in the minor season (Figure 10A)

In both seasons, application of P significantly ($P < 0.001$) affected shoot P concentration under various soil amendments (Figure 10B). A direct relation between shoot P concentration and $[P]_{ext}$ was observed during major and minor season. Compared to 0 kg P/ha, genotypes cultivated on 10 and 45 kg P/ha recorded highest shoot P concentration in the major and minor season respectively (Figure 10B).

Interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) in both seasons (Figure 10C and 10D). The general trend was that, shoot P concentration increased with increasing external P concentration in both seasons. Typical examples include genotypes Asontem, Agyenkwa, WC36 among others which obtained high shoot P with increasing $[P]_{ext}$ rates (Figure 10C and 10D).

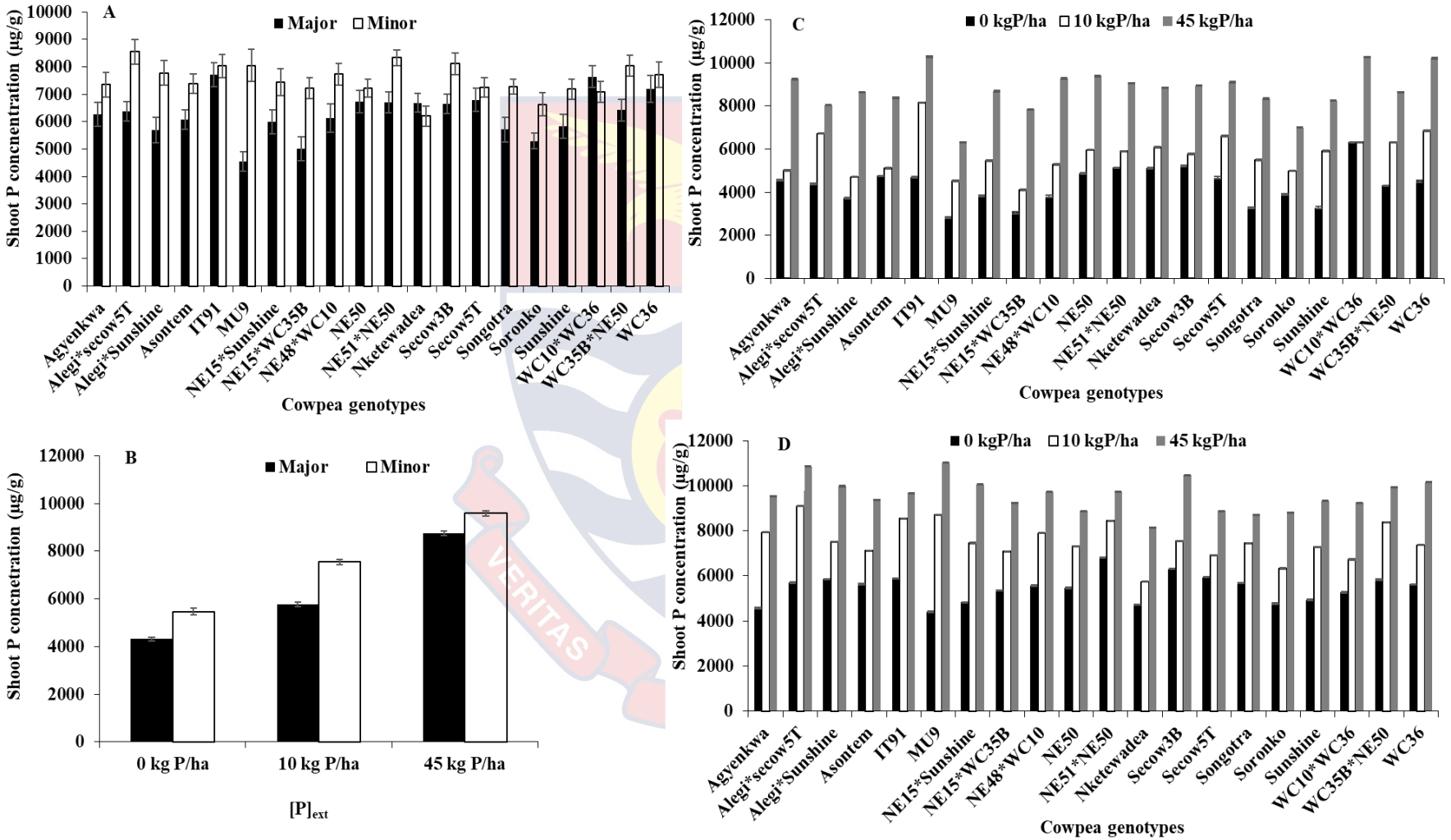

Figure 10 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on shoot P conc. Interaction of genotype and $[P]_{ext}$ on shoot P conc in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Root P concentration

Genotypes significantly ($P < 0.001$) influenced root P concentration in both seasons (Figure 11A). Genotypes IT91 (2571.5 µg/g) had the highest root P concentration in the major season followed by WC10*WC36, WC36 and Nketewadea (Figure 11A). In the minor season, root P concentration ranged from 2379 - 4588 µg/g of which genotype Nketewadea, Soronko and WC10*WC36 were the last three (3) genotypes within the distribution with least root P concentration (Figure 11A).

Root P concentration varied significantly ($P < 0.001$) depending on the concentration of $[P]_{ext}$ in the major and minor season (Figure 11B). In both seasons, root P concentration under various soil treatments increased with increasing $[P]_{ext}$ concentrations. In the major season, plants grown at 45 kg P/ha had more root P concentration relative to 0 kg P/ha (Figure 11B). Similarly, greater root P concentration was observed among genotypes grown at soil amended with 45 kg P/ha compared to 10 kg P/ha in the minor season (Figure 11B).

Significant ($P < 0.001$) interaction of genotype and $[P]_{ext}$ was observed in both seasons for root P concentration (Figure 11C and 11D). Majority of genotypes screened under varying P conditions in both seasons increased root P concentration in response to increasing P application. In the major season, Alegi*Secow5T, Asontem, NE50 and MU9 obtained high root P at high P concentration (Figure 11C). Similarly, in the minor season, genotypes Sunshine, Soronko, MU9 and Asontem increased root P with increasing P concentration (Figure 11D).

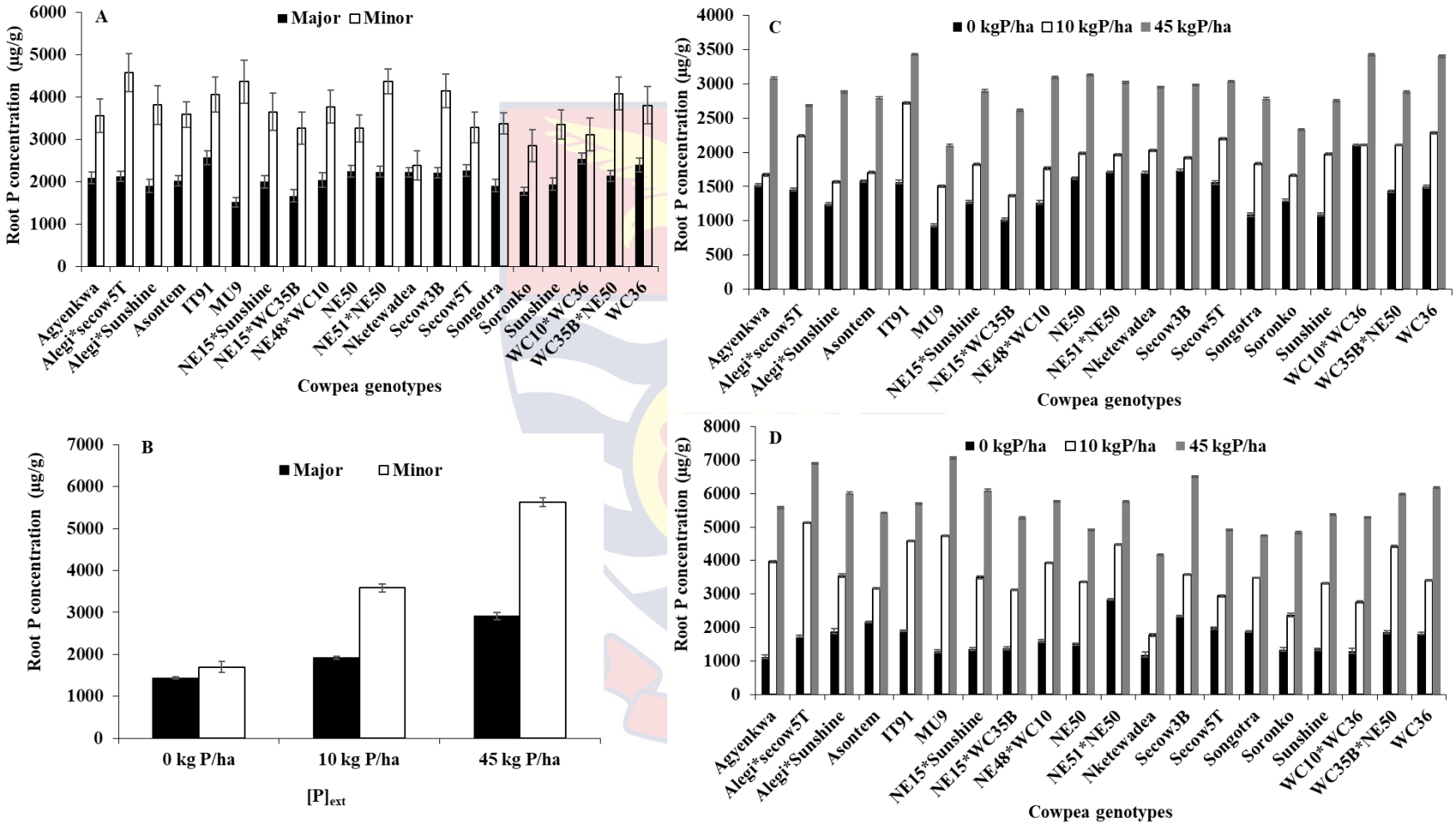

Figure 11 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on root P conc. Interaction of genotype and $[P]_{ext}$ on root P conc in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Shoot P content

Cowpea genotypes evaluated in the major and minor season showed a significant ($P < 0.05$) variation in shoot P content (Figure 12A). Shoot P content was high for genotype WC35B*NE50 (255.2 µg/g DM) and WC10*WC36 (234.0 µg./g) shoot compare to Asontem (168.3 µg./g) shoot which had the least value for shoot P content in the major season (Figure 12A). In the minor season, genotypes WC35B*NE50 and Alegi*Secow5T were superior in shoot P content compared to the remaining genotypes (Figure 12A).

The application of $[P]_{ext}$ had a significant effect ($P < 0.001$) on shoot P content in both major and minor season (Figure 12B). An increasing trend in shoot P content was observed with increasing $[P]_{ext}$ concentration. In all, shoot P content on soil amended with 45 kgP/ha was 73% greater compared to P content obtained on unamended soils in the major season (Figure 12B). Shoot P content obtained at 10 kgP/ha was 63.94% greater compared to shoot P content recorded at 0 kgP/ha in the minor season (Figure 12B).

Interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for shoot P content in the major season (Figure 12C) as well as the minor season (Figure 12D). In the major season, genotypes Alegi*Secow obtained high shoot P content at 10 kg P/ha whilst Soronko and WC10*WC36 obtained high shoot P content at 0 kg P/ha compared to 10 kg P/ha (Figure 12C). In the minor season, genotypes MU9, IT91, Agyenkwa, Asontem, WC10*WC36, NE15*Sunshine and NE51*NE50 obtained high shoot P content at 10 kg P/ha compared to 0 and 45 P soil amendment. Genotype Alegi*Secow5T recorded high shoot P content at control treatment (Figure 12D).

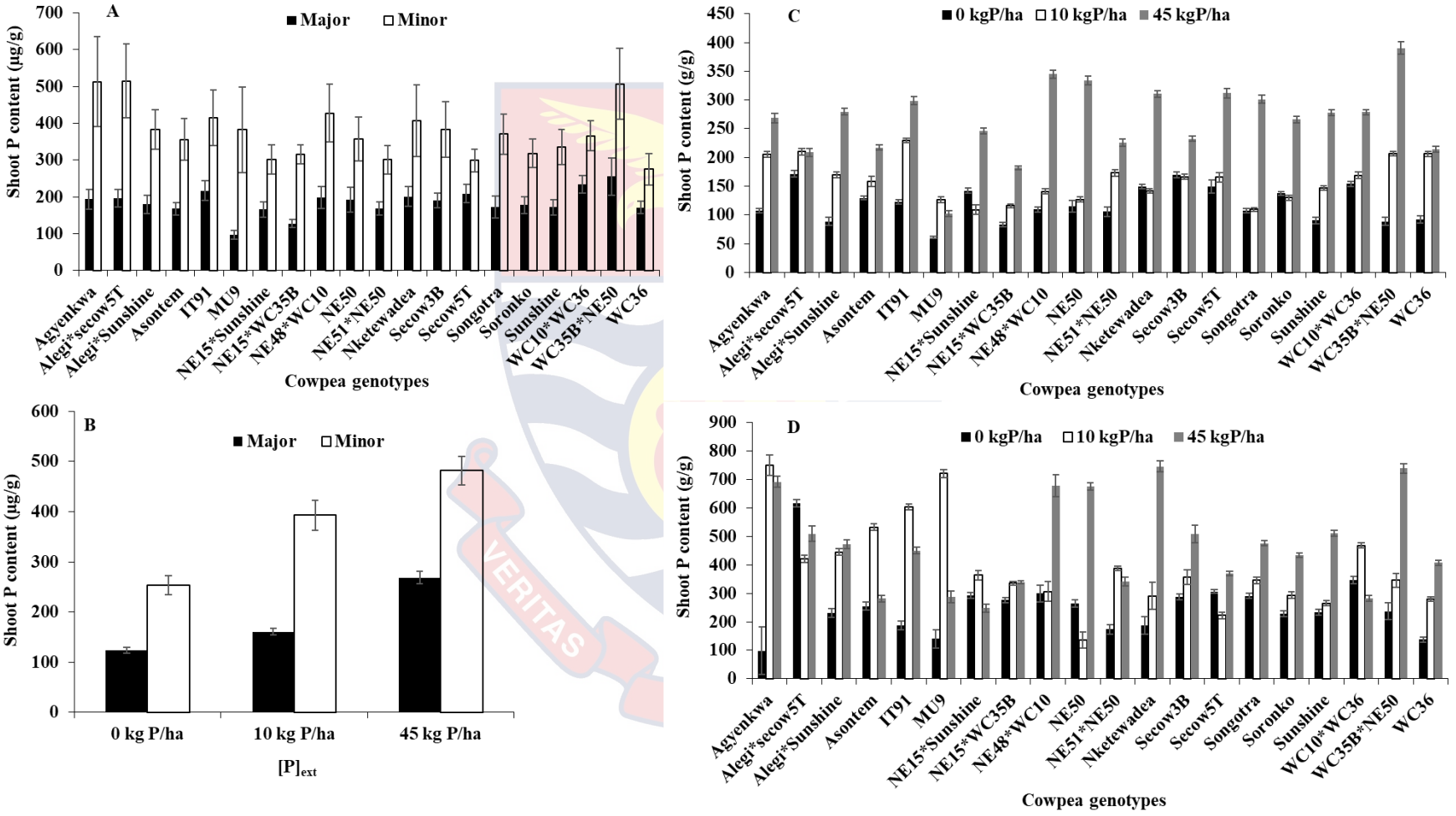

Figure 12 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on shoot P content. Interaction of genotype and $[P]_{ext}$ on shoot P content in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Root P content

Evaluated cowpea genotypes significantly ($P < 0.001$) varied in root P content during the major and minor season (Figure 13A). The most five (5) genotypes with high root P content in the major season were WC36, NE51*NE50, Secow5T, Alegi*Secow5T and IT91 whilst lower value of root P content was obtained by Songotra (Figure 13A). In the minor season, genotypes Alegi*Secow5T - 23.56, NE51*NE50 (21.76), WC35B*NE50 (20.92) and MU9 (19.28 µg./g) DM obtained the highest root P content compared to WC10*WC36 (13.68 µg./g) root which had the least root P content (Figure 13A).

Root P content varied significantly ($P < 0.001$) under varying $[P]_{ext}$ concentration (Figure 13B). An increasing trend in root P content was observed with increasing P concentration. Compare to 0 kg P/ha, root P content on soil amended with 10 kgP/ha was 49.71% greater in the major season (Figure 13B). Averagely, root P content on soil amended with 45 kgP/ha was 50.97 and greater compared to 0 kgP/ha in the minor season (Figure 13B).

An insignificant ($P = 0.839$) and ($P = 0.872$) interaction between genotype and $[P]_{ext}$ was observed for root P content in the major and minor season respectively (Figure 13C and 13D).

