# EVALUATION OF SELECTED GROUNDNUT GENOTYPES FOR BIOLOGICAL NITROGEN FIXATION AND YIELD IN P-DEFICIENT SOILS OF THE NIGERIAN SAVANNAHS

**BY**

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**AUGUST, 2021**

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**NIGERIA**

**AUGUST, 2021**

## DECLARATION

I, Alhassan Idris Gabasawa, declare that the work in the Thesis entitled 'Evaluation of selected groundnut genotypes for biological nitrogen fixation and yield in P-deficient soils of the Nigerian savannahs' has been performed by me in the Department of Soil Science. The information derived from literature has been duly acknowledged in the text and list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other Institution.

Alhassan Idris GABASAWA

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|---|---|---|
| Name of Student | Signature | Date |

## CERTIFICATION

This Thesis entitled "EVALUATION OF SELECTED GROUNDNUT GENOTYPES FOR BIOLOGICAL NITROGEN FIXATION AND YIELD IN P-DEFICIENT SOILS OF THE NIGERIAN SAVANNAHS" by Alhassan Idris GABASAWA meets the regulation governing the award of the degree of Doctor of Philosophy of the Ahmadu Bello University and is approved for its contribution to knowledge and its literary presentation.

Prof. Ado A. Yusuf Signature _____ Date _____

Chairman, Supervisory Committee

Prof. E.N.O. Iwuafor Signature _____ Date _____

Member, Supervisory Committee

Prof. C.A. Echekwu Signature _____ Date _____

Member, Supervisory Committee

Prof. Nafiu Abdu Signature _____ Date _____

Head of Department

Prof. Sani Abdullahi Signature _____ Date _____

Dean, School of Postgraduate Studies

## DEDICATION

To my parents, paternal and maternal brothers and sisters and my second born child - AbdulHakeem, all deceased.

## ABSTRACT

Phosphorus (P), the second most important nutrient element for plant growth, is majorly not readily available in tropical soils for plant assimilation, mainly due to fixation by Fe and Al oxides (sesquioxides). Therefore, there is a need to apply P fertilisers for optimum growth of crop plants. However, mineral fertilisers may not be readily available and /or affordable to smallholder farmers. Field experiments were conducted during the 2015 and 2016 cropping seasons in Samaru (northern Guinea savannah, NGS) and Minjibir (Sudan savannah, SS). The objectives were to identify groundnut genotypes, grown on P-deficient soils that are of the highest level of biological nitrogen fixation (BNF) and yield at a given source of P applied in the two agro-ecological zones of Nigeria. The experiments were laid out in a split-plot design, with P fertiliser sources [control (0), single superphosphate (SSP) and Sokoto rock phosphate (SRP)] in the main- and 16 groundnut genotypes in the sub-plots. The pod yield and most of the yield components were observed to be significantly higher in Minjibir than Samaru. The genotypes responded differently to the application of P fertiliser from all the three sources tested in both agro-ecological locations. This was attributable to the observed soil enzyme activities, P availability in the soil solution, its adsorption/desorption cycles and weather conditions. Under the control P, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ had the highest values of 30 kg $ha^{-1}$ and 46 kg $ha^{-1}$ respectively for $N_2$-fixed and Ndfa in Minjibir in the 2015 trial season. ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and SAMNUT 21 had the highest N uptake of 40 kg $ha^{-1}$ with the same P source, location and season. SAMNUT 21 had the highest $N_2$-fixation under both SSP (41 kg $ha^{-1}$) and SRP (52 kg $ha^{-1}$) in Minjibir. In Samaru however, the highest $N_2$ fixation, under the control (25 kg $ha^{-1}$) and SSP (33 kg $ha^{-1}$) was observed with SAMNUT 10. SAMNUT 22 had the highest N uptake of 27 kg $ha^{-1}$, 26 kg $ha^{-1}$ and 32 kg $ha^{-1}$ under control, SSP and SRP P sources respectively in the same location. There were also higher activities of the enzymes amidohydrolase (urease) and phosphomonoesterases (acid and alkaline phosphatases) observed, under most of the P sources, in the soil of the Minjibir than that of Samaru. The economic analysis of groundnut production in Minjibir showed the highest net return in both trial seasons without the addition of any P source, followed by SSP and then SRP in that order. The analysis also revealed that groundnut production without P application in Samaru increased the net return compared to using the other two P sources. However, the SRP P source followed the control in this location, and in

both seasons. Therefore, profitable cultivation of groundnut crops without the application of P fertiliser may be possible. Genotypes like ICGV-IS 07083 and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ had a good pod yield without P application in Minjibir and Samaru locations respectively. Also, ARRORS ICGX 000201/5/$P_4$/$P_{10}$, SAMNUT 21 and SAMNUT 22 performed well in terms of dry haulms while SAMNUT 10 and SAMNUT 14 displayed a dual-purpose potential for good pod and haulm yields, especially with no fertiliser P application. More research efforts should be vested on evaluating more P sources with SRP, especially at different SRP rates. Genotypes observed with low-P tolerance features can be included in farmers' farming systems to circumvent the soil fertility problems of P-deficient soils. Understanding more (soil and plant) mechanisms involved in the genotypic P utilisation would be of paramount importance to research activities centred towards the resource-constrained farmer.

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# CHAPTER ONE

# 1 INTRODUCTIONS

## 1.1 General Preamble

Improved methods for selecting cultivated varieties based on their capability of growing well on P-deficient soils is bound to improve crops' productivity and will result in a reduced pollution catastrophe to the barest minimum (Greenwood *et al*., 2006). Estimates of important physiological parameters of different genotypes, that define yield response to increasing rates of plant-available soil P, are therefore needed. Groundnut (*Arachis hypogaea* L.), derived from two Greek words: *Arachis*, meaning 'legume' and *hypogaea*, meaning 'below ground', referring to the formation of pods in the soil (Raemaekers, 2001), is an important, tropical and sub-tropical, leguminous crop (Norman *et al.*, 1995; Raemaekers, 2001). It is grown on nearly 25 million hectares, of various soil types, and tantamount to a pod yield of about 41 million tonnes (Virmani and Singh, 1986; Norman *et al.*, 1995; Raemaekers, 2001, FAOSTAT, 2014). The crop thrives best in a warm growing season with a well-distributed rainfall that ranged from 500 to 1000 mm. It is mainly cultivated in semi-arid regions of the world, including Nigeria, Senegal, Sudan, India, China, the United States of America (USA), Myanmar, Indonesia, Argentina and Vietnam (FAO, 2003). It is an energy-rich crop, yet more often grown on light-textured soils, mainly by resource-poor farmers in a vast range of environments full of frequent drought and poor soil fertility, that limit its productivity (Singh, 2011; Singh *et al*., 2015). It contains about 50% oil, 25 - 30% protein, 20% carbohydrate and 5% fibre and ash, making substantial contributions to human nutrition (Fageria *et al.*, 1997). The oil is used in cooking, soap-making, cosmetics and as lubricants. The world average groundnut yield is around 1,650 kg $ha^{-1}$, yet only less than 1,000 kg $ha^{-1}$ is being realised in more than 30% of the groundnut growing countries of the world as reported by FAOSTAT (2014). This is mainly due to P-deficiency problems (Singh, 2004, 2014; Ajay *et al*., 2015).

Groundnut is also one of the leguminous plants that fix atmospheric nitrogen ($N_2$). This is made possible by working, in symbiosis, with rhizobia, a special class of bacteria. *Rhizobia* are a diverse group of organisms that are united by a common ability to produce nodules on roots (and sometimes, stems) of leguminous plants (Weaver *et al*.,

1994). The *rhizobia* living in the roots of these legumes infect the root hairs of the plants, which action culminates in the production of root nodules. The nodules, in turn, become an abode for these bacteria from where they also obtain energy produced by the host plants. They also take free $N_2$ from the soil air and process same into a combined N. In return, however, the plant also receives the fixed N from the nodules and produces food and forage protein (Peoples *et al*., 1989). The process of biological nitrogen fixation (BNF) by the groundnut root nodules, however, requires large amounts of phosphorus (P) (Danso, 1992; Mortimore *et al*., 1997), which is a pre-requisite for plant growth and adenosine triphosphate (ATP) synthesis. Both (growth and ATP) are essential for $N_2$-fixation. Hence, P has been specially found to be the most critical nutrient for legumes (Greenwood, 1951; Heathcote, 1973; Spiers and McGill, 1979; Ogoke *et al.,* 2003; Lekberg and Koide, 2005a).

Rock phosphate (RP) is among the important P fertilisers directly sourced from various natural phosphate rock (PR) deposits available. It is reported that about 95% of the PR reserves mined is used in agriculture through the production of fertilisers, pesticides and animal feeds (Cisse and Mrabet, 2004). This large percentage of phosphate being used in the agricultural sub-sector indicates the significance of PR as a driving force for sustainable food production (World fertilizer, 2017a). Phosphate rock can also be a cheaper source of P (Schilling *et al*., 1998).