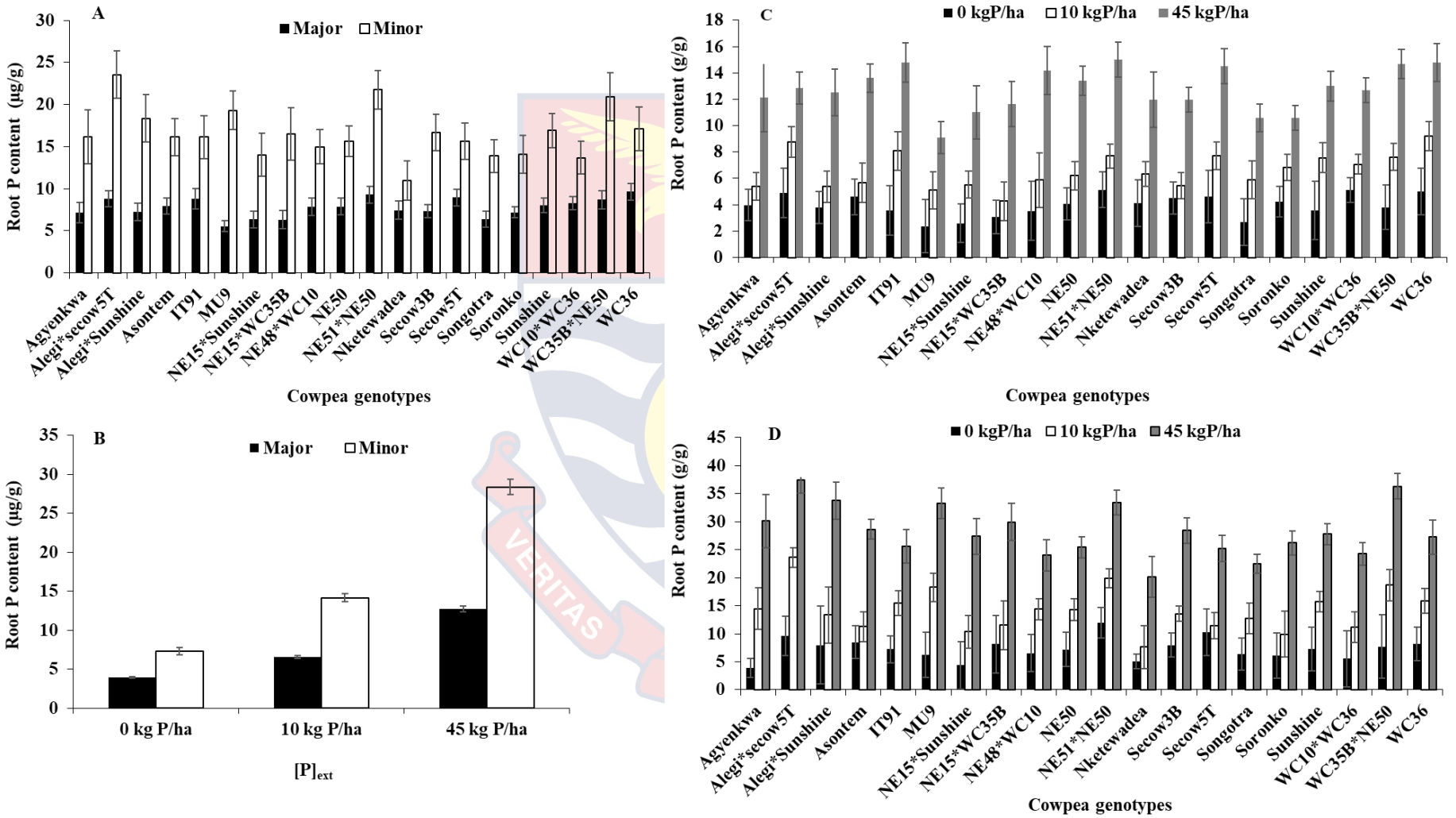

Figure 13 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on Root P content. Interaction of genotype and $[P]_{ext}$ on root P content in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Phosphorus uptake efficiency

There was significant genotypic effect in the major ($P = 0.003$) and minor season ($P = 0.009$) on phosphorus uptake efficiency (PUpE) (Figure 14A). Genotypes Secow3B (913 g DM g^{-1} P_f), IT91 (907 g DM g^{-1} P_f) and NE50 (879 g DM g^{-1} P_f) obtained significantly greater PUpE compared to Alegi*Secow5T which obtained the least value in the major season (Figure 14A). In the minor season, the topmost two (2) genotypes with high PUpE was Secow3B (978 g DM g^{-1} P_f) and NE50 (945 g DM g^{-1} P_f) (Figure 14A).

Phosphorus application had a significant ($P < 0.001$) effect on PUpE under varying $[P]_{ext}$ concentrations (Figure 14B). In both seasons, genotypes cultivated on soil amended with 10 kg P/ha recorded highest PUpE compared to 45 kg P/ha (Figure 14B). In the major season, 47% more PUpE was obtained at treatment 10 kg P/ha than 45 kg P/ha (Figure 14B). However, PUpE obtained by genotypes grown on soil amended with 10 kgP/ha was 67% greater compared to 45 kgP/ha in the minor season (Figure 14B).

An insignificant interaction of genotype and $[P]_{ext}$ was observed in the major season ($P = 0.593$) and minor season ($P = 0.693$) for PUpE (Figure 14C and 14D).

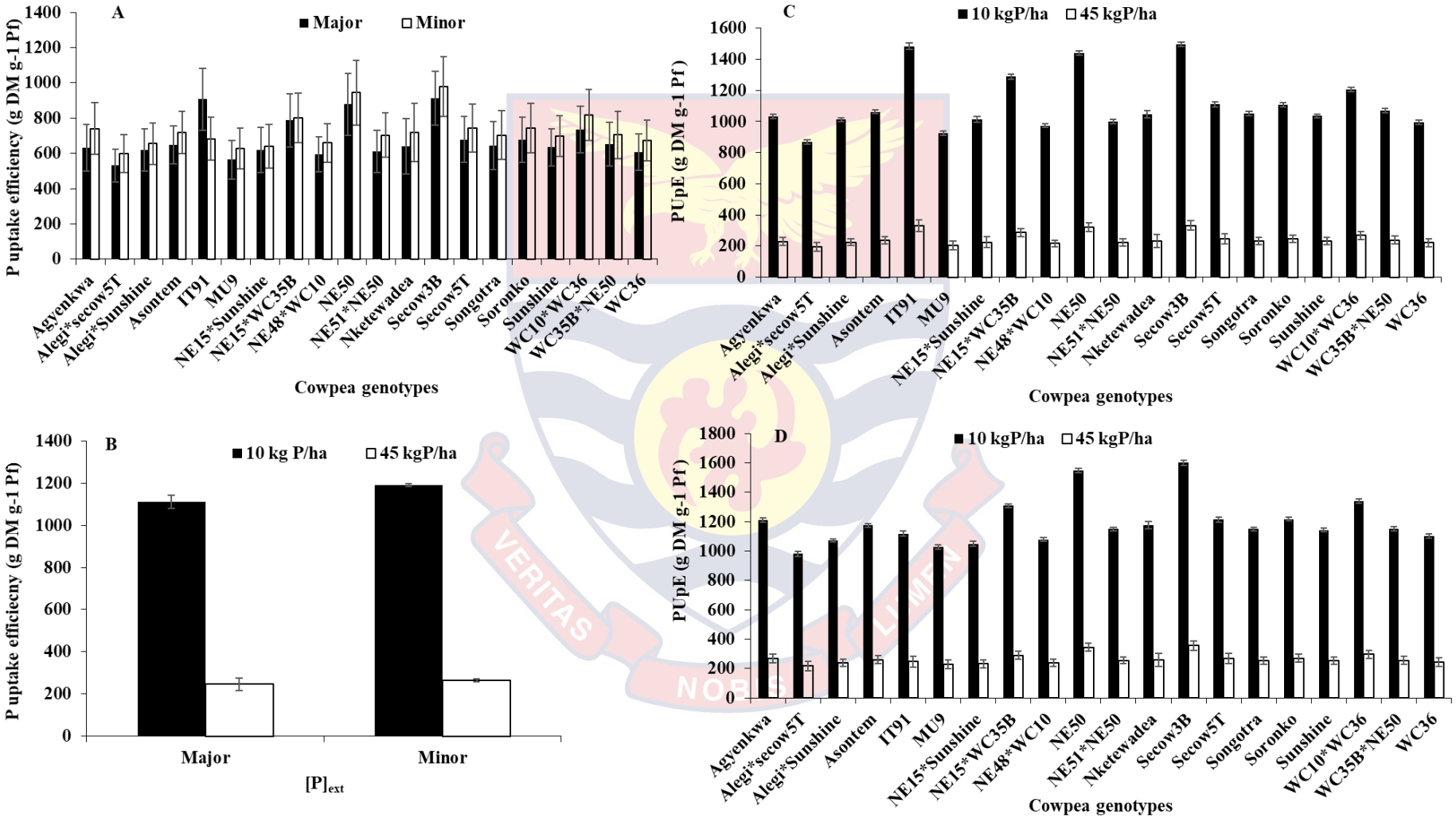

Figure 14 -Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on PUpE. Interaction of genotype and $[P]_{ext}$ on PUpE in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Agronomic phosphorus use efficiency

There was significant genotypic effect major ($P = 0.024$) and minor season ($P = 0.043$) on agronomic phosphorus use efficiency (APE) (Figure 15A). Genotypes Sunshine (5.63 g DM g^{-1} P_f), Alegi*Secow5T (4.94 g DM g^{-1} P_f) and Secow5T (4.49 g DM g^{-1} P_f) obtained significantly greater APE compared to IT91 which obtained the least value in the major season (Figure 15A). In the minor season, APE ranged from 0.44 - 4.90 g DM g^{-1} P_f of which the topmost two (2) genotypes with high APE was Sunshine and Songotra (Figure 15A)

Phosphorus application had a significant ($P < 0.001$) effect on APE under varying $[P]_{ext}$ concentrations (Figure 15B). In both seasons, plants cultivated at soil amended with 10 kg P/ha recorded highest PUpE compared to 45 kg P/ha (Figure 15B). In the major season, 84.60% more PUpE was obtained by genotypes planted at treatment 10 kg P/ha than 45 kg P/ha (Figure 15B). However, PUpE obtained at 10 kgP/ha was 81.80% greater compared to 45 kgP/ha in the minor season (Figure 15B).

An insignificant interaction of genotype and $[P]_{ext}$ was observed in the major season ($P = 0.683$) (Figure 15C) and minor season ($P = 0.692$) for APE (Figure 15D).

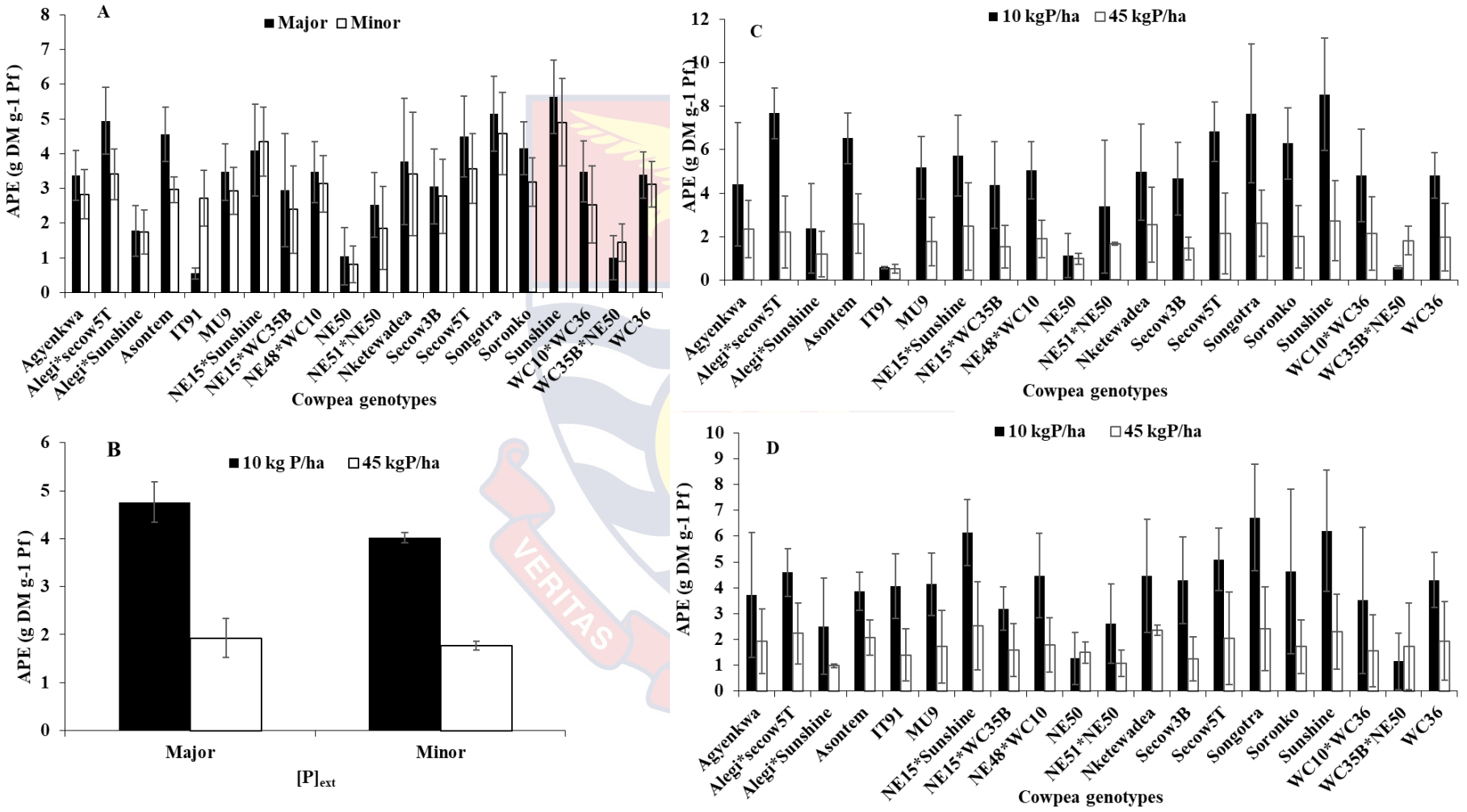

Figure 15 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on APE. Interaction of genotype and $[P]_{ext}$ on APE in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Phosphorus utilization efficiency

Cowpea genotypes significantly ($P < 0.001$) varied in phosphorus utilization efficiency (PUtE) in the major season (Figure 16A). Genotypes MU9 (0.26), NE15*WC35B (0.24), Alegi*Sunshine (2.00) and Sunshine (0.200) obtained the highest PUtE during the major season (Figure 16A). In the minor season, PUtE for genotypes ranged from 0.12 - 0.17 g DM g^{-1} P for genotype NE51*NE50 and Nketewadea respectively (Figure 16A).

Phosphorus utilization efficiency was significantly ($P < 0.001$) affected by $[P]_{ext}$ in the major and minor season (Figure 16B). In general, PUtE decreased with increasing P application. Averagely, phosphorus utilization efficiency by genotypes planted at 45 kgP/ha was 47.55% lower than PUtE obtained at 0 kgP/ha in the major season (Figure 16B). In the minor season PUtE of genotypes cultivated on unamended soil treatment was 23.22% greater compared to PUtE obtained at 10 kgP/ha (Figure 16B).

The interaction of genotypes with $[P]_{ext}$ was significant ($P < 0.001$) for PUtE in the major season and the minor season ($P = 0.017$) (Figure 16C and 16D). Generally, increased $[P]_{ext}$ concentration resulted in a significant decrease in PUtE among cowpea genotypes. Typical example is illustrated by genotypes Agyenkwa, Asontem, WC36 among other genotypes in the major season (Figure 16C). Similarly, in the minor season genotypes IT91, MU9, Alegi*Sunshine and Agyenkwa had high PUtE at 0 kg P/ha (Figure 16D)

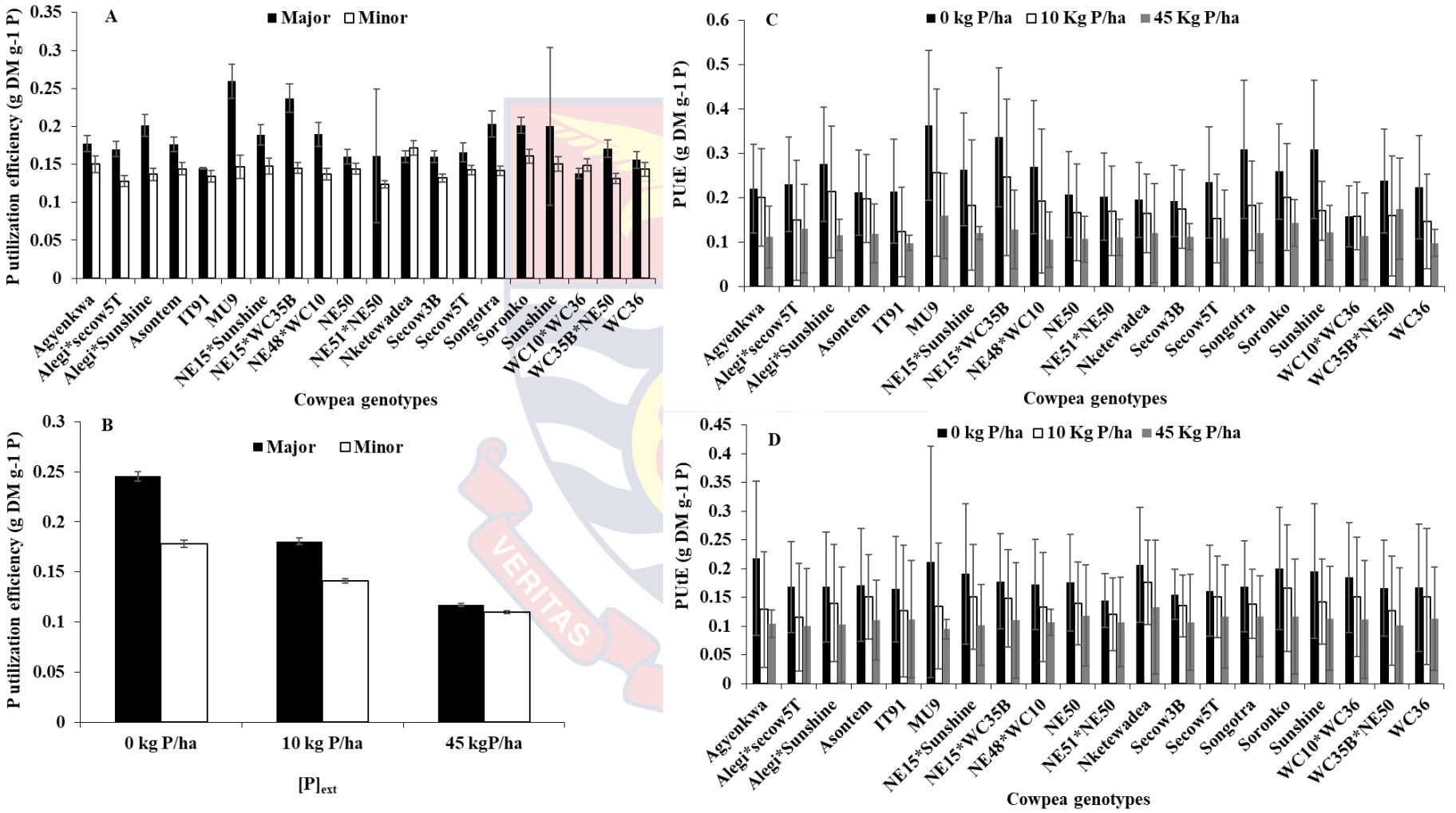

Figure 16 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on PUpE. Interaction of genotype and $[P]_{ext}$ on PUpE in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Phosphorus efficiency ratio

Genotypes differed significantly ($P < 0.001$) in phosphorus efficiency ratio (PER) during the major and minor season (Figure 17A). Genotypes Nketewadea (0.17 g DM g^{-1} P), Soronko (0.16 g DM g^{-1} P), Agyenkwa (0.15 g DM g^{-1} P) and Sunshine (0.15 g DM g^{-1} P) had highest values for PER in the major season which was significantly greater compared to NE51*NE50 (0.12 g DM g^{-1} P) which obtained the least PER (Figure 17A). Phosphorus efficiency ratio was high for Nketewadea, Soronko and Agyenkwa in the minor season (Figure 17A).

Phosphorus efficiency ratio in both seasons was significantly ($P < 0.001$) affected by $[P]_{ext}$ (Figure 17B). In the major season, a decreasing trend in PER was observed with increasing level of external P with, cowpea genotypes cultivated at 0 kg P/ha soil treatment recording the highest value of PER of 0.18 g DM g^{-1} P compared to 10 and 45 kg P/ha which had 0.14 and 0.11 g DM g^{-1} P respectively (Figure 17B). In the minor season, genotypes grown on soil amended with 0 kgP/ha obtained 23.22% PER compared to P amended soil treatments (Figure 17B).

Interaction of genotypes and $[P]_{ext}$ was significant in the major season ($P = 0.017$) (Figure 17C) and minor season ($P = 0.020$) for PER (Figure 17D). The observed trend was a decrease in PER among cowpea genotypes with increasing rates of P. Thus, majority of the genotypes recorded high PER at control treatment compared to P amended soil treatment. Typical example includes genotypes NE51*NE50, MU9, IT91 and Agyenkwa (Figure 17C and 17D).

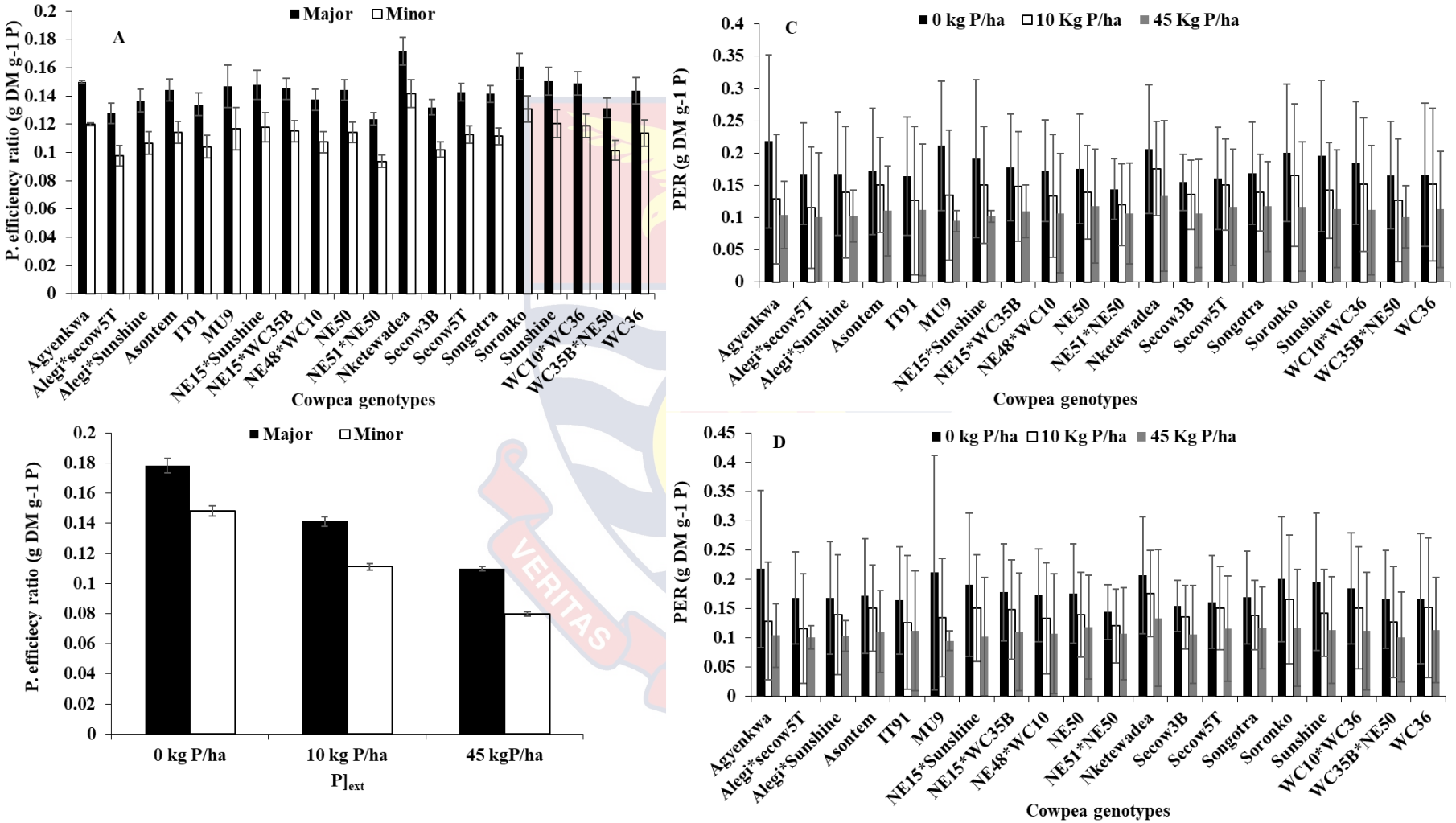

Figure 17 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on PER. Interaction of genotype and $[P]_{ext}$ on PER in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Physiological P use efficiency

Genotypes varied significantly ($P < 0.001$) in both growing seasons (Figure 18A). Genotype NE15*WC35B (37.46 g DM g^{-1} P) recorded the highest PPUE in the major season followed by MU9, Songotra, Soronko, Sunshine and Secow3B while WC (21.44 g DM g^{-1} P) had the least PPUE (Figure 18A). In the minor season, genotype Nketewadea (28.85 g DM g^{-1} P) obtained the highest value of PPUE which was significantly greater compared to Alegi*Sunshine (18.36 g DM g^{-1} P) which recorded the least PPUE (Figure 18A).

Phosphorus application significantly ($P < 0.001$) affected PPUE in the major season (Figure 18B) but had an insignificant ($P = 0.223$) in the minor season (Figure 18B). At 10 kgP/ha, 4.41% more PPUE compared to soil amended with 45 kgP/ha in the major season (Figure 18B). In the minor season, treatment 10 kg P/ha obtained the highest PPUE of 23.90 g DM g^{-1} P while 0 and 45 kg P/ha recorded 22.40 and 22.87 g DM g^{-1} P respectively (Figure 18B).

Interaction effect of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for PPUE in the major season (Figure 18C) but insignificant in the minor season ($P = 0.923$) (Figure 18D). Variation in response to P by genotypes existed in several folds. In the major season, genotypes Agyenkwa, Secow3B, Secow5T, Soronko, WC10*WC36, Asontem and MU9 obtained high PPUE at 10 kg P/ha compared to 0 and 45 kg P/ha treatment but genotypes IT91, Alegi*Sunshine, NE50, WC35B*NE50 and WC36 had high PPUE at 0 kg P/ha (Figure 18C). In the minor season, Agyenkwa, NE50 and MU9 obtained high PPUE at control treatment (Figure 18D) while high PPUE was recorded at 10 kg P/ha by genotypes WC36, WC10*WC36, Secow5T, Secow3B, Asontem and NE15*Sunshine (Figure 18D).

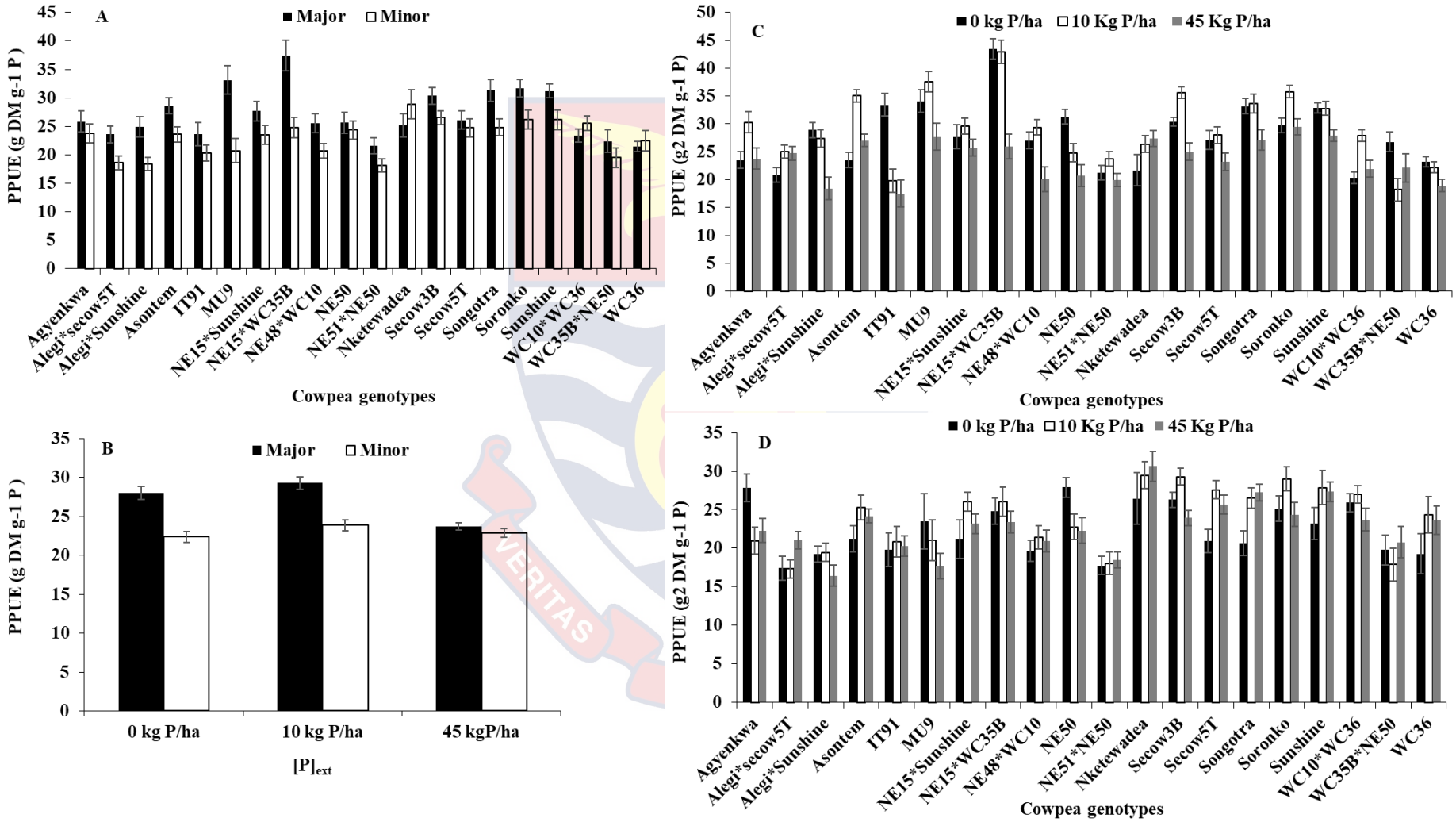

Figure 18 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on PPUE. Interaction of genotype and $[P]_{ext}$ on PPUE in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Relationship between yield and responsiveness to $[P]_{ext}$

Responsiveness of genotypes to $[P]_{ext}$ measured as phosphorus utilization efficiency (PUtE) and yield produced at low $[P]_{ext}$ (Figure 19A) revealed that, genotypes NE15*Sunshine, Songotra, Soronko, Asontem, Sunshine, Alegi*Secow5T, Nketewadea, MU9, WC 35B*NE 50 and Alegi*Sunshine were within the non-efficient but responsive (NER) group. However, two (2) genotypes including NE 15*WC 35B and Secow 5T were within the efficient and responsive (ER) quadrant (Figure 19A). The efficient but non-responsive (ENR) quadrant was made up of genotype WC 10*WC 36, NE50 and IT91. Genotype Secow 5T, NE48*WC10, WC36, NE 51*NE 50 and Agyenkwa were within the NENR group (Figure 19A).

Responsiveness of genotypes to $[P]_{ext}$ measured as APE and yield produced at low $[P]_{ext}$ (Figure 19B) revealed that, genotypes Secow 5T, Alegi*Secow 5T, Asontem, Sunshine, WC36, NE48*WC10, NE15*Sunshine, Soronko, Nketewadea and Songotra were grouped within the NER quadrant (Figure 19B). Genotypes NE50, IT91, Secow 3B and NE 15*WC 35B were within the ENR (Figure 19B). Genotypes Alegi*Sunshine, NE 51*NE 50, MU9 and WC 35B*NE 50 were within the non-responsive and non-efficient (NENR). However, genotype WC 10*WC 36 was within the efficient and responsive (ER) group (Figure 19B).