## 1.2 Problem Statement

Phosphorus is the second major macronutrient for many crops' production, as it is involved in transforming solar energy into chemical energy during photosynthesis and is essential for a healthy root system development, as observed in many studies (Foth, 1984; Marschner, 1995; Schachtman *et al*., 1998; Meyer *et al*., 2011). It is, therefore, an integral part of many soil fertility programmes and hence applied to agricultural land as either organic manure or inorganic fertiliser to meet crop demands. However, besides being the most expensive of the macro-nutrients per unit price, wide variations in soil properties greatly complicate the process of accurately estimating fertiliser P requirements (Miles *et al.,* 2013). In acid soils, for example, the predominance of Fe and Al oxides (sesquioxides, both crystalline and amorphous) strongly reduce the solubility of soil inorganic P by a fixation on positively charged surfaces and by forming insoluble Fe and Al precipitates (Warren, 1994; Hinsinger, 2001; Gichangi *et*

*al*., 2007; Meyer *et al*., 2011). In alkaline soils, P readily reacts with calcium (Ca) to form sparingly soluble calcium phosphates. These reactions may result in a very high proportion of applied fertiliser P becoming chemically bound with only a meagre proportion of soil P being present in the soil solution that is available for plant uptake (Johnston *et al*., 1991; Gichangi *et al*., 2008). Studies have also shown that, at the same *pH*, soils with higher clay content have higher P fixing capacity compared with more sandy soils (Johnson *et al*, 1996; Warren, 1994; Bainbridge *et al*., 1995) and that organic matter (humus-Al complexes) does contribute to soil P availability as observed by Haynes (1984), Owusu-Bennoah and Acquaye (1989). Such variable charge minerals as aluminosilicates are also reported to be part of the major components, of many tropical soils, that make nutrient P dearth to crop plants due to their P-fixation effects.

Most Nigerian soils are, on the other hand, are composed of variable charges dominated by Alfisols, Ultisols and Oxisols (Tsado *et al*., 2012). The low amount of total and available P in these soils makes it imperative that problems associated with P availability be investigated. Nwoke *et al*. (2004) reported that P can miserably be as low as 2 mg $kg^{-1}$ in the savannah soils of Nigeria, thereby making it one of the most deficient nutrients in such soils. Also, P levels were reportedly lower than the critical values of 7 mg $kg^{-1}$ (Mehlich-3 extractable P) in 93 and 92% of the fields respectively surveyed in the Nigerian Sudan and northern Guinea savannahs (Kamara *et al*., 2008). Kwari (2005) reported mean soil P level ranges of 1.50 to 2.51 mg $kg^{-1}$ and 3.68 to 4.70 mg $kg^{-1}$ in the dry and moist savannahs of Nigeria, respectively. A judicious amelioration of soil P deficiency in the savannah zones of Nigeria remains one of the most crucial questions facing resource-handicapped farmers and soil scientists. Commercial mineral P fertilisers are usually costly and hence inaccessible. Where accessible, an indirect problem due to soils still exists. This is, partly, in terms of P unavailability to plants due to its affinity for fixation by iron (Fe) and aluminium (Al) oxides, common in such problem tropical soils (Sample *et al.,* 1980). This sometimes makes the application of such fertilisers, for sustainable groundnut production, relatively futile (Sanginga *et al.,* 2000). Besides, there is always an increasing demand for more nutrients, which is expected to further hike its need by 3.6% in (mainly in sub-Saharan) Africa by 2020/2021 (World Fertilizer, 2017a).

Supply of the needed nutrients to crop plants for a profitable production involves paying attention to the four major fertilisation factors (called the 4Rs): right rate, right source, right placement and right timing (IPNI, 2014). Observing these factors provides adequate nutrition for a bumper crop harvest, vis-à-vis minimising the risk of nutrients loss to the environment (IPNI, 2014). Most farmers are, however, lacking in the technical know-how about these factors, and hence the obvious repercussions. Incorporation of plant residues and animal manure may have, alternatively, been employed to supplement the much-needed plant nutrients. This is, however, limited by the necessity of huge quantities required, worsened by the most often poor quality of the materials (Ogoke *et al.,* 2003). The handy established knowledge on the extent of genotypic differences among the existing cowpea genotypes, in terms of P utilisation, therefore, makes it easier to postulate a similar scenario in groundnuts. This is a primarily vital step, and only a few reports on groundnuts are available (Singh, 2004; Singh and Basu, 2005a). This is because there is no well-defined selection criterion (Ajay *et al*., 2015; Singh, 2004). Work was, however, initiated in many laboratories worldwide to understand the mechanism and to develop screening methodologies for the search of nutrient-efficient genotypes in various crops (Blair, 1993; Randal, 1995; Pan *et al*., 2008; Hammond *et al*., 2009; Sepehr *et al*., 2009; Yaseen and Malhi, 2009). Sawadogo *et al*. (2021), consequently identified some promising groundnut genotypes that a good candidate for peasant environments in India.

### 1.3 Justification of the Research

About 36% of the tropics are occupied by soils of limited P-supplying capacity (Sanchez and Logan, 1992). This situation is even more acute in West Africa, where more than 50% of the soils have a bicarbonate-extractable P content of less than 8 mg $kg^{-1}$ (Mokwunye *et al*., 1986). This situation is expected to even worsen given the negative P balance of 10 kg $ha^{-1}$ $year^{-1}$ (Stoorvogel and Smaling, 1998), considered a major reason for the declining per capita food production (Sanchez *et* al., 1997). Plant available P, however, increases over time with the application of P fertiliser at rates that exceed crop removal (Kumaragamage *et al*., 2011). As a result of a continuum of P forms, from soluble to insoluble, there is also an especial need to measure the P fractions of soils using appropriate testing procedures. This will in a way, amongst other advantages, aid in monitoring environmental risk assessment due to P level and source, and/or fractions in the soils and its agronomic effect on crop production

(Kumaragamage *et al*., 2007). Various studies have been conducted to determine factors that influence changes in soil test P, that include the source of P applied (Kumaragamage *et al*., 2011). Agronomic soil test focuses on the availability of extracted P to the crop, *vis-à-vis* its regulation by soil and plant factors.

Some of the soil factors, of especial importance in regulating available P, include soil *pH*, organic matter, adsorption capacity, mineralogy, soil texture, temperature, soil moisture, *et cetera* (Obikoya, 2016). The plant factors, on the other hand, include microorganisms, the presence of plant roots and roots architecture, residues and others (Ciampitti *et al*., 2011). Availability of inorganic P to plant can, however, be limited by a formation of sparingly soluble calcium phosphate in alkaline and calcareous soils; by adsorption onto Fe and Al oxides in acid soils and by a formation of Fe and Al phosphate complexes with humic acids (Gerke, 1994). The distribution and nature of the various P forms provide useful information for the assessment of the available P status of soils, and for estimating the extent of chemical weathering of the soil, P deficiency, and others. Estimation of available P, however, indicates only the amount of P present in soil surface and solution, which is available to plants, but it does not indicate the relative contribution of different P fractions towards available P.

A judicious application of P fertiliser/fertiliser type, vis-à-vis increasing its use efficiency, remains a vital economical option for, especially, leguminous crops cultivation. However, a problem of involving an inconsistent response of, for example, groundnut crop to P is a serious stumbling block. This is mainly because P uptake majorly depends on crop genotype, soil type, form of inherent soil P, method of fertiliser P application; and presence of arbuscular mycorrhizal fungi (AMF) and phosphorus solubilising microorganisms in the soil (Singh and Chaudhari, 1996; Singh, 1999; Singh *et al*., 2004). This implies that P, being an inevitable nutrient for groundnut production, needs efficient management practices that will safeguard against its unnecessary depletion by genotypes with high abilities of mining out available soil-P reserves. The plant-available P in soils is also generally in a minute fraction compared to the total P of the soils. A second option, therefore, is the development and/or identification of P-efficient groundnut genotypes, characterised by their ability to thrive and yield relatively well in a P-deficient soil environment (Singh *et al*., 2004; Yan *et al*., 2004). Such genotypes can access sparingly soluble P sources and efficiently utilise the

same (Ae *et al.*, 1996; Krasilnikoff *et al*., 2003). This will allow a window for the resource-poor farmer to, sustainably, harvest reasonable yield with little or no extra input demands (Singh and Basu, 2005b). Also, low level of soil available P and large crop response to P fertiliser application is common, especially, for legumes in the savannah zones of West Africa (Bationo *et al.*, 1986). On the other hand, mineral P fertilisers may sometimes be expensive conjoined with their privation to plants due to their compatibility for fixation by sesquioxides, characteristic in tropical soils (Sample *et al.*, 1980). This, consequently, renders P fertiliser application relatively delusive for a real sustainable groundnut production (Sanginga *et al.*, 2000). There is also an ever-increasing need for even more nutrients, which attracts more input costs.

Screening/selection of P-efficient groundnut genotypes, having a superior yield at both low and high levels of P availabilities in the field is, therefore, of practical significance (Singh, 2004; Singh and Basu, 2005a, b). Such P-efficient genotypes grow better in the absence of P fertilisation, as well as being more responsive to P where the earlier mentioned fixation of fertiliser-P is a problem (Singh *et al*., 2004). The P-efficient groundnut genotypes, with high yielding abilities, under both high- and low-input systems, once identified, would reduce the cultivation costs, and contribute to the maintenance of P resources (Singh *et al*., 2015). A multiple-parameter screening of P-efficiency has been proposed for the identification of P-efficient genotypes as reported by Pan *et al*. (2008). This is because, according to Singh *et al*. (2015) there exist enough genotypic differences in groundnut, so it was felt essential to identify suitable traits and P-efficient genotypes using multiple parameters for P-deficit conditions.