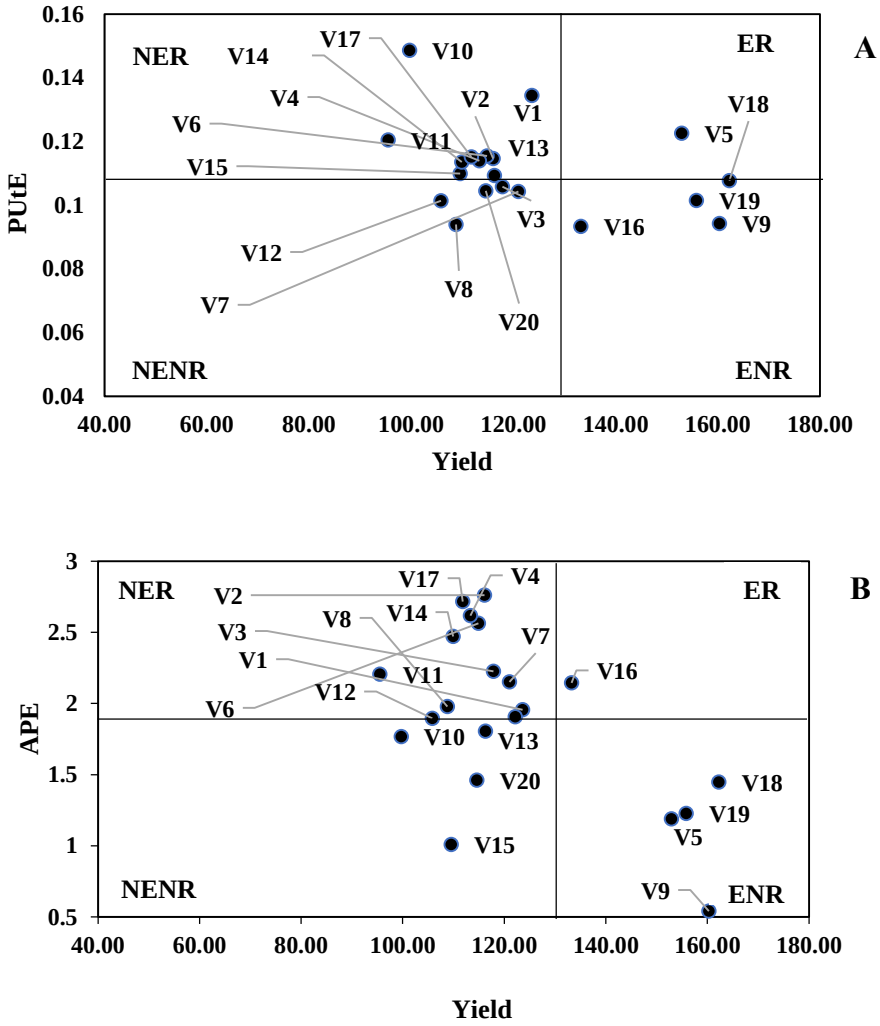

Figure 19 - Relationship between yield at low P and responsiveness to $[P]_{ext}$ measured as (**A**) P utilization efficiency (PUtE) and (B) Agronomic P use efficiency (APE).

Where, V1- *Soronko,* ***V2-*** *Asontem,* ***V3-*** *Agyenkwa,* ***V4-*** *Songotra,* ***V5-*** *NE 15*WC 35B,* ***V6-*** *Nketewadea,* ***V7-*** *Secow 5T,* ***V8-*** *WC 36,* ***V9-*** *IT91,* ***V10-*** *MU9,* ***V11-*** *Alegi*Secow 5T,* ***V12-*** *NE 48*WC 10,* ***V13-*** *WC 35B*NE 50,* ***V14-*** *NE 15*Sunshine,* ***V15-*** *Alegi*Sunshine,* ***V16-*** *WC 10*WC 36,* ***V17-*** *Sunshine,* ***V18-*** *Secow 3B,* ***V19-*** *NE 50* ***and V20-*** *NE 51*NE 50.*

NER*= Non efficient but responsive,* ***NENR****= Non efficient and non-responsive,* ***ER****= Efficient and responsive and* ***ENR****= Efficient and non-responsive.*

Effect of $[P]_{ext}$ on physiological seed quality among cowpea genotypes

Germination percentage

Genotype significantly ($P < 0.001$) influenced germination percentage (G%) during the major and minor season (Figure 20A). Germination percentage was high for genotypes Alegi*Sunshine, NE15*Sunshine, NE15*WC35B, IT91, WC10*WC36 and NE50 in the major season (Figure 20A). Genotypes Nketewadea, NE15*Sunshine, Songotra, Soronko, Agyenkwa, WC36 and NE50 recorded hundred percent germination in the minor season (Figure 20A).

Germination percentage (G%) in both seasons was significantly ($P < 0.001$) affected by G% (Figure 20B). In the major season, an increasing trend in G% was observed with increasing level of external P with 45 kg P/ha soil treatment recording the highest value of G% of 99.93% compared to 10 and 0 kg P/ha which had 99.77 and 98.70% respectively (Figure 20B). In the minor season, soil amended with 45 kgP/ha obtained 1.95% more G% compared to soil amended with 0 kg P/ha (Figure 20B).

Interaction of genotypes and $[P]_{ext}$ was significant in the major season ($P < 0.001$) (Figure 20C) and minor season ($P = 0.011$) for G% (Figure 20D). The observed trend was an increase in G% among cowpea genotypes with increasing rates of P. However, in the major season, genotype IT91, NE50 and NE15*Sunshine recorded 100% G% at various levels of P treatments. Genotypes WC10*WC36, WC35B*NE50 and Secow5T obtained high G% at 0 kg P/ha than 10 kg P/ha (Figure 20C). In the minor season, NE48*WC10 recorded high G% at 0 kg P/ha compared to P amended soils (Figure 20D).

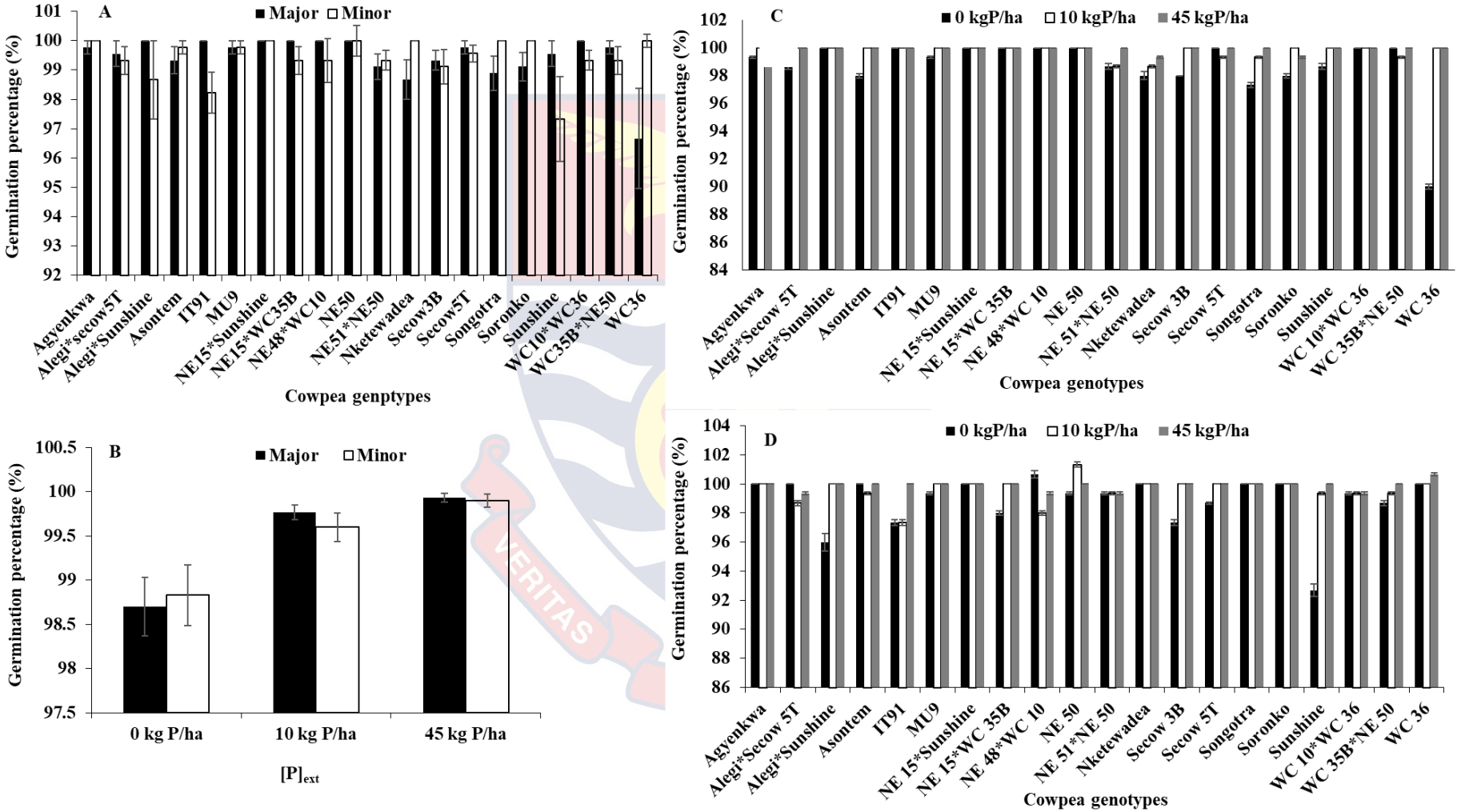

Figure 20 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on germination percentage. Interaction of genotype and $[P]_{ext}$ on germination percentage in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Coefficient of velocity of germination

Genotypes evaluated in the major and minor season showed a significant ($P < 0.001$) variation in coefficient of velocity of germination (Figure 21A). Genotypes MU9 (43.57%) topped the distribution with high coefficient of velocity of germination followed by NE15*WC35B (43.40%) and Agyenkwa (43.03%) (Figure 21A). Least value for coefficient of velocity of germination in the major season was recorded by WC36 (36.12%). In the minor season, genotypes MU9 was superior in coefficient of velocity of germination compared to Secow3B (39.98%), IT91 (38.51%) and WC36 (35.89%) which had the least values (Figure 21A).

Application of P significantly ($P < 0.001$) affected coefficient of velocity of germination in the major and minor season (Figure 21B). In all, an increasing trend in coefficient of velocity of germination with increasing P rates. In the major season, application of P resulted in 30% more velocity of germination more among genotypes cultivated at treatment 45 kg P/ha compared to the control treatment (Figure 21B). Similarly, in the minor season, P application increased coefficient of velocity of germination by 28.57% among plants grown on amended soil compared to control treatment (Figure 21B).

Interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for coefficient of velocity of germination in both seasons (Figure 21C and 21D). Genotypes screened both in the major and minor season increased coefficient of velocity of germination with increasing P levels. Typical example includes coefficient of velocity of germination of genotypes NE50, WC36, Sunshine and Secow3B (Figure 21C and 21D).

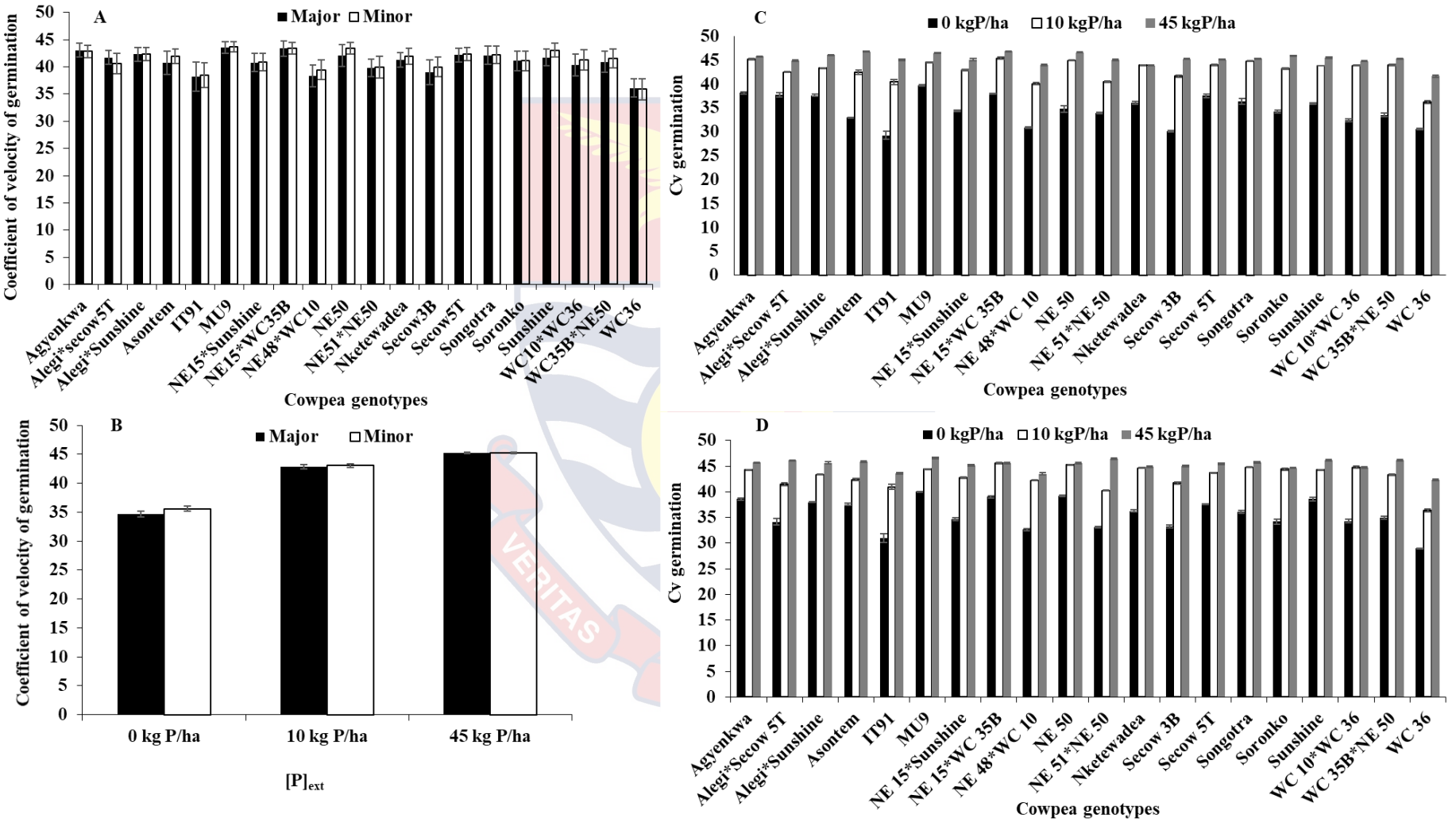

Figure 21 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on coefficient of velocity of germination. Interaction of genotype and $[P]_{ext}$ on coefficient of velocity of germination in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Germination index

Analysis of variance indicated a significant ($P < 0.001$) genotypic effect on GI in both seasons (Figure 22A). Germination index ranged from 19.23 - 22.99 in the major season of which genotypes NE15*WC35B, MU9, Agyenkwa, Alegi*Sunshine and NE50 made up the topmost five (5) genotypes with high GI (Figure 22A). In the minor season, genotype MU9 (22.99) recorded the highest GI followed by Agyenkwa (22.79) and NE15*WC35B (22.78) (Figure 22A).

Germination index in both seasons was significantly ($P < 0.001$) influenced by $[P]_{ext}$ concentration (Figure 22B). A direct relationship was observed between GI and concentration of P. In the major season, application of P resulted in 17.3% more GI at 45 kg P/ha compared to treatment 0 kg P/ha (Figure 22B). Similarly, int the minor season, compared to 0 kg P/ha, 3.66% more GI was observed at treatment 10 kg P/ha (Figure 22B).

Interaction of genotype and $[P]_{ext}$ was significant ($P < 0.001$) for GI in both seasons (Figure 22C and 22D). In general, genotypes increased GI with increasing P levels. In the major season, genotypes Agyenkwa, WC36, IT91 and MU9 had high GI at soil amended with 45 kg P/ha (Figure 22C). Similarly, in the minor season, genotypes Asontem, Sunshine, Songotra and NE15*Sunshine obtained high GI when cultivated at 45 kg P/ha (Figure 22D).