Many legumes, such as mungbean (*Vigna radiate*), soya beans (*Glycine max*) and cowpea (*Vigna unguiculata*), *et cetera*, have their P potentials reported by many authors, including Gunawarden *et al.* (1993), Abdelgadir (1998) and Sanginga (2000, 2003). There are, however, no similar readily available reports for groundnuts. This also symbolises the scenario in Nigeria. Hence, there is not much quantitative data on the $N_2$ fixed by many groundnut varieties in Nigeria. There is also still less reported information on intra-specific differences in their $N_2$-fixation, P efficiency and, especially, the mechanisms by which these legumes exhibit differential abilities to be productive at (especially) low and/or high P supply, with only a few been vaguely understood (Singh *et al.*, 1997). Groundnuts fix $N_2$ and so are important in the N

economy of low-input cropping systems. This ensures the improvement of soil fertility and a reduced acute need for synthetic nitrogen (N) fertilisers.

When the differences in P and N nutrition of genotypes of the same leguminous crop is clearly understood, breeding new cultivars for less fertile soils with equally difficult access to mineral fertilisers may be more feasible (Sanginga *et al.,* 2000). Ascertaining optimum P, level(s) from different sources, for sustainable agricultural production will also be possible following that appreciation (Vance, 2001). The consequences of identifying and introducing high $N_2$-fixing and P-efficient genotypes in terms of increased food security can, therefore, never be over-measured. The key mechanisms accounting for high P efficiency in the plants have been speculated to include high calcium (Ca) uptake, the exudation of protons and secretion of organic acids (Hayes *et al*., 1999). A comprehensive analysis of response to P-deficiency with the high P-efficient crop plants is still not so clear. It is also not clear why different plants employ different mechanisms in their adaptation to P-deficiency (Nielsen, 1993).

### 1.4 Objectives of the Research

Consequently, therefore, this work broadly aims at identifying promising groundnut genotypes, grown on P-deficient soils, which are of the highest level of biological nitrogen fixation (BNF) and yield under different sources of P. The specific objectives of this study are as thus:

i. To identify groundnut genotypes with the highest $N_2$-fixation under different P sources.
ii. To unravel the soil mechanisms involved in low-P tolerance in groundnuts.
iii. To determine the effect of P source on biological nitrogen fixation of groundnut genotypes.
iv. To determine the effect of P source on groundnut yield.
*v.* To compare the cost-benefit analysis for groundnut production under different P sources.

# CHAPTER TWO

# 2 LITERATURE REVIEW

## 2.1 The Nigerian Agro-ecological Zones

### 2.1.1 The Nigerian environment

Nigeria, located in the tropical zone of West Africa with a land area of about 92.4 million hectares (World Bank, 1992), lies at about $4^0$ north of the Equator and stretches northwards to $14^0$. It also stretches from $4^0$ to $14^0$ longitudinally. Nigeria opens to the Atlantic Ocean in the south. It is made up of a complex of erosional inselberg landscapes and sediment-filled basins which are derived through many cycles of erosion (Ojanuga, 2006). Topographically, Nigeria is made up of basement complex rocks evident in about 66%, that is two-thirds (2/3), of the land and sedimentary rocks and alluvia occupying the remaining land mass. Rainfall builds up northwards from 4000 mm, close to the equator to 500 mm in the north-eastern part of the country, unimodal in high rainfall areas close to the equator and low rainfall areas above $9^0$ and bi-modal in areas of between 1250 – 1500 mm between latitudes $4^0$ and $9^0$ from the equator (FAO, 1984). The annual precipitation distribution in most years (*i.e.* 6 out of 10) can be remarkably erratic. A conspicuous dry season, ranging from 3 – 8 months, occurs from the high rainfall areas in the south to the driest areas in the north. Nigeria enjoys a high insolation and uniformly high temperatures throughout the year.

The mean annual temperature ranges from 25 $^O$C – 33 $^O$C, and are never below 18 $^0$C in any month, indicating the tropical nature of the environment. Solar radiation, according to FAO (1984), varies from about 300 – 400 g calories$^{-1}$ cm$^{-2}$ day$^{-1}$ in areas close to the equator to about 400 – 500 g calories$^{-1}$ cm$^{-2}$ day$^{-1}$ above $10^0$ north of the equator. This high level of radiation is massively attenuated by cloud cover in the high rainfall areas during the rainy season, which has a detrimental effect on crop yields and fertiliser responses in those areas. Vegetation varies from evergreen forest in the wettest south-eastern part through moist Guinea savannahs to the driest Sahel savannah in the north-eastern part of the country (Ojanuga, 2006).

The country has about 79 million hectares of arable land, 214 billion $m^3$ of surface water and 87 $km^3$ groundwater both of which can partly be used for irrigation (AQUASTAT-FAO). Despite this large natural resource endowment, total cultivable area is estimated at 61 million ha, which is 66% of the total area of the country. The cultivated area was 33 million ha, of which arable land covered 30.2 million ha and permanent crops 2.8 million ha. Irrigation potential estimates in Nigeria vary from 1.5 to 3.2 million ha. The latest estimate gives a total of about 2.1 million hectares of land, of which about 1.6 million from surface water and 0.5 million ha from groundwater. In 2011, the agricultural sector contributed 40.2% to gross domestic products (GDP), followed by wholesale and retail trade with 19.4%, and oil and natural gas with 14.7%, while remaining sectors (including services,) contributed with 25.7% of GDP (NBS, 2012). In spite its importance, the budgetary allocation to agriculture has consistently remained below the 10% goal set by African leaders in the 2003 Maputo agreement (FPRI, 2008).

The situation is being aggravated by socio-political insecurity that has resulted in some terrorist attacks. These especially affected the north-eastern states of the country, forcing many residents to abandon their farmlands with subsequent effects on crop and livestock productions. The effect was worsened by periodic drought and flood related agro-ecological conditions, partially induced by climate change in the north and environmental degradation caused by oil-extracting activities in the south and Niger Delta. The country also has around 79 million hectares of arable land, 214 billion $m^3$ of surface water and 87 $km^3$ groundwater, the two of which are not judiciously utilised (AQUASTAT-FAO). Regardless of this immense and regular resource advancement, there is a significantly vast cultivable land assessed at 61 million ha of the total land area of the country. The developed segment was 33 million ha, of which arable land anchored 30.2 million ha and everlasting products 2.8 million ha. Water system potential gauges in Nigeria advanced from 1.5 to 3.2 million ha. The latest measure gives an entirety of around 2.1 million hectares of land, of which around 1.6 million is from surface water and 0.5 million ha from groundwater (ATA, 2011).

### 2.1.2 Agriculture in Nigeria

Going before the oil boom of the mid 1970s, the country was among the world's leading producers of groundnuts (*Arachis hypogaea*), cocoa (*Theobroma cacao*), palm oil

(*Elaeis guineensis*), cotton (*Gossypium hirsutum*), and hides and skins. The agriculture sector contributed in an excess of 60% to the gross domestic products (GDP), 70% of export and 95% of its sustenance needs. The discovery of petroleum, and its products, in the mid-1970s however, incredibly lead to the neglect of the agricultural sector. In spite of this menace, agriculture remained the dominant financial source for most Nigerians (NBS, 2012). In disdain its significance, the budgetary allocation to agriculture has remained under the 10% target set by leaders of African in the 2003 Maputo agreement (FPRI, 2008). The country's economy is seeing measurable advancement in recent years, that physical development rate was assessed at between 7.4 and 8.0% for every year. It is depended upon to create at 6.5% in 2012, 8.1% in 2013, 7.4% in 2014 and 7.3% in 2015 (NBS, 2012). Regardless of this improvement, the human advancement markers remained unacceptably low and do not seem to improve as the three tiers of government continue to be as poor as ever.

As back as 1984, CSNRD (1984) observed that agriculture is the main occupation of most Nigerians, engaging more than 70% of the labour force. About 90% of the primary agricultural produce comes from smallholder farmers, cultivating about 0.8 – 1.2 ha in the forest areas and 2 – 4 ha in the savannah areas, where land preparation is easier. Root and tuber crop production dominates the forest and forest-savannah transitional areas, while grain crops such as sorghum (*Sorghum bicolor*), millet (*Pennisetum typhoideum*), corn (*Zea mays* L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) predominate in the savannah areas. Other such important crops, to the diets of Nigerians, as groundnuts (*Arachis hypogaea*), cowpea (*Vigna unguiculata*), soya beans (*Glycine max*), melon (*Citrullus lanatus*), beniseed (*Sesanum indicum*), okra (*Abelmoschus esculentus*), peppers and chillies (*Capsicum* spp.), *et cetera* are widely dispersed in the different agro-ecological zones (Ojanuga, 2006).