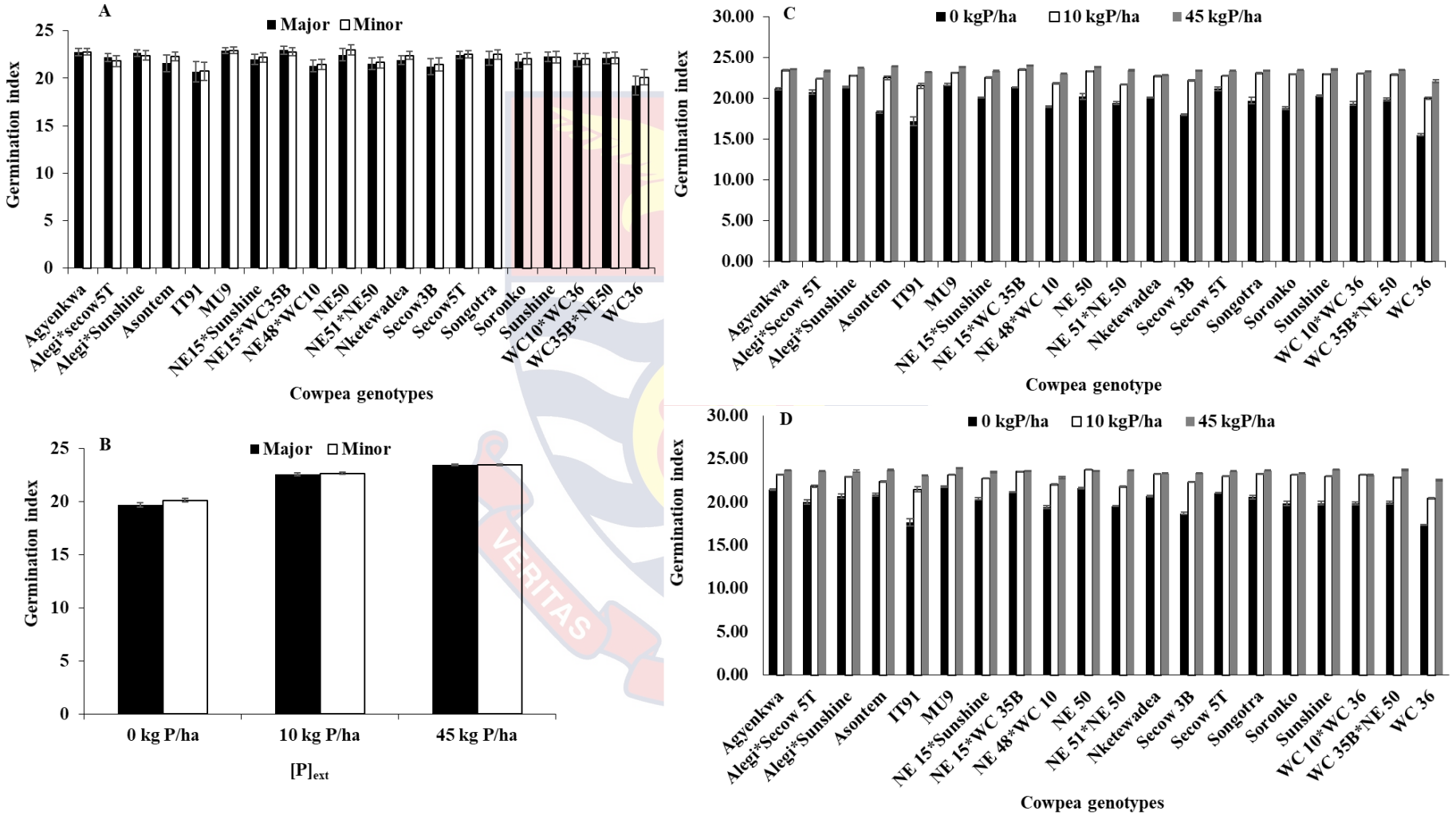

Figure 22 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on germination index. Interaction of genotype and $[P]_{ext}$ on germination index in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Germination rate

Genotype varied significantly ($P < 0.001$) in GR for the major and minor season (Figure 23A). Germination rate ranged from 0.36 – 0.43 and 0.36 - 0.44 for the major and minor season respectively (Figure 23A). Genotype MU9 (0.43) had the highest GR in the major season with IT91 (0.38) and WC36 (0.36) recording the least GR (Figure 23A). Genotypes MU9, NE50 and Sunshine were the top three (3) genotypes with high GR in the minor season (Figure 23A).

The application of P had significant ($P < 0.001$) influence on GR in the major as well as the minor season (Figure 23B). It was observed that, GR of cowpea genotypes increased with increasing $[P]_{ext}$ application such that 26.39% increase in GR was obtained at P amended soils compared GR obtained at 0 kgP/ha in the major season (Figure 23B). Value of GR obtained at 45 kg P/ha was 5.37% greater compared to 10 kg P/ha soil treatments in the minor season (Figure 23B).

Interaction of genotype and $[P]_{ext}$ was significant for GR in the major ($P < 0.001$) (Figure 23C) and minor seasons ($P = 0.002$) (Figure 23D). Majority of the genotypes increased GR with increasing P. Typical example includes genotypes MU9, NE50, WC36 and Soronko which obtained high GR at 45 kg P/ha in the major season (Figure 23C). In the minor season, genotypes Alegi*Sunshine, Secow3B and MU9 recorded significantly high GR at 45 kg P/ha compared to the remaining treatments (Figure 23D).

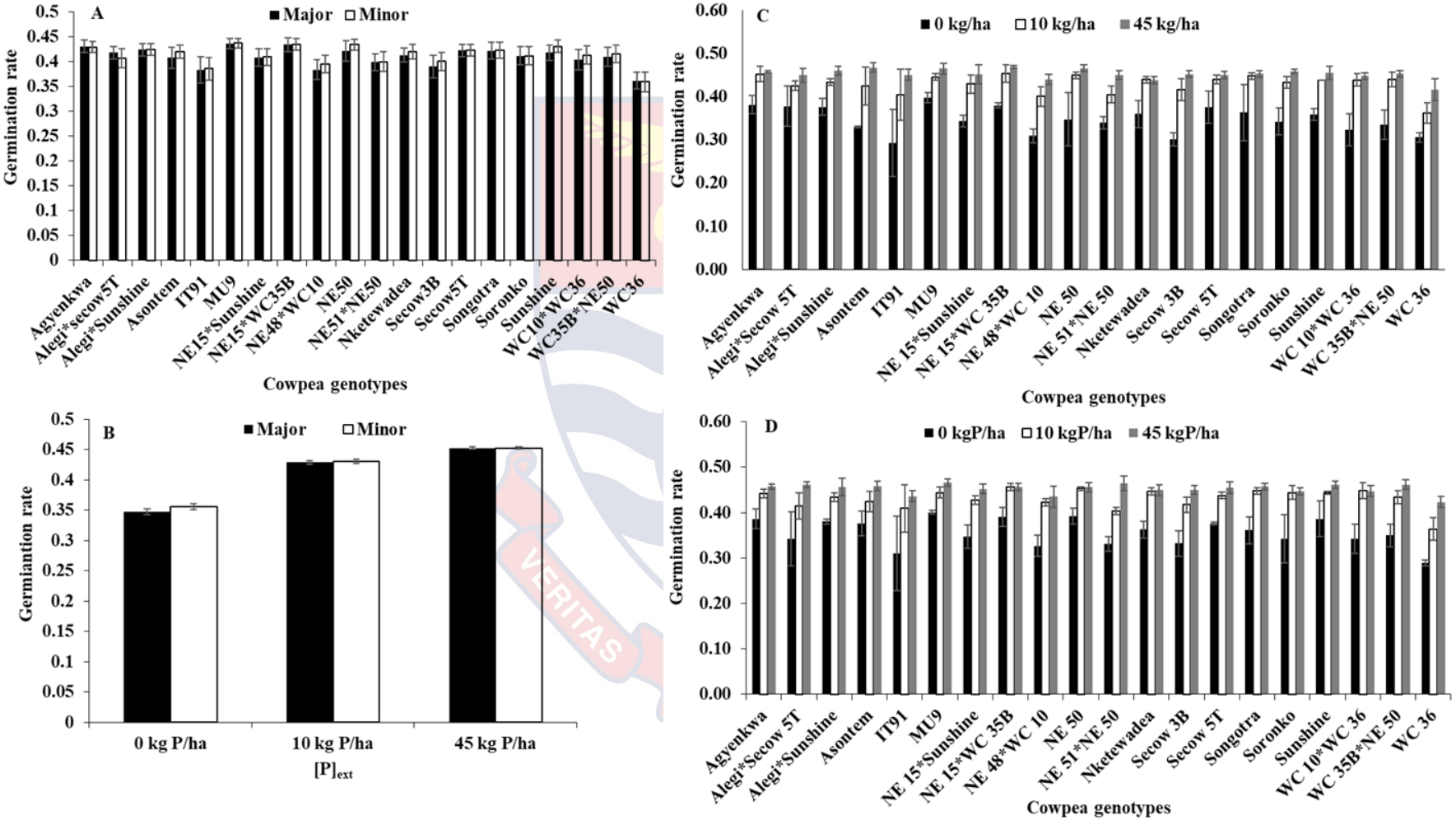

Figure 23 - Effect of; **(A)** Genotype and **(B)** $[P]_{ext}$ on germination rate. Interaction of genotype and $[P]_{ext}$ on germination rate in; **(C)** Major season and **(D)** Minor season. Error bars representing the s.e.m.

Principal component analysis

Varimax with Kaiser Normalization principal component analysis (PCA) was carried out independently for the major and minor season as well as a combined season. A Kaiser-Meyer-Olkin measure of sampling adequacy of 0.749 and 0.721 was obtained for measured traits in the major and minor season. In all, eleven (11) distinct principal components were obtained in the major season based on components with Eigen values > 1 and factor loadings of ±0.3 which explained 73 % of the total variance in the major season (Appendix 1). However, twelve (12) distinct principal components were obtained in the minor season and explained 77 % of the total variance (Appendix 2).

A Kaiser-Meyer-Olkin measure of sampling adequacy of 0.934 was obtained in the combined season data for measured traits. In all, twelve (12) distinct principal components were obtained in the combined seasons based on components with Eigen values > 1 and factor loadings of ±0.3 which explained 76 % of the total variance (Table 12).

The first principal (PC 1) component contributed to 16% of the total variation observed. This was mainly explained by shoot P concentration, root P concentration, root P content, root dry weight, P utilization efficiency, P efficiency ratio and P uptake efficiency (Table 12). The second principal component was defined by coefficient of velocity of germination, germination rate and germination index. The second principal component contributed 12 % of observed variation (Table 12). Principal component three (3) accounted for 8% of the total variation observed among measured traits. The variation was explained by pod length, 100-seed weight, and number of seeds per pod (Table 12). Number of pods per plant and number of pods per peduncle accounted for

6% of variation explained by the fourth principal component (PC 4). The fifth principal component (PC 5) explained 6% of the observed variation among measured traits and was contributed by days to flowering and days to 50% flowering (Table 12). The sixth principal component contributed to 5% of variation among measured parameters. Hypocotyl root length, hypocotyl root diameter, hypocotyl root number and hypocotyl root growth angle resolved on the sixth principal component (Table 12). The seventh principal component (PC 7) contributed to 4% of total variance observed among measured traits. This was explained by yield, physiological P use efficiency and agronomic P use efficiency (Table 12). The eighth principal component (PC 8) contributed 4% of total variance observed among measured traits. This was explained by shoot dry weight and shoot P content (Table 12). The nineth principal component (PC 9) was explained by nodule diameter and nodule number which constituted 4% of total observed variance. The eleventh (PC 11) and twelfth component (PC 12) explained 3% of observed variation among measured traits. The eleventh component was explained by basal root growth angle, number of branches and basal root number whilst basal root length and third order branching density resolved on the twelfth principal component (Table 12).

Table 12 - Estimates of variance components of field grown cowpea genotypes under varying $[P]_{ext}$

	Components-												
Measurements	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**	**PC 9**	**PC 10**	**PC 11**	**PC 12**	**Communalities**
Shoot P concentration	**.879**	.172	.111	-.024	.112	.044	-.113	-.008	.029	.143	.067	.024	.868
Root P concentration	**.879**	.172	.111	-.024	.112	.044	-.113	-.008	.029	.143	.067	.024	.868
P utilization efficiency	**-.822**	-.039	.036	-.115	.153	.000	.196	-.158	.056	.082	-.096	-.026	.798
P efficiency ratio	**-.818**	-.109	.189	-.044	-.084	-.009	.166	-.027	.058	-.050	-.172	.015	.790
Root P content	**.816**	.015	-.168	-.134	-.035	-.105	.054	.176	.098	-.077	-.282	-.006	.853
P uptake efficiency	**-.618**	-.363	-.198	-.159	.014	-.102	-.162	.003	-.019	-.118	-.057	-.174	.662
Root dry weight	**.516**	.030	-.242	-.038	-.073	-.104	.208	.162	.165	-.023	-.375	.094	.590
Mean germination rate	.168	**.972**	.062	.026	.090	-.041	.014	.023	.012	-.030	.007	.002	.989
Coefficient of velocity of germination	.168	**.972**	.062	.026	.090	-.041	.014	.023	.012	-.030	.007	.002	.989
Germination index	.170	**.959**	.038	.061	.125	-.038	.043	.028	.025	.029	-.011	-.040	.976
Pod length	.036	.067	**.881**	.132	-.055	.036	.061	-.083	-.081	.050	.041	.034	.826
100-seed weight	-.125	.034	**.740**	.294	.180	.085	.028	-.086	.039	.138	-.095	-.030	.729
Number of seed per pod	-.002	.094	**.734**	-.105	-.060	-.028	.271	-.020	-.153	-.034	.233	.020	.716
Number of pods per plant	.011	.063	.153	**.886**	-.066	.036	.039	-.111	-.033	-.028	.212	.063	.883
Number of pods per peduncle	-.009	.023	.090	**.870**	-.059	.060	.050	-.054	-.014	-.020	-.084	.029	.788
Days to 50% flowering	.039	.201	.019	-.058	**.935**	-.049	-.027	-.004	-.009	-.038	.034	.049	.928
Days to flowering	.025	.085	.014	-.057	**.930**	-.035	-.081	.014	-.015	-.077	.017	.020	.891
Hypocotyl root length	.021	.042	-.096	-.159	-.029	**.792**	.005	.085	.104	.029	-.148	.028	.706
Hypocotyl root diameter	.084	-.039	.036	.076	-.217	**.741**	.091	.025	-.029	.118	.034	.157	.661
Hypocotyl root growth angle	-.045	-.150	.081	.157	.161	**.734**	.010	-.079	-.103	.059	.160	-.116	.680
Hypocotyl root number	-.091	.041	.425	.195	-.009	**.539**	-.152	-.203	-.057	.157	-.073	-.013	.617
Physiological P use efficiency	-.461	.112	.148	.043	-.034	.020	**.770**	-.080	-.016	.097	-.041	-.079	.866
Yield	.220	.198	.156	.215	-.209	.018	**.755**	.058	-.070	.060	.044	-.076	.792
Agronomic P use efficiency	-.239	-.125	.037	-.071	.058	.018	**.725**	-.053	.050	-.070	-.005	-.016	.618
Shoot P content	.217	.051	-.012	-.031	.000	.019	-.059	**.936**	.083	-.021	.059	.031	.942
Shoot dry weight	.052	.019	-.187	-.157	.016	-.046	-.008	**.926**	.147	-.045	-.005	-.013	.946
Nodule number	-.040	-.011	-.002	.014	-.042	-.013	-.019	.043	**.875**	-.001	.124	.048	.789
Nodule Diameter	.083	.065	-.170	-.079	.057	.008	-.001	.208	**.735**	.045	-.181	.088	.676
Taproot diameter	.022	-.079	.123	.029	-.067	.111	-.008	-.036	-.137	**.787**	-.030	.020	.680
Stem diameter	.105	.078	.042	-.118	-.120	.144	-.007	-.052	.121	**.719**	-.065	.250	.669
Germination percentage	.214	-.008	-.088	.273	.294	-.012	.169	.061	.143	**.433**	-.048	-.239	.514
Basal root growth angle	.024	-.015	.045	.063	.038	-.003	.012	.079	.008	-.053	**.636**	.077	.429
Number of branches	.106	.091	.093	.522	.015	.037	-.025	-.065	-.129	.100	**.540**	.096	.634
Basal root number	-.120	.003	.065	.093	.068	.101	-.053	.023	-.441	.222	**-.517**	.205	.599
Basal root length	.078	-.032	.209	.001	-.005	-.021	-.069	.032	.083	.025	-.042	**.807**	.718
Third order branching density	.067	.011	-.287	.144	.085	.096	-.042	-.012	.007	.168	.138	**.696**	.658
Eigen values	5.799	4.334	2.988	2.302	2.117	1.828	1.597	1.495	1.468	1.282	1.124	1.003	
% of Variance	16.108	12.038	8.300	6.396	5.882	5.079	4.437	4.152	4.077	3.561	3.121	2.787	
Cumulative %	16.108	28.146	36.446	42.842	48.724	53.802	58.239	62.391	66.468	70.029	73.151	75.937	

Variance component and broad sense heritability (H^2)

Variation observed among measured traits during the study was due to effects of genotype, $[P]_{ext}$ and the interaction between genotypes and $[P]_{ext}$ (Table 13). Genotypic effect ranged from 0.02% for shoot P content to 72% for HRA. Genotype effect accounted for more than 50% variation in hypocotyl root growth angle (5 and 10 arc), germination percentage and basal root number (Table 13). Genotype effect contributed to less than 50% variation in agronomic P efficiency (44%), P uptake efficiency (24%), P efficiency ratio (7%), physiological P efficiency (8%) and hypocotyl root diameter (31%) (Table 13). Genotypic effect accounted for less than 1% variation in taproot diameter, basal root growth angle, days to flowering, number of pods per peduncle, number of seeds per pod and shoot P content (Table 13).

Phosphorus application accounted greater than 50% variation in P uptake efficiency (53%), shoot P concentration (51%), coefficient of velocity of germination (79.59%), germination index (71%), number of peduncles per plant (55%) and mean germination rate (79%) (Table 13). Phosphorus application accounted for less than 20% P uptake efficiency, P efficiency ratio, physiological P use efficiency, shoot P content, basal root diameter, basal root length, nodule diameter, hypocotyl root length, hypocotyl root growth angle, shoot dry weight and root dry weight (Table 13).