### 2.1.3 Attempts at agro-ecological zoning and Demarcation in Nigeria

Some positive attempts have, in the past, been made to demarcate Nigeria into homogenous agro-ecological zones for agricultural development objectives. This was with an assumption that all major variations in agriculture in Nigeria are due to differences in climate. This made a United States Agency for International Development (USAID) – sponsored CSNRD demarcated and mapped the country into six ecological areas. In 1992, however, World Bank, following its study report on “Land Resource

Management, Policy and Implementation for Nigeria" identified eight agro-ecological zones map for the nation. This delineation was based on agroclimate and characteristics of the zones. Drawback observed in the two efforts is that they only covered either agroclimate or climate and natural vegetation (*i.e.* bioclimate) of the country and not, in anyway, the country's strict agro-ecological characteristics (Ojanuga, 2006). This shortcoming necessitated for another attempt to revisit the demarcation so far made, and which is closest to the definition of agro-ecological zones of Nigeria. In that, Ojanuga (1989) made a good attempt of dividing the country into yet another different agro-ecological resource regions, bearing in mind the combined climatic zones and physiographic provinces of the country Nigeria. This was to assist in soil classification and management in the country.

The term "ecological" has, in relation to land, been duly defined, by Balasubramanian (2019), as a relationship between all various environmental factors which influence land and its capability and suitability for supporting the array of uses of an especial interest to man. In this sense, therefore, agro-ecological can be seen as pertaining to such characteristics of an environment that influence agriculture or that qualify an area on the surface of earth as an agricultural land resource. Agricultural land can, therefore, be explained as an area of land with soil, water, climate and topography that is best suited for production of commonly grown adapted crops in a given area or environment (Peterpiece, 1989; Peterpiece and Hiley, 1989). The quality of any agricultural land resource base generally dictates the measure of success or failure in its agricultural activities and quality of its environment. Efforts in attaining food security in Nigeria must, therefore, recognise this fact. As such, attention has been given to two key factors, in Nigeria in delineating broad areas with similar biophysical potential, as thus: i) agro-climate and ii) physiography (Ojanuga, 2006).

### 2.1.4 Agro-climate

An agro-climate signifies, for a specific land area, the climate that influences agriculture as measured by rainfall and temperature. Rainfall, and to some extent length of growing season (SRB, 1968; GADP, 1978; Walter, 1967), is perhaps the most limiting climatic factor of agricultural production in Nigeria, whereas temperature (both atmospheric and soil's) is non-limiting to all-the-year-round agricultural (farming and cropping) activities. This is for being the country in the tropical regions. agro-climate is, therefore,

especially considered on the basis of amount and pattern of rainfall, humid and dry months, temperature and soil moisture regime. A humid month is the month when rainfall exceeds evaporation and relative humidity is relatively high (FAO, 1984). More specifically, it is a month with ≥ 50 cm of rain, twice the amount specified by Pullan (1962). He described a dry month as a month with less than 25 mm (*i.e.* 1 inch) of rain. Based on this concept, the prevailing agro-climatic regimes in the country have been categorised by Ojanuga (2006) as follows:

#### *2.1.4.1 Humid zone*

Rainfall is greater than evaporation (or evapotranspiration) in 9 or more months of the year. Rainfall is about 1270 mm or more per annum with an even distribution and lowest mean monthly relative humidity is not less than 70%. Dry forest vegetation or wet savannah (northern Guinea savannah – NGS) is the indicator-vegetation. Perhumid (where mean annual rainfall (MAR) is about ≥2000 mm causing excessive leaching and so lower yields) and Very Humid (where MAR is between 1270 and 1500 mm inclusive indicating a strongly leaching environment) zones are more humid zones. Semi-deciduous forest or wet savannah (southern Guinea savannah) is the indicator-vegetation.

#### *2.1.4.2 Sub-humid zone*

This is an area of noticeable wet and dry seasons and with humid months ranging from 5 to 8 months, a MAR ranging between 1016 and 1300 mm, and rainfall greater than half of evaporation in the humid months. Moist savannah (NGS) is the indicator-vegetation. Dry sub-humid zone is a subdivision with a, relatively, more dry climate apparent with a MAR of between 508 and 1016 mm. Dry savannah (Sudan savannah) is the indicator-vegetation, and the zone is characterised by a short growing season. Semi-arid zone – rainfall is far less than evaporation (evapotranspiration), MAR is between 250 and 508 mm; and humid months are 3 to 4 months indicating a very short growing season and a non-leaching environment regarding soil. The indicator-vegetation here is Sahel savannah. Arid zone: a desert environment peculiar with < 250 mm MAR and humid months of 0 and 2 months. This is non-existent in Nigeria (Ojanuga, 2006).

Appendix I present the agro-ecological zones (AEZs) of Nigeria.

## 2.2 The Crop Groundnut

### 2.2.1 Groundnut origin, distribution, taxonomy and classification

Groundnut (*Arachis hypogaea* (L).), also variously known, in some places, as peanut, monkeynut, earthnut, and gobblernut, belongs to the *Fabaceae* family, a sub-family *Papilionaceae,* tribe *Aeschynomeneae* and sub-tribe *Stylosanthinae* (Savage and Keenan, 1994). This family also has soya beans (*Glycine max* (L.) Merr.), cowpea (*Vigna unguiculata* (L.) Walp) and pigeonpeas (*Cajanus cajan* (L.) Millsp.) as members. The *Arachis* genus is South American in origin, with an earliest archaeological record of cultivation from Peru. It was probably domesticated in the valley of the Paraguay and Parana rivers (Savage and Kenan, 1994). In the $16^{th}$ century, however, the Portuguese took them from Brazil to West Africa (Smith, 1995). The crop is now cultivated throughout the world (Norman *et al.,* 1995), especially in the tropical and sub-tropical countries lying between latitudes 45 $^{O}$N and 35 $^{O}$S and up to an altitude of 1000 m (Virmani and Singh, 1986). This comprises of about 100 countries in six continents under diverse agro-climatic conditions (Naidu *et al.,* 1999). This is on nearly 26.5 million hectares with a total production of 43.9 million tonnes and producti vity of 1654 kg $ha^{-1}$ in 2014 (FAO, 2017). The areas of greatest global production are China, India, USA and Africa. In the West African sub-region, Nigeria, Senegal, Ghana, Niger and Gambia are the leading producers (Smith, 1995; Pazderka *et al*., 2010). It is grown on various soil types, especially sandy-loam and loamy soils, and in a range of temperature regimes, from warm temperate to equatorial (Norman *et al.,* 1995; Raemaekers, 2001). Countries producing more than 500,000 t nuts-in-shell are shown in Appendix II, and all the major producers, except the USA, are tropical countries as indicated in Figure 2.2.1 (below). A high proportion of the production is, however, consumed in the producing countries, although in some countries, such groundnut products as nuts-in-shell, shelled nuts, oil, cake and meal are important export items.

Although groundnut export has declined in Africa (Norman *et al.,* 1995; Raemaekers, 2001), Nigeria is the world's third largest producer of groundnut and its oil after China and India followed by USA and some other countries (Figure 2.2.1). China and USA are the world's largest groundnut exporters while India is the major cake and meal exporter, although their exports are now reduced (Tiwari *et al*., 2018).

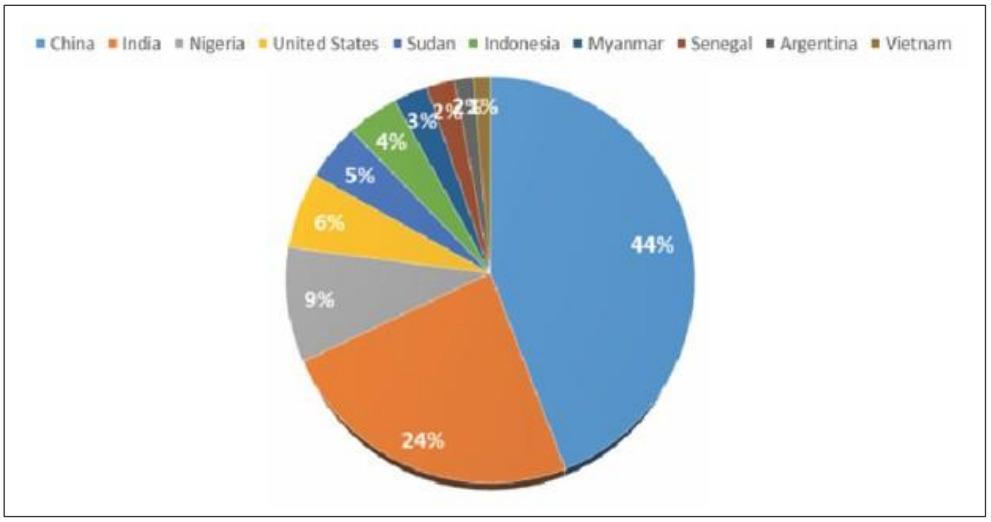



Figure 2.2.1: Top 10 groundnut producing countries of the world

Adapted from Ethical post (2017)

Groundnut production, and therefore its export, has considerably gone down in the last few decades, due to drought in 1972 and 1973, the destructive rosette virus disease of 1975 and 1976 and the neglect of agriculture due to crude oil discovery in the country (Echekwu, 2003; Othman, 2017; Vabi *et al*., 2019). Total production in Nigeria (and China) has, however, increased in the last few years due to increase in productivity per hectare (Echekwu, 2003; FAO, 2009). Production increases and productivity remained modest in other tropical countries, while it falls in some (FAO, 2009). Kano, Jigawa and Katsina states are the main producers in Nigeria, although most of the States in the country, especially the 19 in the North also produce the crop (Vabi *et al*., 2019). Production improved from 12%, in 2003, to 32%, in 2007, (Echekwu, 2003; ICRISAT, 2007). Around 65% of about 34 million tonnes per year of the crop's seed produced in more than 100 countries is crushed to extract groundnut oil and the rest used in making other edible products (ICRISAT, 2007).

Different ecotypes of groundnuts are cultivated under different conditions and for different markets in some geographical areas. In Sudan, for example, late-maturing types are grown under irrigation for export, whereas quick-maturing types are grown, by small-scale farmers, under rain-fed conditions, for local sale or subsistence. In the southern Guinea and derived savannah zones of West Africa, with extended rainfall, two rain-fed groundnut crops are usually grown sequentially in a year (Osunde *et al.*, 2003). In the northern Guinea savannah zone of West Africa, however, about 70% of the crop is grown in mixtures with two or more other crops, especially maize (*Zea mays*), sorghum (*sorghum bicolor*) and/or cowpea (*Vigna unguiculata*) (Pypers *et al.*, 2007). The crop (groundnut) is of four major cultivar groups, mainly distinguished by

branch length and branching habit. They are Spanish, Virginia, Valencia and Runner types.

The small Spanish types are grown, mainly, in South Africa and South-western and South-eastern USA. They are large-seeded, higher yielding, more disease resistant cultivars with higher oil content, compared to other varieties. Virginia types are also large-seeded, mainly grown in Virginia, North Carolina and Tennessee also in the US. They are increasingly becoming more popular due to demand for larger groundnuts for processing purposes. Valencia types are coarse with heavy reddish stems and foliage. They are grown on a small scale in Mexico, their best flavour makes them more preferred boiled groundnuts. Runner types are, on the other hand, found in Georgia, Alabama, Florida and South Carolina. These cultivars also have good flavour; and better roasting characteristics and are higher yielding compared to the Spanish types (Onwuema, 1979). Specific cultivar groups are preferred for particular uses because of differences in flavour, oil content, size, shape and disease resistance (Butterworth, 2004). Predominantly, however, two main growth forms of groundnuts are found in Nigeria, viz: bunch and runner types, which grow upright and near the ground, respectively. Othman *et al.* (2017), still, stated that both local and improved varieties of groundnuts are available in Nigeria, although the latter is usually most preferred for high pod, haulm and oil yields.

### 2.2.2 Taxonomy, anatomy, physiology, pests and diseases of groundnuts

#### *2.2.2.1 Taxonomy of the crop*

The genus *Arachis* was taxonomically described by Gregory and Gregory (1976), Gregory *et al*. (1980) and Smartt (1990). It includes 37 named species and some others not described. The groundnut, *Arachis hypogaea*, is within the section *Arachis*, one of the seven into which the genus has been divided. The section *Arachis* comprises annual and perennial diploid (2n = 2x = 20) and two annual tetraploids (2n = 4x = 40), one of which is the cultivated *A. hypogaea* (Norman *et al*., 1995). *Arachis hypogaea* is cross-compatible with all diploid species within the *Arachis* section, forming infertile or partially fertile triploids. The present candidates for this parentage are the quasi-annual *A. batizocol* and the perennial *A. cardenasii* (Norman *et al*., 1995). Numerous attempts have been made with a view to classifying genotypes within the species on the basis of

agronomic characters (Gregory *et al*., 1973) in vain, however, a grouping of Krapovickas (1973)'s is in vogue to date.

#### *2.2.2.2 Anatomy and physiology of the crop*

Groundnuts are classified as dicotyledonous that grow up to 30 - 50 cm in height with a well-developed tap-rooting system with numerous lateral roots (Onwuema, 1979). Root nodules are present on both the tap and lateral roots. Their leaves are opposite, pinnate with four leaflets (two opposite pairs with no terminal leaflets). Their typical leguminous flower structure has five united sepals and five yellow petals that arise in the leaf axles at the base of the stem (Savage and Keenan, 1994). 'Pegging' starts immediately following fertilisation of the crop. This is achieved when the region behind the ovary begins to elongate, to up to 6 cm long; and geotropically grow into the soil. The peg tip matures, in the soil, into an indehiscent pod. Depending on the genotype, the pod may contain one to four or more seeds each covered with a reddish brown, papery membrane as the seed coat. Each seed has two massive cotyledons covered by a thin seed coat without an endosperm. The groundnut fruit is an indehiscent legume (*i.e.* a pod without statures or split open freely). It is made up of 40 chromosomes genome called an allotetrapoid, which means 'from two different species' (Stalker and Moss, 1987).

#### *2.2.2.3 Pests and diseases of the crop*

The occurrence of an unprecedented rosette epidemic in 1975, which followed an outbreak of the viruliferous aphid vector are the major cause of low groundnut production in Nigeria (Ajeigbe *et al*., 2015). This attack averaged 50 – 100% in the main groundnut growing areas of the northern Guinea and Sudan savannahs and caused considerable yield losses which amounted to about 55 – 70% of the expected production. This resulted in a substantial decrease in the overall output of groundnut in the country. Examples of other diseases that affect, and can do a great deal of damage in, groundnut, are leaf spots. They are reported to cause losses of up to 50% in West Africa. Many other seedling diseases are also very common in groundnuts and can do a great deal of damage (Smith *et al*., 1992).

#### *2.2.2.4 Socioeconomic importance of groundnuts*

Groundnut is cultivated mainly in semi-arid tropical and sub-tropical regions of many countries in six continents (Naidu *et al*., 1999). This translates the crop into a, socio-economically, global significance. Groundnut is the world's 13$^{th}$ most important food crop, 6$^{th}$ most important source of edible oil, of about 51%, and the 3$^{rd}$ most important source of vegetable protein, contributing about 22 - 30%. It is also a good source of such minerals as phosphorus (P), calcium (Ca), magnesium (Mg) and potassium (K), as well as vitamins E, K and B (Olorunju *et al*., 1999; Mukhtar, 2009). The groundnut seeds contain 24 - 34% protein and 47 - 50% oil (FAO, 1997). All parts of the plant can be used. It is grown primarily for human consumption but has several other uses as whole seeds or as processed in the form of groundnut oil, butter and other products. One pound of groundnuts provides about the same energy value as 2 pounds of beef, 1.5 pounds of cheddar cheese, 9 pints of milk, or 36 medium-sized eggs (Woodroof, 1983), hence high in food energy. Non-edible products such as lubricants, cosmetics and soaps can also be made from groundnuts, as can medicines also be. The vines with leaves are rated excellent in terms of the high protein hay they provide for horses and ruminants. The pods or shells are also used as high fibre roughage in livestock feed, mulch, fuel and are also used in the manufacture of particle board or fertilisers. *Arachis hypogaea* is, therefore, an important household crop for consumption and/or sell to both rural and urban populations. Groundnut cake, made from straw and stems, is used in many countries as livestock feed (Smatt, 1994).

As a legume, groundnut, improves soil fertility by fixing $N_2$ and hence it contributes to food security of smallholder semi-arid farmers through their legume-cereal inter-cropping systems. This further makes the crop important in sub-Saharan Africa (Smatt, 1994). The crop requires few inputs, which makes it appropriate for production in low-input agricultural systems by the smallholder farmers who are mostly engaged in subsistent agriculture (Naidu *et al*., 1999).

#### *2.2.2.5 Role of groundnuts in biological nitrogen fixation*

Groundnut, like its other leguminous counterparts, has the ability of biologically fixing atmospheric nitrogen ($N_2$) into the soil. This process enriches the soil N fertility and, hence, benefits especially succeeding crops. This enumerates the crop as an important component of tropical intercropping systems. High and stable productivity of groundnut

is, therefore, an essential element in improving efficient cropping and/or farming systems in the semi-arid tropics of the globe. Process of the biological nitrogen fixation (BNF) by the groundnut is made through the root nodules, but requires a tremendous quantity of P (Mortimore *et al*., 1997) being a general precursor for plant growth and adenosine triphosphate (ATP) synthesis. Phosphorus has, therefore, been especially identified to be the most essentially critical nutrient for almost all legumes (Lekberg and Koide, 2005b).