The interaction effect of genotype and $[P]_{ext}$ ranged from 0.00% for agronomic P efficiency to 20.37% for germination percentage (Table 13). Interaction of genotype and phosphorus accounted for 19.36% variation in root fresh weight, 14% in P uptake efficiency, 17.78% in P efficiency ratio, 16.91% in hypocotyl root number and 10.91% in hypocotyl root angle. However,

interaction between genotype and $[P]_{EXT}$ contributed to less than 10% variation in the remaining measured parameters during the study (Table 13).

Broad-sense heritability ranged from 0.00 for shoot phosphorus content to 1.00 for germination percentage (Table 13). Except for agronomic P use efficiency (0.08), P uptake efficiency (0.09), P utilization efficiency (0.39), physiological P use efficiency (0.38), root P content (0.19), shoot P content (0.00), coefficient of velocity of germination (0.36), germination index (0.25), mean germination rate (0.36), basal root angle (0.21), basal root number (0.31), basal root length (0.18), hypocotyl root angle (0.46), taproot diameter (0.00), third order branching (10cm) (0.11), nodule diameter (0.13), nodule number (0.24) and hypocotyl root length (0.26), days to 50% flowering (0.35), number of branches (0.21), number of pods per peduncle (0.17), number of peduncles per plant (0.25), 100 seed weight (0.29) and yield (0.29), the remaining traits obtained broad-sense heritability larger than 0.50 (Table 13).

Table 13 - Estimates of broad-sense heritability (H^2) of field grown cowpea genotypes under varying $[P]_{ext}$

Traits	Genotype	Phosphorus	Trial	Genotype × Trial	Genotype × phosphorus	Phosphorus × Trial	Genotype ×Phosphorus × Trial	Error	H^2
APE	43.87	27.61	0.17	24.63	0.66	0.17	0.00	2.90	0.08
PUpE	23.89	11.38	7.71	20.25	14.00	6.98	1.46	14.33	0.09
PUtE	7.01	53.43	3.36	3.07	8.77	12.46	4.23	7.66	0.39
PER	7.50	3.62	17.78	0.00	17.78	17.78	17.78	17.76	0.91
PPUE	6.99	0.91	0.00	2.31	5.29	4.46	0.00	80.04	0.38
Root P conc	1.16	42.01	45.03	0.00	7.14	4.10	0.00	0.56	0.98
Shoot P conc	27.50	51.30	1.95	0.43	7.30	9.12	1.59	0.82	0.82
Root P cont	29.59	26.20	8.14	8.22	2.70	10.16	0.00	14.98	0.19
Shoot P cont	0.02	1.13	83.22	0.14	0.00	0.21	0.00	15.30	0.00
%CV germ.	12.08	78.59	0.09	3.50	0.00	0.19	0.00	5.54	0.36
Germination index	10.26	71.28	0.15	6.06	0.18	0.39	0.00	11.67	0.25
Germination percentage	95.50	0.02	4.42	0.00	0.00	0.00	0.03	0.04	1.00
Mean germination rate	8.36	78.57	0.09	3.50	0.00	0.19	0.00	9.29	0.36
BRA	0.61	0.26	52.88	2.06	0.00	0.26	3.11	40.82	0.21
BRD	1.03	3.21	2.02	0.00	9.27	3.21	62.90	5.11	0.83
BRL	35.45	18.04	0.81	9.27	1.61	0.00	15.62	19.20	0.18
BRN	50.48	0.00	0.00	4.43	3.65	1.79	10.15	29.50	0.31
HRA	70.46	0.00	0.00	2.31	10.91	0.26	4.30	11.75	0.46
HRD	30.61	29.85	3.34	0.52	3.61	0.00	5.41	26.65	0.77
HRL	21.44	6.35	4.48	5.45	5.22	1.36	11.04	44.67	0.26
ND	0.57	8.25	4.07	1.55	3.06	0.01	3.49	79.01	0.13
NN	28.29	40.64	2.77	6.24	1.97	2.66	1.89	15.54	0.24
3rd BD	18.10	29.01	12.64	15.37	2.17	1.89	7.74	13.08	0.11
TBD	5.40	0.00	20.28	0.73	2.48	0.00	8.60	62.50	0.54
TD	0.00	0.00	1.65	3.11	1.12	1.41	20.06	72.65	0.00
HRN	26.23	21.71	4.67	0.80	16.91	4.27	10.82	14.59	0.70
SG	26.79	25.87	0.00	1.01	9.25	13.60	6.97	16.52	0.65
RDW	43.61	4.33	0.11	0.39	3.52	0.00	0.00	0.41	0.71
SDW	42.44	10.79	15273	2.05	7.07	10.20	0.50	33.04	0.45
DTF	0.67	4.89	0.00	0.00	0.00	0.00	100.00	0.00	0.96
DT50%	3.63	3.63	0.00	3.63	78.25	3.63	3.63	3.63	0.35
NB	34.24	28.75	0.00	7.71	0.00	14.81	0.00	14.49	0.21
NPP	0.39	39.93	0.64	0.00	3.20	7.66	1.54	46.64	0.17
NPPP	0.35	54.88	2.14	1.79	1.69	21.90	0.00	17.25	0.25
NSP	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.98
PL	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.96
SW	33.43	27.08	0.00	4.84	0.00	10.33	0.00	24.32	0.29
YLD	27.39	46.35	0.41	4.75	0.03	0.15	0.00	20.93	0.29

Traits in matrix are SDW: shoot dry weight, RDW: root dry weight, HRL: hypocotyl root length, HRN: Hypocotyl root number HRD: hypocotyl root diameter, HRGA: hypocotyl root growth angle, BRL: basal root length, BRN: basal root number, BRD: basal root diameter, BRGA: basal root growth angle, 3rd BD: 3rd order branching density, TRD: taproot diameter, NN: number of nodules ND; nodule diameter, SD: stem diameter, SP conc: shoot P concentration, RP conc: root P concentration, SP cont: shoot P content, RP cont: root P content, PPUE: physiological P use efficiency, PER: P efficiency ratio, PUtE: P utilization efficiency, APE: agronomic P use efficiency, PUpE: P uptake efficiency and %CV germ: coefficient of velocity of germination, YLD: yield, DTF: days to flowering, DT50%: days to 50% flowering, NB: number of branches: NPP: number of pods per peduncle, NPPP: number of pods per plant, NSP: number of seeds per plant, PL: pod length, SW: 100 seeds weight and YLD: yield per plot.

Cluster analysis

Cluster analysis for measured traits exhibited a clear grouping of the cowpea genotypes. Based on these traits, the dendrogram divided the genotypes into three main clusters (Figure 24). Cluster I included the genotypes NE 51*NE 50, Secow 5T, Sunshine, Asontem, NE 15*WC 35B, NE 48*WC 10 and WC 35B*NE 50 (Figure 24). Cluster II was made up of genotypes WC 10*WC 36, WC36, IT91, Secow 3B and Nketewadea. Cluster III included genotypes MU9, Alegi*Secow 5T, Agyenkwa, NE 15*Sunshine, Alegi*Sunshine, NE50, Songotra and Soronko (Figure 24).

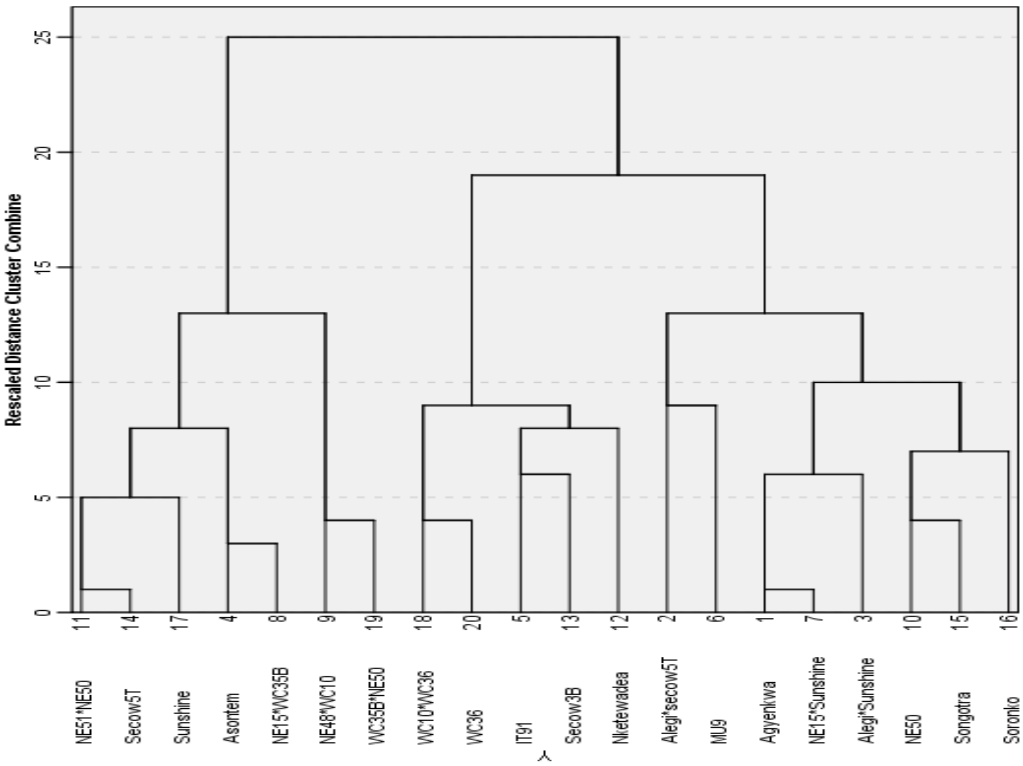

Figure 24 - Clustering of twenty (20) cowpea genotypes grown under field condition. Clustering was performed using the Ward's hierarchical approach based on the minimum variance linking method with Euclidean distance as the similarity measure.

Correlation between measured RSA, biomass, seed physiological quality, yield and P uptake parameters

Correlational analysis between measured plant traits (biomass, RSA, P concentration, content, nodulation, and P efficiency) is presented in Table 14. Stem diameter had a positive significant correlation with HRN ($r = .263$, $P < 0.01$), HRL ($r = .203$, $P < 0.01$), TRD ($r = .426$, $P < 0.01$), BRL ($r = .168$, $P < 0.01$) but had a negative insignificant correlation with BRGA ($r = -.029$, $P = .525$). Hypocotyl root length had a significant correlation with HRD ($r = .530$, $P < 0.01$), HRGA ($r = .416$, $P < 0.01$) but had an insignificant negative correlation with BRGA ($r = -.024$, $P = 595$). Basal root length negatively correlated with BRGA ($r = -.0.26$, $P = .566$) but positively related with BRD ($r = .404$, $P < 0.01$) (Table 14).

Nodule number had an insignificant negative correlation with RSA parameters such as HRN ($r = -.088$, $P = 0.055$), HRL ($r = -.001$, $P = 0.981$) and HRD ($r = -.042$, $P = .353$). Similarly, nodule diameter had an insignificant correlation with HRL ($r = .055$, $P = .231$) and BRL ($r = .008$, $P = .853$) (Table 14).

A significant positive correlation existed between yield and PL ($r = .420$, $P < 0.01$), NSP ($r = .570$, $P < 0.01$) and NPPP ($r = .489$, $P < 0.01$) whilst yield had a negative significant correlation with DTF ($r = -.172$, $P < 0.01$) and DT50% ($r = -.116$, $P < 0.05$) (Table 14). Yield positively correlated with HRD ($r = .220$, $P < 0.01$) and HRGA ($r = .121$, $P < 0.01$) but had a negatively insignificant relationship with BRL ($r = -.035$, $P = .0448$) and BRD ($r = -.061$, $P = .185$). Number of pods per plant recorded a high significant positive correlation with NB ($r = .616$, $P < 0.01$) and NPP ($r = .811$, $P < 0.01$). Days to

flowering had a strong significant correlation ($r = .913, P < 0.01$) with DT50% (Table 14).

Shoot P concentration significantly correlated with SD ($r = .246, P < 0.01$), HRL ($r = .103, P < 0.05$), *RDW* ($r = .409, P < 0.01$), PL ($r = .366, P < 0.01$), NB ($r = .326, P < 0.01$) and NPPP ($r = .402, P < 0.01$). However, Shoot P concentration had a weak insignificant correlation with HRN ($r = .076, P = .097$), ND ($r = .036, P = .428$), NN ($r = .070, P = .128$) and SDW ($r = .077, P = .093$) (Table 14). Root P concentration had significant positive relationship with SD ($r = .253, P < 0.01$), TRD ($r = .184, P < 0.01$), NPP ($r = .320, P < 0.01$) and RDW ($r = .410, P < 0.01$) but strongly correlated with shoot P concentration ($r = .992, P < 0.01$) (Table 14).

Seed physiological quality parameters exhibited a highly positive relationship with tissue P concentration (Table 14). Germination percentage had a positive relation with shoot P concentration ($r = .268, P < 0.01$) and root P concentration ($r = .255, P < 0.01$). Germination rate significantly correlated highly with shoot P concentration ($r = .661, P < 0.01$) and root P concentration ($r = .660, P < 0.01$). Similarly, both germination index and coefficient of velocity of germination had a strong positive correlation with tissue P concentrations (Table 14).

CHAPTER FIVE

DISCUSSION

Effect of $[P]_{ext}$ on root system architecture (RSA) traits among cowpea genotypes.

Root system parameters

Genotypic variation existed among cowpea genotypes for hypocotyl root length with some genotypes developing longer and others shorter root length. Such variation is mostly associated with variation in genetic buildup among genotypes as well as variation in adaptive mechanism in different environmental condition among cowpea genotypes. Efficient genotypes increased length of root as an adaptive mechanism among legumes to ensure greater exploration of the soil for the uptake of unevenly distributed soil resources. However, certain genotypes rather develop shorter and denser roots under resource poor environment. Phosphorus application influenced hypocotyl root length among cowpea genotypes due to the plastic nature of plant roots (Sultan, 2000) and genetic control (Sandhu *et al.,* 2016). Longer hypocotyl root observed under high P levels is due to the immobile nature of P which tends to become fixed on soil surface hence, plants develop longer and denser roots to form top foraging to ensure uptake of nutrients. The results of the present study corroborate with the study by Linkohr *et al*. (2002), Reymond *et al*. (2006) and Williamson *et al*. (2001) who observed in *Col-0* accession of *Arabidopsis* that low phosphorus reduces the primary root length. The result of the present study contradicts the findings of Fernández *et al*. (2009) who noted in a study on soybean an increase in the specific root length with a decline in P supply. Such

contradiction could be due to variation in genetic make of genotypes used for the study.

It is well known that root growth and characteristics play a key role in plant adaptation to low P stress. Wide genotypic variation observed among genotypes for basal root length is due to variation in response to environmental conditions among genotypes. Additionally, variation in adaptive mechanism among cowpea genotypes accounted for longer basal roots among certain genotypes used for the study. However, certain genotypes trade off longer root systems for shorter roots under poor environmental conditions. Longer and well dispersed root length are significantly important to optimize the capture of mobile and immobile resources as they reduce inter- and intra-plant competition for nutrients. This observation is consistent with Zhu *et al*. (2005) that, P deficiency in the top soil of P-efficient corn cultivars enhanced the total root length and specific root length. In a research with soybean, Fernández *et al*. (2009) noted an increase in the specific root length with a decline in P supply. Additional, a study in maize reported that, some genotypes respond to low P by increasing the number and length of lateral roots, while others have the opposite effect (Bayuelo-Jiménez *et al*., 2013).

This study indicated that, hypocotyl root diameter and number differed among cowpea genotypes. In most of the genotypes, diameter of hypocotyl root increased with increasing phosphorus application since P plays a significant role in the growth and development of roots especially at the early growth stage of plants (Haruna & Aliyu, 2011). Responsiveness of hypocotyl root diameter and number to P application among certain genotypes could not be accounted for by genotypic variation and prevailing soil conditions. Greater root diameter

observed in the minor season could be explained by the slow-release nature of P since the same plot used in the major season was repeated in the minor season with subsequent application of P. Cowpea genotypes differ genetically for root system traits related to growth in marginal soils and dry environments (Krasilnikoff *et al*., 2002, Matsui and Singh, 2003; Singh *et al*., 2002).

Variation in basal root diameter among cowpea genotypes is attributed to genotypic composition of genotypes and availability of phosphate, which is highly immobile in soil such that the arrangement of roots within the soil will profoundly affect the ability of the plant to acquire this essential nutrient. Consistent with this, the concentration of phosphate was found to have a marked effect on the root system architecture traits. Additionally, phosphorus plays a vital role in development of root system among cowpea genotypes. Thus, phosphorus is essential for yield of cowpea because it stimulates the development of shoot and roots (Haruna & Aliyu, 2011).

Basal root number on the other hand was higher at low phosphorus treatment. Thus, basal root number increased as soil phosphorus concentration decreased. This is due to morphological mechanisms of genotypes to deal with insufficient P availability in soil leading to prolific root development and growth. Legume roots can be adapted to low soil P condition by increasing root growth such as basal and adventitious roots, modified root architecture (Lynch, 1995). However, certain genotypes had more basal root growth under high phosphorus concentration. Hence, there was a genetic disposition among cowpea genotypes in the production of basal root under varying phosphorus levels. This result is in line with López-Bucio *et al*. (2002) who reported that, low phosphate availability results in increasing lateral root number and

developing lateral roots closer to the primary root tip. Studies with *Arabidopsis thaliana* and other rape cultivars showed that when crops were cultivated under low P soil, there was reduced primary root and an increase number of lateral roots in the root system (Akhtar *et al*., 2008; Pérez-Torres *et al*., 2008).

Basal and hypocotyl root growth angle of field grown cowpea were significantly affected by genotype, $[P]_{ext}$ and their interaction during the experiment. The results of the study indicate that, shallower root angles were developed by hypocotyl roots compared to basal roots under various phosphorus concentrations in both major and minor season. In general, root angles were wider under phosphorus amended soils. Genotypes with shallower root angles are mostly efficient and adapts to marginal soil condition due their ability to form top foraging which is an efficient mechanism used by cowpea varieties to respond to low P conditions. Under low phosphorus, cowpea genotypes reduces branching ensuing top foraging an important mechanism to respond to low phosphorous (Miguel *et al*., 2015). The results of the present study correlates with the findings of Lynch (2007) and Remans *et al*. (2010) who during their study with cowpea find that, low P levels influence the angle of the basal roots to expand outward rather than downward, leading to a shallower and wider root system as seen in common beans. This argument is supported by the correlation found between the capacity of bean cultivars to decrease root angle in low-P and yield in poor P soils (Bonser *et al*., 1996). A shallow root system efficiently exploits top-soil resources that are useful in low-P soils. This may, however, inadvertently result to lower water absorption (Sanders & Markhart, 1992).

Taproot diameter of cowpea genotypes used for the experiment was significantly affected by genotype, phosphorus levels and their interaction.

Cowpea genotypes responded differently to phosphorus application in relation to taproot branching density. This further justifies the role of phosphorus in root development. As reported by Li *et al*. (2016), substrate P availability can considerably improve root morphology. Cowpea genotypes responded different to phosphorus application in relation to taproot branching density. Branching density reduced under low phosphorus level suggesting that phosphorus plays a significant role in the initiation and growth of plant roots. Root growth is reduced under P-limiting medium. This is due to reduced cell differentiation in the primary root meristem and cell proliferation inhibition in the root elongation zone (Ticconi *et al*., 2004).

Nodule number and diameter of cowpea genotypes screened under field condition on various P amended and unamended soils were significantly affected by genotype, $[P]_{ext}$ and their interactions during the major and minor seasons. This suggests that, genetic variation exist among cowpea genotypes in the formation of nodule under varying phosphorus conditions. Genotypic variation in the effect of phosphorus on cowpea nodulation (Ankomah *et al*., 1995) have been reported earlier. Cowpea genotypes produced greater number of nodules under high availability of phosphorus because phosphorus initiates nodule formation as well as influence the efficiency of the rhizobium-legume symbiosis, thereby enhancing nitrogen fixation. The results of the present study reveal that, phosphorus plays a vital role in the formation of nodules and fixation of nitrogen by cowpea genotypes. This confirms the study by Oladiran *et al*. (2012) that, adequate supply of phosphorus significantly increased the number of nodules among cowpea genotypes during their study. Similarly, Luse *et al*. (1975) and Agboola and Obigbesa (1977) concluded that, application of

phosphorus causes a significant increase in the number of nodules in cowpea. The P is reported to stimulate root and plant growth, initiate nodule formation, and influence the efficiency of the rhizobium–legume symbiosis (Subbarao and Otani 1997). Singh *et al.* (2011) also reported that P application increased the number of branches, dry weight of shoots and nodules per plant.

Effect of $[P]_{ext}$ on biomass traits among cowpea genotypes.

The results of the study indicate that, increased level of phosphorus leads to increase stem diameter among cowpea genotype. This suggest that, adequate amount of soil phosphorus plays a vital role in improving biomass production among crops. Thus, production and distribution of dry matter is influenced by phosphorus application. Grain legumes such as cowpea require P in large amounts because it also helps during photosynthesis for energy transfer and root development. Phosphate is often the limiting nutrient for plant growth because of its low mobility in soil. Greater stem diameter observed in the minor season compared to major season was due to high concentration of P absorbed by genotypes in the minor season in addition to slow release of P which was applied in the major season. Therefore, it is not surprising that high concentration of phosphate significantly increased stem diameter among cowpea genotypes. Productivity of crops depends both on dry matter accumulation and effective partitioning to the seed (Kumar, Reena, Sharma, & Kumar, 2010). Root and shoot dry weight exhibited a significant response to phosphorus application (Odundo *et al*., 2010; Okeleye & Okelana, 1997).

The significant differences in root dry biomass yield among the genotypes could be attributed to genetic effect of the individual varieties. Magani and Kuchinda (2009) made similar observation. Root dry weight

recorded in the both major and minor seasons increased with increasing phosphorus level. Phosphorus application significantly increased root dry weight among cowpea genotypes. The results indicate the role of phosphorus in the production of biomass and yield among cowpea genotypes. The study revealed that the production and development of root weight are under genetic control, but environmental factors such as mineral nutrition also affect root biomass production. The present results agree with Odundo *et al*., 2010; Okeleye & Okelana (1997) who reported that, root and shoot dry weight exhibit a significant response to phosphorus application. Approximately, 74% increase in dry matter was observed at 30 kg P/ ha in cowpea compared to control (Odundo *et al*., 2010). Singh *et al*. (2011) noted a significant increase in dry matter production as phosphorus application increases.

Effect of $[P]_{ext}$ on agronomic and yield parameters of cowpea genotypes

Agronomic parameters

Phosphorus is critical to cowpea yield because it stimulates growth and plays a significant role in yield. Results of the present study suggest that, genotype, application of phosphorus and their interactions significantly influenced days to flowering as well as days to 50% flowering among cowpea genotypes in both the major and minor seasons. Generally, decrease in days to flowering was observed with increasing external P concentration. Thus, days to flowering among cowpea genotypes screened during the major and minor season decreased with increasing external P concentration. The positive effect of phosphorus on flowering among genotypes could be due to the significant role of the element on cell division. This result is in agreement with Egle *et al*.

(1999) who noted that, phosphorus application significantly improves reproductive yields as well floral growth and development. Additionally, phosphorus deficiency can delay blooming and maturity as shown by Holland *et al*. (1999). The use of phosphorus in cowpea reduced the time between planting and green pod harvesting and hastened maturity (Kudikeri *et al*., 1973). Unlike days to flowering, results on 50% flowering indicates that, phosphorus application as well as their interaction with genotype had insignificant effect on 50% flowering. This suggests that, 50% flowering among cowpea is genetically controlled.

Mean number of branches and peduncles per plant varied significantly among cowpea genotypes grown under varying external P concentrations. Higher number of branches and peduncles were recorded at P amended treatment indicating that application of phosphorus increases the number of branches and peduncles among cowpea genotypes. Hence phosphorus plays a significant function in improving yield parameters as well biomass production among cowpea (Douglas & Philip, 2002). The positive effect of phosphorus on number of branches per plant could be due to the significant role of the element on cell division and elongation which resulted in the production of more lateral buds that developed into branches.

Number of pods per peduncle and seeds per pod recorded in both major and minor seasons were significantly affected by phosphorus, genotype, and their interaction. Results of the study indicated that, these parameters increased significantly with an increase in phosphorus level. Thus, mean number of pods per peduncle and mean number of seeds recorded by cowpea genotypes screened at soil amended with 10 and 0 kgP/ha was significantly lower than

values obtained at soil amended with 45 kgP/ha. Similar result was obtained for mean pod length of cowpea genotypes obtained in various seasons. This agrees with the findings of Nkaa *et al*. (2014) that, phosphorus application significantly improved pod length per plant among cowpea varieties. Yield characteristics such as number of pods, length of pods, yield of crops and weight of 50 seeds are enhanced due to the application of phosphorus (Haruna & Usman, 2013; Odundo *et al*., 2010).

Genotype, phosphorus and interaction of genotype and phosphorus had a significant effect of 100 seed weight during the major and minor season. In both the major and minor seasons, yield of cowpea genotypes was significantly affected by phosphorus and genotype. This suggests that, phosphorus application increases yield among cowpea genotypes. Phosphorus plays a key role in many plant processes such as energy metabolism, nitrogen fixation, synthesis of nucleic acids and membranes, photosynthesis, respiration, and enzyme regulation. Another contributing factor that probably enhanced seed weight and yield per plant could be the soil moisture content which was relatively high in the major season compared to the minor season. There was adequate soil water for the crop usage especially in photosynthesis, translocation of assimilate and other physiological processes. Similar observation has been made by Nkaa *et al*. (2014) that, phosphorus application significantly increased seed weight among cowpea genotypes. Supply of phosphorus fertilizer to cowpea impacted cowpea yield by doubling the pod number per plant and mean weight of seeds (Owolade *et al*., 2006; Singh *et al*., 2011). Variation in yield between season could be as a result of prevailing environmental conditions noticeably rainfall. Some yield characteristics such as

pod fresh and dry weight, number of pods, length of pods, number of plants, yield of crops and weight of 50 seeds are enhanced due to the application of phosphorus (Haruna & Usman, 2013; Odundo *et al*., 2010).

Variation in the tissues P concentration and content among cowpea genotypes

Genotype, phosphorus application as well as their interactions significantly affected shoot and root phosphorus concentration in both the major and minor season. `In both seasons, tissue phosphorus concentration increased with increase in phosphorus application. However, phosphorus concentration was high in the minor season compared to the major season. This was due to over saturation of the phosphorus fertilizer in the soil in the minor season hence increasing soil P due to slow-release rate of P applied in the major season which resulted in buildup of soil P in the minor season. Genetic variation among the cowpea genotype accounted for difference in nutrient uptake efficiency observed among genotypes. Additionally, variation in root length among cowpea genotypes could account for variation in tissue P concentration observed among cowpea genotypes during the study since root length plays a vital role in exploitation and uptake of soil resource especially P. Plant root systems are essential for acquisition of soil resources (Adu *et al*., 2019). Substantial genetic diversity in cowpea for root traits associated to growth in nutrient-poor have been reported (Krasilnikoff *et al*., 2002, 2003; Matsui and Singh, 2003; Singh *et al*., 2002). Shoot phosphorus concentration was greater than root phosphorus concentration in both major and minor season. This response could be due to translocation of absorbed phosphorus into tissues of

the plant where high-energy requirements are needed for the formation of seeds and fruit compared to the roots.

Phosphorus use efficiency among cowpea genotypes

Phosphorus use efficiency parameters varied among cowpea genotypes in both seasons and phosphorus application levels and this might probably be due to variation in the ability of individual genotypes to absorb and utilize P. Genotypic variation in P efficiency has been identified in cowpea genotypes used for the study. Similar observation was made by Kolawole *et al.* (2002) and Sanginga *et al*. (2000) who reported genotypic variation in P uptake and use efficiency among cowpea genotypes. Higher P use efficiency among genotypes is attributed to the ability to produce longer and shallow root system which increases root-soil contact and top foraging leading to increases in the P uptake from the soil solution. Additionally, the slightly acidic nature of experimental field enhanced P availability hence increasing concentration of P in soil solution hence high P availability. Phosphorus uptake was strongly correlated with the inter correlated root length (Vesterager *et al*., 2006). This result implies that the P uptake per unit soil exploited is relatively low among the genotypes with short root length and wider angle.

Effect of $[P]_{ext}$ on physiological seed quality

Genotype, phosphorus, and their interaction had a significant ($P < 0.001$) effect on germination percentage recorded by various cowpea genotypes in both the major and minor seasons. The significant differences observed in mean percent germination of the samples tested could be due to the genetic

constitution of the seeds as well as response to seed phosphorus content. This confirms the study of Varis and George (1985) that, high mineral nutrition significantly affects seed quality parameters such as germination and vigor. However, the results disagree with the studies by Amjad and Akbar (2003); Sinha, Mehta and Joydip (2000) who concluded during their study that, phosphorus application improves seed vigor of pea but have an insignificant effect on germination of seed.

Germination rates recorded in both major and minor seasons was significantly ($P < 0.001$) affected by phosphorus and genotype as well as interaction between genotype and $[P]_{ext.}$ Overall, germination rate increased under higher phosphorus levels in both seasons. Pequerul *et al*. (1993) established that, germination rate and germination vigor were significantly influenced by different doses of phosphorus. Thus, germination rate increases under high phosphorus conditions or dose. The results of the present confirms the findings of, Amjad and Akbar (2003) who stated that, time to complete 50% germination in pea was significantly affected by P application.

Coefficient of velocity of germination was significantly ($P < 0.001$) influenced by genotype, $[P]_{ext}$ and the interaction between genotype and phosphorus rates in both seasons. The observed significant difference is due to genetic variation among cowpea genotypes. The high coefficient of velocity of germination recorded under high phosphorus level is due to effects of seed phosphorus on germination. Since high germination percentage positively correlates with high velocity of germination. This is in line with Asiedu *et al*. (2012) who established that, high coefficient of velocity is indicative of high germination percentage; seeds taking less time to germinate and rapidly

(Hartmann *et al*., 1997). Hence, the lower the coefficient of velocity, the lower the germination percentage and the longer seeds take to germinate (Fenner, 1991).

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

Conclusion

The present study evaluated genotypic variation and the effect of $[P]_{ext}$ on RSA, yield, P efficiency and physiological seed quality among twenty (20) field grown cowpea genotypes. Three (3) $[P]_{ext}$ levels (0, 10, 45 k/ha) were used for the study. Cowpea genotypes exhibited wide range of diversity for RSA traits noticeably HRL, BRL, HRA, TRBD, root number etc. Additionally, genotypic variation was observed among cowpea genotypes in relation to biomass production, yield parameter, P use efficiency and physiological seed quality. This genetic disposition for these traits presents a greater selection opportunity for the breeding of future efficient genotypes to ensure effective and efficient utilization of limited soil resources of which immobile P is paramount.

Application of phosphorus resulted in production of longer root length for majority of cowpea genotypes however, for genotypes IT91, Agyenkwa and WC36, hypocotyl root length increased with increasing P to the point where it declined. Genotype Asontem, NE 51*NE 50 and Songotra had longer root hairs on unamended P soils. Basal root length was significantly influenced by $[P]_{ext.}$ Generally, the length of basal roots increased with increasing P concentration. Genotypes Sunshine, WC36, Asontem etc. obtained longer basal root on unamended P soil. Root diameter of cowpea genotypes increased with increasing P concentration. Genotypes Agyenkwa, Sunshine, Songotra MU9 and WC 36 obtained high root diameter on unamended P soils. In general, basal

root number among cowpea genotypes decreased with increasing P concentration. Root growth angles of cowpea genotypes cultivated under P amended soils was wide compared to genotypes grown on unamended P soils. However, for genotypes Agyenkwa, Songotra, WC36 and NE 50, growth angles increased to a certain point with increasing P and begun to decline. Nodulation among cowpea genotypes was influenced by P application. Phosphorus application at 45 kgP/ha produced more nodules.

Stem girth among cowpea genotypes increased with increasing P concentration however, genotypes Soronko, WC36, MU9, Nketewadea and Alegi*Sunshine obtained high stem diameter under P unamended soil. Similarly, genotypes WC36, Soronko and Agyenkwa among the remaining genotypes obtained significantly higher root biomass under P amended soils. This indicates that, P application resulted in increasing root biomass production among cowpea genotypes.

Results of the study suggest that, flowering of cowpea is influenced by P concentration such that, cowpea genotypes cultivated on P amended soils exhibited early flowering. Although number of seeds per pod increased with increasing P however, with certain genotypes, number of seeds increased in response to P concentration to a point where it declined. Majority of cowpea genotypes screened during the study produced high yields under P amended soils compared to unamended soils.

The results of the study suggest that, $[P]_{ext}$ significantly affects tissue P concentration among cowpea genotypes. However, shoot P concentration was higher compared to root P concentration. Similarly, $[P]_{ext}$ had a consistent effect on tissue P content among cowpea genotypes. Genotypes cultivated on P

amended soils had 49.2% more biomass P content relative to plants grown on unamended P soils. Phosphorus uptake efficiency among cowpea genotypes was high for crops grown on soil amended with 10 kgP/ha compared to 45 kgP/ha. Genotypes IT91, Secow3B and NE50 had high PUpE. However, among the genotypes cultivated on P amended soils, NE50, IT91 and WC 35B*NE 50 had low APE during the study. Phosphorus utilization efficiency was high for genotypes cultivated at 0 kgP/ha. Generally, PUtE decreased with increasing P concentration. A significant interaction effect of genotype and $[P]_{EXT}$ on PPUE was observed. Genotype Asontem had high PPUE at 10 kgP/ha whilst IT91, NE50 and Secow 3B exhibited a decrease in PPUE in response to increasing P concentration. Germination percentage, germination rate, coefficient of velocity of germination and germination index among cowpea genotypes increased with increasing P indicating the need to increase and ensure sufficient supply of P to cowpea genotypes.