#### *2.2.2.6 Groundnut production in Nigeria*

Nigeria is rated as the largest groundnut producer in West and Central Africa, thereby accounting for up to 51% of the total region's production (Ndjeunga and Ibro, 2010; Ajeigbe *et al*., 2015). Nigeria was, in 2012, ranked as the 11$^{th}$ world's largest groundnut producer, producing 3.071 million tonnes; and 5$^{th}$ by value, which was, estimated at 130 million USD (FAOSTAT, 2015). The country has earlier been reported, by FAOSTAT (2013), to be producing 7% and 29% of the World's and Africa's total production, respectively. Recent estimates, however, indicate an estimated 3.55% contribution of groundnut to the GDP of Nigeria (NAERLS/NBS, 2013). Most recently, however, it was reported that Nigeria is rated the world's 3$^{rd}$ groundnut producing country, producing 3.4 MT, after China (15.7 MT) and India that is at 6.5 MT (Vabi *et al*., 2019). Groundnut is an all important component of the farming systems, as cash earning crop and source of employment for smallholder farmers (Ndjeunga *et al*., 2013). Haulm of the crop is also a very important source of feed for livestocks, especially during the dry season. Also, many large and medium scale oil mills abound in the main cities of Northern Nigeria such as Kano, Kaduna, Katsina, Zaria, Bauchi and Jos (Ajeigbe *et al*., 2015). There is an all-year-round demand for groundnut grains, implying that the smallholder farmers could, comfortably, increase their production capacities without being vulnerable to seasonal and/or market glut threats. Ndjeunga and Ibro (2010) reported that the annual demand for the crop at well over 3.7 million tonnes, and which is expected to increase by 8.2% every year.

In spite of these potentials, the productivity of this crop is low, with a yield of about 1.2 t ha$^{-1}$ on average, when compared to USA (1.5 t ha$^{-1}$) and China (> 3.0 t ha$^{-1}$). This low yield is attributable to biotic and abiotic stresses; and other socio-economic factors. Contamination of groundnut and its products by aflatoxin, not only limits the export

potentials but also, have health repercussions among resource-poor consumers. Prior to the 1980s, groundnut production significantly declined due to rosette virus disease and recurrent droughts (Ajeigbe *et al*., 2015). However, production has been increasing at an annual growth rate estimated at 8% since 1984. This was due to production area expansion of 6% and productivity increase of 2% (Echekwu, 2003; Ndjeunga and Ibro, 2010). Groundnut production is highly labour intensive. This, coupled with low rate of seed multiplication, limits the rate at which production can be enhanced. Appropriate mechanised farm-level agronomic practices (*e.g.* planting, weeding and lifting/harvest) and post-harvest (*e.g.* stripping, decortications and small scale oil processing) activities are highly desirable to increase production and productivities (Ndjeunga and Ibro, 2010).

This necessitated for the urgent need for developing groundnut varieties that are not only adaptable to different agro-ecologies but which also considers market preferences, especialy high oil content and quality haulms. The main agro-ecological zones more conducive for groundnut production in Nigeria are the Sahel, Sudan, northern Guinea, most parts of southern Guinea and the derived Savannahs. The crop is produced in at least 15 States namely: Kano, Katsina, Kaduna, Jigawa, Sokoto, Zamfara, Kebbi, Adamawa, Bauchi, Yobe, Taraba, Borno Benue, Plateau, Nasarawa, FCT Abuja, Kogi, Niger and Kwara (FAOSTAT, 2015).

### 2.3 Phosphorus

The term phosphorus (P), although used as a general term when a particular chemical P form is not being designated, refers to the element. The total P content of a soil or plant material, for example, is usually expressed as a percent P. However, fertiliser analyses are usually reported as a percent $P_2O_5$ (*i.e.* the phosphate or oxide form). The phosphate form ($P_2O_5$) is a chemical produced during fertiliser analysis but does not exist in either fertilisers or soils (Busman, *et al*., 2008). Phosphorous is one of the nutrients whose availability is very limited for plant growth in calcareous soils where most of the P applied is fixed with a very low recovery rate. It is the second most important macronutrient, second only to nitrogen (Vance *et al.*, 2000), that is crucial for the stability and continued existence of life. It is often the most limiting nutrient for crop and forage production. Phosphorus' primary role in a plant is to store and transfer

energy that is produced via photosynthesis for use in processes of growth and production (Panhwar *et al.,* 2011).

An adequate P level also enhances root growth, stimulates tillering/branching and early flowering; and hastens maturity (USDA Natural Resource Conservation Service, 2014) and general plant growth (Panhwar *et al.,* 2011). It is also important for many other functions like metabolic activities, especially synthesis of protein (Panhwar *et al.,* 2011). It is an integral component of adenosine triphosphate (ATP) and adenosine diphosphate (ADP) molecules, phospholipids and nucleic acids, which are significant in cellular membranes, and provide necessary compounds to plants and animals for photosynthesis and respiration, respectively. Many elementary and principal roles of P exist in various plant physiological processes, including utilisation of sugar and starch and energy transfer. Aside this vital metabolic role, P is still an indispensable structural component of numerous molecules, like the aforementioned nucleic acids, which are the building blocks of genes and chromosomes in the cell nucleus (Rai *et al.,* 2013). Studies have indicated that, at the same *pH* level, soils with higher clay content have higher P fixing capacity when compared with soils more in sand (Warren, 1994; Bainbridge *et al*., 1995) and that organic matter contributes to the availability of P in soils (Haynes, 1984; Owusu-Bennoah and Acquaye, 1989).

In a study conducted, in north-east France, to evaluate the soils' phosphate fixing capacity by isotopic exchange techniques, it was found that there was a significant correlation between amount of P fixed, *pH*, exchangeable cations, clay content and soluble phosphate (Morel *et al*., 1989). Similarly, Owusu-Bennoah and Acquaye (1989) also studied the characteristics of phosphate sorption of some soils in Ghana and found that the sorption maxima were highly correlated with the soil properties in the order of: $Al_2O_3$> clay content > free $Fe_2O_3$> organic C. Plant available P soil tests are globally used in the determination of soils' current P status so as to estimate fertiliser P requirements for specifically aimed yields. A normal soil P management approach is to (i) determine the exact soil 'available' P level using a defined soil test extractant, and (ii) compute the soil P deficit from the difference between a known critical level applicable to that particular crop (which is established by means of field trial calibration studies) against the actual available P level obtained from soil P-test. This deficit is then converted into a mass of nutrient required per unit area by multiplying same with a

conversion factor that reflects the soil properties responsible for the P sorption and the depth of incorporation of the fertiliser P (*i.e.*, the P requirement factor (PRF). Thus:

$$Field\ P\ requirement\ (kg/ha) = (optimum\ soil\ P - measured\ soil\ P)\ \ x\ PRF\ \ldots.(eqn.\ 1.1)$$

The PRF is, therefore, defined as a soil specific factor which represents the amount of P required per hectare for a unit increase in P rate for a particular soil test and allows for the effect of P fixation on the recovery of added P (Johnston *et al*., 1991; Henry and Smith, 2004). For a given soil P-test, therefore, PRF has been shown to vary widely across different soils due to differences in the ability of different soils to sorb P (Henry and Smith, 2004). Determination of the PRF for a particular soil is, however, laborious because it involves: (i) a 6-week incubation experiment (with alternated cycles of wetting and drying designed to stimulate the fate of added P under field conditions) of soils with additional P in incremental rates to induce P fixation, followed by (ii) the extraction of P (using approved extraction methods) from the soil solution, and (iii) plotting the amount of P recovered in the extraction solution versus added P (Johnston *et al.*, 1991; Henry and Smith, 2004). This relationship generally gives a linear regression function, the inverse of the slope of which is the PRF for the particular soil. For a given soil P-test, PRF has been shown to be a characteristic that varies widely across different soils. Johnston *et al*. (1991), in a study, found that the range in PRF values varied amongst soils and extraction methods. They also observed that the level of P sorption was strongly related to clay content and 2:1 clay minerals (Poswa, 2016).

### 2.3.1 Phosphorus deficiency

Phosphorus deficiency may be confused with that of N. However, P deficiency is a plant disorder associated with an insufficient supply of the element P. In this context, P refers to salt of phosphates: monohydrogen phosphate ($HPO_4^{2-}$) and dihydrogen phosphate ($H_2PO_4^-$). These anions readily interconvert, and the predominant species is determined by the *pH* of the solution or soil. Phosphates are required for the biosynthesis of genetic material as well as ATP, which is essential for life. Its deficiency symptoms include poor growth, and leaves that turn blue/green but not yellow. The oldest leaves are affected first. The deficiency can be corrected by application of P-based fertilisers (Heinrich, 2000). Amongst the major factors

constraining reliable soil fertility and sustainable agriculture in the tropics are low reserves inherent nutrients, high P fixation, erosion, moisture stress problems, low soil biodiversity and high acidity with aluminium toxicity (Cardoso and Kuyper, 2006). Many soils of the tropics are, therefore, fragile which limits their food production efficiency.

Generally, nutrition is a vital component of plant health. A nutrient deficiency is a physiological disorder caused by shortage of that plant nutrient (Mengel and Kirkby, 2001). A nutrient deficiency will, therefore, reduce a plant's capacity to complete its life cycle (of *e.g.* flowering and fruiting). Such nutrients as N, P, K and Mg are easily translocated within the plant and are referred to as "mobile". Other nutrients, like Fe, Zn, Ca and B, are immobile and are not moved around the plant. Symptoms here generally occur on the growing tips. Mobility of Mn is rather complex, depending on the plant species and age. The Mn deficiency can appear on old or new leaves. Plants can also suffer from nutrient toxicity if an excess nutrient is applied (Castalanelli and Mcpharlin, 2009).