Recommendations

Recommendations made based on the results of the study include.

1. Genotypes with high yield and high P use efficiency should be crossed in hybrid breeding programmes to develop improved hybrid for production in poor soils.
2. Subsequent study should examine the concentration of seed P after harvest on physiological seed quality.
3. Similar studies should be carried out under controlled environment to ascertain the correlation between field and controlled environmental conditions.

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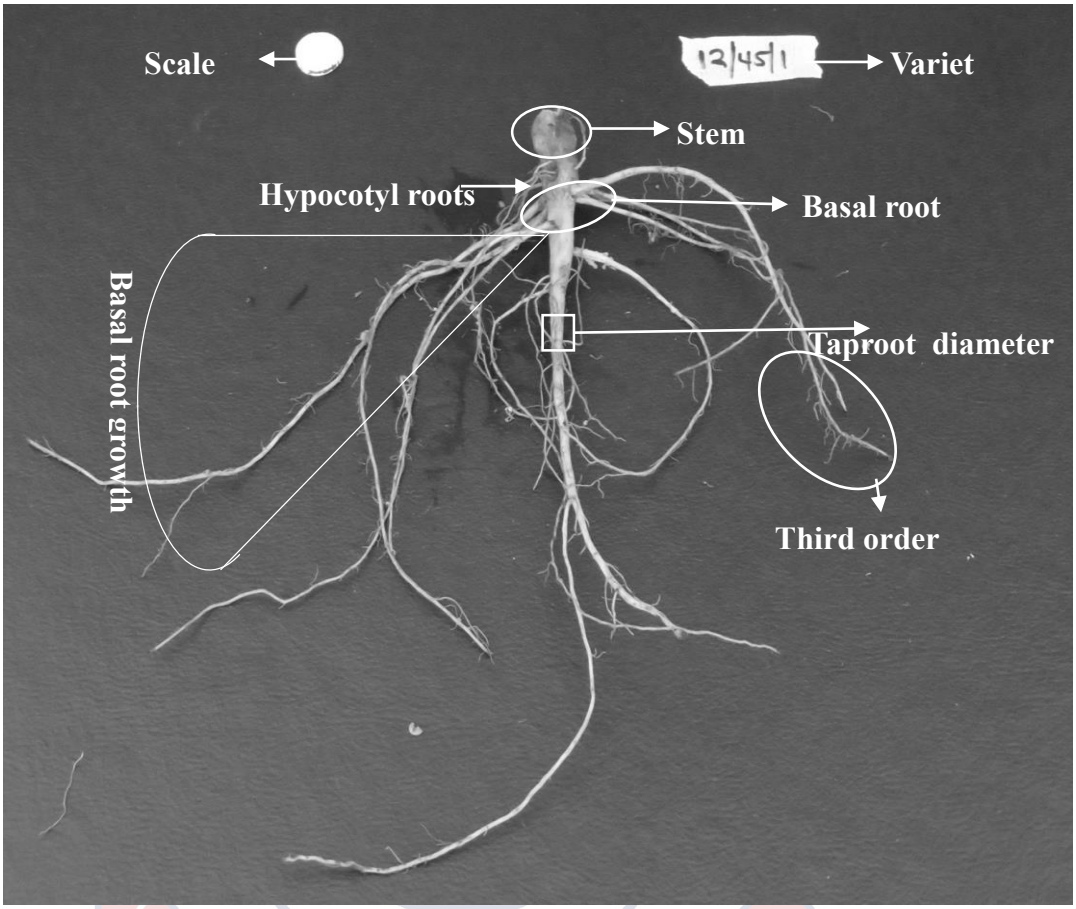
APPENDIX

Appendix 1



Appendix 2

Table 14 - Estimates of variance components of field grown cowpea genotypes under varying $[P]_{ext}$ in the major season

	Component											
Measurements	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**	**PC 9**	**PC 10**	**PC 11**	**Communalities**
Root P content	**.699**	.065	.216	.246	.056	-.127	.008	-.062	.049	-.059	.122	.644
Root P concentration	**.695**	.495	.017	.004	.046	.140	-.121	.245	-.082	.111	.040	.845
Shoot P concertation	**.695**	.495	.017	.004	.046	.140	-.121	.245	-.082	.111	.040	.845
P utilization efficiency	**-.682**	-.077	-.373	-.039	-.091	.254	.189	.068	.111	.207	-.076	.786
P efficiency ratio	**-.639**	-.286	-.174	.427	-.012	-.085	.137	-.053	.106	.084	.100	.760
P uptake efficiency	**-.586**	-.348	-.262	-.268	-.067	-.016	-.075	-.184	.141	.084	-.157	.701
Germination percentage	**.354**	-.061	.081	-.014	.036	.231	.339	.304	.153	.103	-.198	.471
Coefficient of velocity of germination	.167	**.950**	.075	.081	-.028	.092	.017	-.053	.017	-.028	.030	.957
Mean germination rate	.167	**.950**	.075	.081	-.028	.092	.017	-.053	.017	-.028	.030	.957
Germination index	.191	**.934**	.080	.063	-.034	.114	.076	-.005	.061	-.014	-.002	.943
Number of pods per plant	.227	.101	**.849**	.027	-.057	-.047	-.040	.000	-.173	.074	-.104	.837
Number of pods per peduncle	.171	.072	**.746**	.154	.011	-.064	-.148	.003	.089	.024	.091	.658
Number of branches	.256	.120	**.587**	-.206	.016	.026	.022	.077	-.477	.006	-.085	.709
Pod length	.178	.066	.074	**.873**	-.048	-.033	-.009	.031	.043	-.094	-.013	.819
100-seed weight	-.054	.050	.199	**.707**	-.129	.206	.048	.080	.268	.114	.128	.714
Number of seeds per pod	.055	.164	-.105	**.639**	.031	-.093	.243	-.012	-.273	-.059	-.054	.599
Basal root length	.065	.000	.033	.123	**.853**	.036	-.060	.005	-.004	.027	.058	.757
Basal root diameter	.049	-.119	-.180	-.048	**.767**	.059	-.170	.166	.191	.106	.168	.775
Third order branching density	.149	-.047	.179	-.352	**.663**	.076	-.130	.193	.090	.135	.089	.714
Shoot dry weight	-.066	.187	.021	-.215	**.454**	-.350	.079	.432	-.006	.042	-.119	.623
Days to flowering	-.025	.116	-.049	-.006	.038	**.914**	-.066	-.062	-.045	-.011	-.103	.874
Days to 50% flowering	-.011	.243	-.060	-.003	.051	**.914**	-.009	.011	-.027	-.002	-.118	.915
Physiological P use efficiency	-.364	.064	-.199	.053	-.128	.069	**.816**	.041	.104	.072	-.008	.884
Yield	.246	.168	.168	.107	-.077	-.173	**.806**	-.007	.024	-.099	.073	.830
Agronomic P use efficiency	-.207	-.115	-.226	.096	-.118	-.025	**.599**	-.004	-.055	.048	-.043	.497
Taproot diameter	.169	-.187	-.053	.034	.042	.014	.048	**.658**	.108	-.029	.326	.623
Root dry weight	.112	.156	.277	.276	.199	-.085	.002	**.618**	-.162	.031	.059	.650
Stem diameter	.035	.043	-.196	-.034	.408	-.077	-.023	**.616**	.082	.118	.122	.630
Hypocotyl root growth angle	-.070	-.197	.231	-.263	-.197	.222	.010	**.409**	.246	-.125	-.042	.499
Basal root number	-.161	.006	.133	-.042	.197	-.046	.093	.063	**.675**	-.102	.262	.633
Hypocotyl root number	.381	.029	-.219	.133	-.062	-.041	-.246	.095	**.633**	.105	-.062	.703
Basal root growth angle	.097	-.059	.131	.026	-.083	.006	-.095	-.016	**-.606**	.075	.126	.436
Nodule number	-.013	-.034	.043	.052	.059	.010	.037	-.008	-.238	**.877**	.047	.838
Nodule Diameter	-.072	-.002	.028	-.102	.139	-.022	-.006	.064	.106	**.867**	.053	.805
Hypocotyl root diameter	.236	-.010	-.004	-.047	.132	-.196	.052	.164	-.063	.038	**.749**	.709
Hypocotyl root length	-.178	.104	-.128	.128	.073	-.057	-.099	.337	.121	.169	**.622**	.638
Shoot P content	.475	.088	.245	.036	.227	-.040	-.010	-.265	-.036	-.059	**.507**	.680
Eigen values	6.603	3.856	3.048	2.843	2.044	1.858	1.711	1.387	1.335	1.166	1.106	
% of Variance	17.847	10.422	8.239	7.682	5.524	5.022	4.623	3.748	3.608	3.152	2.990	
Cumulative %	17.847	28.269	36.508	44.190	49.714	54.736	59.360	63.107	66.715	69.868	72.858	

Appendix 3

Table 15 - Estimates of variance components of field grown cowpea genotypes under varying $[P]_{ext}$ in the minor season

	Component												
Measurements	**PC 1**	**PC 2**	**PC 3**	**PC 4**	**PC 5**	**PC 6**	**PC 7**	**PC 8**	**PC 9**	**PC 10**	**PC 11**	**PC 12**	**Communalities**
P efficiency ration	**-.975**	-.045	-.042	.049	-.033	-.052	-.047	.004	-.035	-.010	-.033	.014	.966
P utilization efficiency	**-.975**	-.045	-.042	.049	-.033	-.052	-.047	.004	-.035	-.010	-.033	.014	.966
Root P concentration	**.974**	.067	.004	-.060	.044	.055	.028	.000	.073	.014	.047	.015	.970
Shoot P concentration	**.974**	.067	.004	-.060	.044	.055	.028	.000	.073	.014	.047	.015	.970
Root P content	**.792**	.103	-.014	.007	.014	.066	.041	-.046	.024	.500	-.042	.095	.908
P uptake efficiency	**-.530**	-.431	-.093	-.068	.011	-.139	.027	-.100	-.203	-.241	.016	-.296	.698
Coefficient of velocity of germination	.084	**.982**	-.069	.001	.084	.045	.026	.015	.003	.010	-.012	.014	.987
Mean germination rate	.084	**.982**	-.069	.001	.084	.045	.026	.015	.003	.010	-.012	.014	.987
Germination index	.087	**.969**	-.054	.041	.125	.015	.030	.029	.001	.033	-.054	.012	.973
Hypocotyl root length	-.021	.032	**.855**	-.010	.037	-.030	.016	-.056	.108	-.028	.054	.048	.756
Hypocotyl root growth angle	.085	-.129	**.840**	.025	.086	-.018	.049	-.029	-.107	-.091	-.009	.022	.762
Hypocotyl root diameter	-.003	-.101	**.801**	.063	-.097	.052	-.003	-.025	.124	.062	.010	.100	.698
hypocotyl root number	.040	.026	**.799**	-.033	-.146	-.099	-.049	.171	-.009	.035	-.073	-.151	.733
Number of pods per plant	-.126	-.023	.013	**.863**	-.057	-.255	-.079	-.010	.033	-.037	.024	.057	.842
Number of pods per peduncle	-.068	-.037	.004	**.862**	-.022	-.246	-.077	-.008	-.040	-.035	.043	.021	.822
Yield	.168	.230	.008	**.681**	-.218	.470	.082	.059	.082	.098	-.060	.030	.845
Physiological P use efficiency	-.556	.148	-.004	**.616**	-.204	.385	.030	.060	.017	.097	-.059	.027	.918
Days to 50% flowering	.044	.214	-.070	-.096	**.906**	-.012	.010	-.063	-.099	-.054	.076	.094	.914
Days to flowering	.039	.102	-.047	-.153	**.893**	-.069	.050	-.082	-.061	-.006	.075	.021	.859
100-seed weight	.144	-.063	-.085	.197	**.426**	.169	-.051	.385	.246	-.277	-.184	-.053	.605
Germination percentage	.260	.021	.091	.305	**.329**	-.136	.042	.126	-.022	.156	-.184	-.071	.377
Number of seeds per pod	.028	.055	-.068	-.153	-.014	**.872**	.080	-.164	-.035	-.094	.045	-.042	.840
Pod length	.185	.051	-.030	-.135	-.049	**.764**	-.055	.084	.057	.013	-.008	.003	.656
Agronomic use efficiency	-.338	-.131	.048	.398	.099	**.399**	-.009	.070	-.144	.232	.050	-.043	.545
Shoot dry weight	-.036	.028	.001	-.045	.031	.015	**.973**	.098	-.043	-.027	.012	.009	.964
Shoot P content	.174	.038	.010	-.050	.018	.017	**.962**	.091	-.022	-.006	.032	.020	.970
Nodule number	-.053	.021	.021	-.005	-.041	-.083	.063	**.834**	-.050	.004	.123	-.077	.735
Basal root number	-.004	-.007	-.021	-.034	.141	-.075	-.080	**-.663**	.117	.140	.278	-.175	.614
Nodule Diameter	.016	.137	.036	.019	.159	-.072	.193	**.568**	.164	.238	.436	-.058	.688
Taproot diameter	.059	-.068	.025	-.015	-.002	.022	-.033	-.162	**.778**	-.038	-.087	-.050	.653
Stem diameter	.187	.125	.106	.028	-.120	.000	-.010	.122	**.757**	.099	.104	.099	.695
Root dry weight	.303	.093	-.008	.119	-.016	.049	.019	-.067	-.057	**.803**	-.117	.087	.791
Basal root growth angle	.062	.052	.052	.087	.094	.129	.115	-.018	-.288	**-.455**	-.045	.265	.418
Basal root diameter	.043	-.079	.042	.093	.106	.022	-.013	-.065	.033	-.175	**.756**	-.036	.640
Basal root length	.140	-.024	-.103	-.200	-.138	.042	.069	.160	-.154	.179	**.456**	.237	.441
Third order branching density	.037	.028	-.032	.050	.006	-.035	-.088	.107	-.070	-.105	.135	**.772**	.657
Number of branches	.016	.030	.116	.005	.116	-.045	.208	-.214	.197	.170	-.197	**.545**	.522
Initial Eigenvalues	6.288	3.509	3.201	2.543	2.285	2.156	1.791	1.617	1.409	1.263	1.205	1.120	
% of Variance	16.995	9.485	8.651	6.873	6.175	5.827	4.840	4.369	3.808	3.413	3.258	3.027	
Cumulative %	16.995	26.480	35.131	42.004	48.179	54.007	58.847	63.216	67.024	70.437	73.695	76.721	

Appendix 4 - Estimating rate of TSP applied per treatment

Three (3) rates of P (0, 10 and 45 kg P/ha) based on initial soil analysis and recommended application rate was used for the study. Zero (0) kg P/ha served as the control treatment for the experiment. The rate of TSP applied per plant to obtain various rates of P is described below.

Each 100g of TSP contains 45 percent of pentoxide(P_2O_5)

Molecular weight of (P_2O_5) = 2(31) × 5(16) = ***142***

Conversion factor = $\frac{62}{142} = 0.437\%$

Hence the pure form of P in TSP is calculated as -

Weight of P_2O_5 in TSP × conversion factor

45 × 0.44 = ***19.8 P***

10 kgP/ha	**45 kgP/ha**
$\frac{100g\ TSP}{X} = \frac{19.8\ P}{10\ kg\ P}$	$\frac{100g\ TSP}{X} = \frac{19.8\ P}{45\ kg\ P}$
Convert 10 kg to g = 10,000g $\frac{10{,}000g \times 100g\ TSP}{19.8\ P}$ **50,505.051 g**	**Convert 10 kg to g = 45,000g** $\frac{45{,}000g \times 100g\ TSP}{19.8\ P}$ **227,272.73 g**
Hence, $\frac{50{,}505.051g\ TSP}{X} = \frac{10{,}000m^2}{5.04m^2}$ $\frac{50{,}505.051g\ TSP \times 5.04m^2}{10{,}000m^2}$ **= 25.45 g TSP**	**Hence,** $\frac{227{,}272.73g\ TSP}{X} = \frac{10{,}000m^2}{5.04m^2}$ $\frac{227{,}272.73g\ TSP \times 5.04m^2}{10{,}000m^2}$ **= 114.5 g TSP**
TSP applied per plant $\frac{25.45g}{30} = 0.85gTSP/plant$	**TSP applied per plant** $\frac{114.5g}{30} = 3.82gTSP/plant$

Size of subplot = 5.04 m^2, Total plant population per subplot = 30