## 2.4 Phosphorus in the Savannah Soils

The soils of the savannah are generally low in fertility (Vanlauwe *et al.,* 2002), and are to a large extent, highly weathered, coarse-textured, and low in organic matter content and cation exchange capacity (CEC). The CEC can be as low as 1 to 5 $cmol_c\ kg^{-1}$ (Agbenin, 1996). They are also generally slightly acidic and poorly buffered in terms of most nutrients (Jones and Wild, 1975). Their total P is generally low (13 - 630 mg $kg^{-1}$). A range of about 100 to 400 mg $kg^{-1}$ in some savannah soils has, however, been reported by Mokwunye (1979). Less than 10 percent, of these amounts, is said to be inactive/labile Al-P, Fe-P and Ca-P forms (Uyovbisere, 1979). A pronounced P deficiency is the result of this low level of available P. This deficiency affects an area estimated at over $2 \times 10^9$ hectares (Fairhust *et al.,* 1999), in almost all crops and its effect on declining crop production (Nto, 1995). Only moderate amounts of P are required to defeat such P deficiencies and effectively satisfy crop needs in the savannah soils (Agboola and Obigbesan, 1974; Uyovbisere and Lombin, 1991). When a soil possesses high initial P contents: (i) amount of fertiliser P to be applied will be reduced, and (ii) the P in the soil could be more judiciously utilised (Nto, 1995).

Phosphorus is turned unavailable as it rapidly forms insoluble complexes with cations and is incorporated into organic matter by microorganisms. The acid-weathered soils of the tropics and sub-tropics are particularly prone to P deficiency and aluminium (Al) toxicity (Brady and Weil, 2002). In intensive agricultural systems, a grain crop yield of 7 metric tonnes per hectare requires an addition of 90 to 120 kg P $ha^{-1}$ (Bumb and Baanante, 1996). Even under adequate fertilisation, only about 20 percent or less of that is applied is removed by the first year's growth. This, therefore, results in P loading of prime agricultural land.

Estimates of rock phosphate (RP) reserves, that are naturally cheaper, could also be depleted in as little as 60 to 80 years (Council for Agricultural Science and Technology, 1988; Hooda *et al.,* 2001). Phosphorus has also been found to be the most critical nutrient for legumes; however, responses with these crops are usually obtained at low levels of application (Heathcote, 1973).

### 2.4.1 Phosphorus status of Nigerian soils

In soils of the Nigerian savannah, widespread P deficiency has variously been reported (Enwezor and Moore, 1966; Jones and Wild, 1975; Uzu *et al*., 1975; Udo and Ogunwale, 1986). Goldworthy and Heathcote (1963) and Enwezor and Moore (1966) reported the total P content of surface savannah soils to ranges from 80 - 150 mg $kg^{-1}$. Jones and Wild (1975) reported the total P content to have ranged between 13 - 630 mg $kg^{-1}$, with means of 143 mg $kg^{-1}$ in 334 top soil samples from the savannah. These low values of P suggested a widespread P-deficiency in the region as indicated by Jibrin (1995).

## 2.5 Forms of Soil Phosphorus

Although different forms of P may exist in soils, in practical terms, it can, however, be thought to exist in soils in "pools", as thus: solution P pool (SPP), active P pool (APP) and fixed P pool (FPP). The SPP is very small and hence usually contains only a small fraction of a weight of P per hactare, usually in the orthophosphate form, although small amounts of organic P may still also exist. The plants can only take their P in the orthophosphate form. This pool is important as it is the pool from which plants take P on one hand, and it is the only pool that has any measurable mobility on the other (Busman, *et al*., 2008). The APP is P in the solid phase which can, relatively, easily be

released into the soil solution, thereby replenishing the phosphate depleted from the SPP by the crops thereby making the soil phosphate-fertile. The FPP contains inorganic phosphate compounds, that are very insoluble, and organic compounds, that are resistant to mineralisation by microorganisms, in the soil. Phosphate in this pool may remain in soils for years without being made plant-available and therefore have a very negligible impact on the fertility of the soils. Although the inorganic phosphate compounds in the FPP are more crystalline in structure and therefore less soluble than those in the APP, some slow conversion between the two pools still occurs in the soils as reported by Busman *et al*. (2008).

Phosphate reactions, and its movement rate, are expected to differ with soil types that occur from differing parent materials. This is likely attributable to the relative abundance of Fe- and Al-oxides and oxyhydroxides contents of the soils. These compounds are known for strongly fixing soil P, and thereby limiting its availability to plants (Barrow *et al.*, 2020; Nakayama *et al.*, 2021). The most common parent material rocks mostly available in the savannah agro-ecologies of Nigeria include basalt, basement complex, sandstones and shale. Soils derived from such parent materials may share some of such common characteristics as kaolinite-dominated colloidal fractions, considerable Fe- and Al-oxides content and deposits of aeolian (*e.g.* harmattan) dust. Rainfall, vegetation and temperature fluctuations from the northern to southern latitudes, however, drastically impart diversity in their various responses and potentials. Therefore, phosphate reactions, and so its management, are expected to differ in such highly diverse soil types as observed by Buehler (2002).

Phosphorus reactions are summarised by phosphate sorption/desorption processes, which control the soil P availability. Among the factors that influence these reactions are: soil reaction (*pH*), soil solution P concentration, temperature, reaction contact period, clay content, free Fe- and Al-oxide contents, organic matter, redox potential, soil mineralogy (parent material), ionic strength of soil solution and surface area. The use of extracting chemicals, phosphate fractionation and adsorption isotherms have been used as indices for evaluating soil P availability. Classical adsorption models, of Langmuir, Freundlich and Temkin, have been regularly utilised with commendable success in soil P reactions studies and quantification of soils' P requirements Nakayama *et al*., 2021). The chemical extractants are, therefore, assumed to simulate the absorbing functions of

plant root. Therefore, a successful extractant should define a concise phosphate pool that would correlate with plant needs, and provide predictive indices for P management (Hedley *et al*., 1982a). This will give way to better understand the diverse nature of the studied Alfisols in the Sudan and northern Guinea Savannah agro-ecological zones in terms of their phosphate availabilities and/or otherwise.

### 2.5.1 Forms of available-P

The forms of residual fertiliser P in soil can be studied using the modified Hedley's sequential extraction procedure (Hedley *et al*. 1982b) or a procedure of Chang and Jackson (1958), with some modifications by Chang (1962) and Peterson and Corey (1966), among others. All the procedures fractionate the soil P into the various P forms, starting with the labile P to the more stable P forms. These methods have been used to study changes in P forms in slightly weathered soils (Chang and Jackson, 1958; Chang, 1962; Peterson and Corey, 1966; Hedley *et al*., 1982b; Tiessen *et al*., 1983; Richards *et al*., 1995) to highly weathered soils (Beck and Sanchez, 1994; Schmidt *et al*., 1996). Amidst soil P fractions, the water and bicarbonate extractable P can be related to the plant available P, while the hydroxide and acid extractable P fractions are considered as sparingly available for plant uptake. Past studies also suggested that the acid-extractable P could be an important source of P replenishment subsequent to the dissolution of Ca-P compounds, thereby, adding to the labile P pools over a long period of time (Vu *et al*., 2008; Saleem *et al*., 2017).

The fertiliser P can also variously exist as labile-, non-labile- or residual-P (Saleem *et al*., 2017). The labile and non-labile pools consist in part, of inorganic phosphate that is adsorbed to soil surfaces or precipitated in increasing quantities as the amount of phosphate in solution increases. The adsorbed phosphate ions are held on active sites on the soil surfaces. In alkaline ($pH > 7$) soils, Ca is the dominant cation that reacts with phosphate to form precipitates such as dicalcium phosphate dihydrate ($CaHPO_4.2H_2O$), octacalcium phosphate ($Ca_8H_2(PO_4)_6.5H_2O$) (also OCP), and hydroxyapatite [$(Ca_5(PO_4)_3(OH)$]. Wagar *et al*. (1986) reported that OCP, a fertiliser P reaction product, has been shown to slowly react and remain moderately available in calcareous soils for a long period. In contrast, however, in acidic ($pH < 5.5$) soils, Fe and Al are the dominant ions that react with phosphate to form amorphous Fe and Al phosphates. These (amorphous Fe and Al phosphates) slowly change into crystalline strengite (Fe-

$PO_4$) and variscite (Al-$PO_4$) compounds. These processes cause a decrease in solubility and availability of phosphate to plants, thereby adding to the non-labile soil P fractions (NaOH-P and HCl-P). This is through fertilisation that increases the amount of remaining P, as the crop will not utilise most of the P fertiliser applied to the soil in the first season. The residual P fraction consists of, sparingly soluble, inorganic phosphate compounds and organic compounds, that are microbially resistant to mineralisation in the soil. Continuous application of more P than crop removal increases phosphate in this pool, which may remain in soils for years without being made available to plants (Busman *et al*., 2009).

Mineral soils contain 50 to 70% of their total P in inorganic forms, majorly as compounds of Ca, Al and Fe, depending on the soil *pH* and weathering stage (Pierzynski *et al.,* 2005). In less or moderately weathered calcareous soils, different forms of apatite minerals are found. In highly weathered acidic soils, however, variscite and strengite are the most common phosphate minerals as Ca and other basic minerals are leached, which results in Fe and Al dissolving with a decrease in *pH* (Pierzynski *et al.,* 2005; Hariprasad and Niranjana, 2008). In neutral and calcareous soils, Ca phosphates are found as films or discrete particles whereas inorganic P either precipitates as Fe- and Al- phosphate secondary minerals and/or is adsorbed to surfaces of Fe/Al oxides and clay or silt surfaces in acidic soils (Havlin *et al.,* 2005). Meyer *et al*. (2011) had cited Heck (1934) as dividing mineral soil P reserves into three fractions, based on their availability to the plant as: (i) readily available - water soluble $(H_2PO_4)^-$ and $(HPO_4)^{2-}$ anions from $Ca(H_2PO_4)^-2.H_2O$; (ii) slowly available ($AlPO_4$); and (iii) very slowly available reserves $Ca_3(PO_4)^2$ and $FePO_4$ (Poswa, 2016).

### 2.5.2 Transformation of P added to soils

Treating mined phosphate rock with acid to aid its solubility led to the majority of phosphate fertilisers produced. When phosphate fertilisers come in contact with the soil, they are initially quite soluble and available until the occurrence of different reactions that reduce the P solubility and availability. These reactions are controlled by such soil factors as *pH*, temperature, moisture content and soil minerals present. Phosphate fertilisers begin to dissolve when in contact with the soil moisture, and there is a slow movement of phosphate ions in solution away from the fertiliser particles. The phosphate ions are mainly adsorbed on surfaces of soil particles or can be precipitated

by soil cations like Ca, Al, Mg and Fe. The adsorbed phosphate gradually forms more insoluble compounds over time thereby causing the phosphate to become fixed and hence unavailable (Busman *et al*., 2002).

On calcareous soils, long-term application of fertiliser above P removal by crops increases both the labile ($H_2O$-P and $NaHCO_3$-P) and non-labile P (NaOH-P and HCl-P) forms as well as residual P (Vu *et al*., 2008). Previous findings also reported increase in these P pools after a long-term application of P fertilisers in other soil types (McKenzie and Bremer, 2003; Tiessen and Moir 1993; Linquist *et al*., 1997). It has also been found that a long-term application of cattle manure increases the $P_i$ forms in the labile, moderately labile and total soil P content (MnKeni and McKenzie 1985; Dormaar and Chang 1995; Tran and N'dayegamiye 1995). Addition of fertilisers, either annually at high rates or with accumulated time was found by Zhang *et al*. (2004) to increase NaOH-$P_i$ at a rate of 6.9 mg P $kg^{-1}$ $yr^{-1}$ and 34.3 mg P $kg^{-1}$ $yr^{-1}$ during the first 6 years and the following 4 years respectively. They also found that increased fertiliser addition linearly increased $NaHCO_3$-$P_i$ at a rate of 15.7 mg P $kg^{-1}$ $yr^{-1}$ and 18.1 mg P $kg^{-1}$ $yr^{-1}$ for the first 6 years and the following 4 years. The great rate of increase during the later part of the study was attributed in $NaHCO_3$-P and NaOH-P fractions to the saturation of the sorption sites on the soil particles. Kashem *et al*. (2004) also reported that an increase in the application rate of P fertiliser to the soil in a laboratory incubation study resulted in a commensurate increase of the $NaHCO_3$-P fraction, which indicates the short-term effect of P addition. An increase in labile P fraction indicates that as the capacity of soil to retain added P in stable fractions decreases, so does the strength of retention, which can lead to increased risk of P losses to surface waters.

Vu *et al*. (2008) found that long-term application of P fertiliser resulted in increases in the inorganic fractions of $H_2O^-$, $NaHCO_3^-$, $NaOH^-$, HCl-P as well as the residual P. Significant increase in the residual P fraction suggested that the applied P was increasingly precipitated at higher rates of P application. This was consistent with the findings of Bertrand *et al*. (2003) that the applied P was mainly precipitated in highly calcareous soils in South Australia but was dissolved by $NaHCO_3$ extractant. According to Qian *et al*. (2004), repeated addition of manure, in black chernozemic soil, resulted in a significant increase in labile inorganic P, which accounted for 15% of the total soil P. The P forms that were loosely sorbed on the soil surface relate to the labile inorganic P,

resin-P and $NaHCO_3$-$P_i$ (Chauhan *et al*., 1981) and $NaHCO_3$-$P_o$ corresponded to the easily mineralisable organic P (Bowman and Cole, 1978). The moderately labile P (NaOH-P fraction) can replenish the soil labile P for plant uptake when the labile P pool is diminished (Tiessen *et al*., 1984; Ivarsson, 1990). It was also reported that soil NaOH-$P_i$ is held strongly by chemisorption to Fe and Al components of soil surfaces which is considered as moderately labile soil P as variously reported by Ryden *et al*. (1977) and McLaughlin *et al*. (1977). Addition and depletion of P fertiliser has no significant effect on HCl-$P_i$, moderately stable fraction (Zhang *et al*., 2004). It has been suggested that HCl-$P_i$ represents apatite, the primary mineral P, and it is not readily available to plants (Williams *et al*., 1980). In a long-term winter wheat experiment carried out on a calcareous soil, path coefficients showed that octa-calcium phosphate ($Ca_8$-P), a labile P pool, accumulated due to the transformation from other fractions ($Ca_2$-P and Al-P) after continuous inorganic fertiliser application, thereby contributing to soil available P (Wang *et al*., 2010). Shen *et al*. (2004, 2011) found that labile P ($Ca_2$-P, $Ca_8$-P and Al-P) could be readily fixed into non-labile P (Fe-P, reductant soluble (Occluded) -P and $Ca_{10}$-P) due to its association with hydrous Fe oxides and calcareous compounds in calcareous soils. Path analysis technique suggests that transformation between P fractions is dependent on the nutrient sources, soil developmental stage, management systems and soil properties (Zheng et al., 2002; Tiessen *et al*., 1984). Zheng *et al*. (2002) reported that 86% of the resin-P originated from inorganic P fertiliser addition but in the dairy manure system, added organic P was transformed into NaOH-$P_o$ and $NaHCO_3$-$P_o$. Thus, moderately labile NaOH-$P_o$ acted as the source of labile $NaHCO_3$-$P_o$ and Pi in this system. This shows that the labile $P_i$ pools resulted from the mineralisation of the moderately labile NaOH-$P_o$ pool. Therefore, transformations of P fractions are dependent on factors like P uptake by plants, soil microbial activities, root exudation, and other rhizosphere processes (Negassa and Leinweber, 2009).

In order to regulate P concentration in agricultural soils and reduce P losses to the environment, the climatic conditions, soil type, soil test P method used, as well as the rate of fertiliser P applied to soil has to be taken into consideration. Soil phosphorus (Olsen-P) test values of 0 - 5, 5 - 10, 10 - 15, 15 - 20, 20 and above 20 mg $kg^{-1}$ has been rated in Manitoba as very agronomically low, low, medium, high, very high and very high plus, respectively (MAFRI, 2007). These soil test values go together with the

recommended fertiliser placement rates either as seed-placed, side banded, banded or broadcasted for each crop type. Knowing the rate at which soil test P values change with fertiliser surpluses and deficits for each soil type will be valuable for P management by farmers. Therefore, there's need to determine the method for estimating changes in soil test P values with fertiliser addition or depletion on several soils (Obikoya, 2016).

### 2.5.3 Reaction of P fertiliser with soil

The reaction between phosphate and soil is one of the most frequently studied subjects in soil science (Barrow, 1983, 1985). One of the reasons being the widespread occurrence of phosphate deficiency and another is the complex nature of the problem (Barrow *et al.*, 2020). Sorption and precipitation are the major reactions of phosphate in soils, with the former occurring at low concentration of phosphate and the latter dominating at high concentrations (Barrow, 1985). Most of the P retained during these two processes is considered to be unavailable to plants in the short term (He *et al.*, 1991). The phenomenon whereby P is made unavailable to plants is termed "fixation".

### 2.5.4 Role of phosphorus in plant nutrition

Crop yield of 40 percent of the world's arable land is limited by P availability (Von Uexküll and Mutert, 1995). This second most limiting element for plant growth (Vance *et al.*, 2000) is also one of the several elements which affect $N_2$–fixation. Along with N, it is also a principal yield-limiting nutrient in many regions of the world (Pereira and Bliss, 1989). Phosphorus has been termed "the key to life", as it is directly involved in most life processes (Ayodele, 1986). As one of the three primary fertiliser elements, P is needed by plants for the synthesis of such organic P compounds as enzymes, nucleic acids and phospholipids, which are essential to the synthesis of proteins, carbohydrates and lipids. Organic phosphates include adenosine di- and tri-phosphate (ADP and ATP); and sugar phosphates which play a vital role in the metabolic process (Marschner, 1990). The amount of P in plants ranges from 0.05 percent to 0.3 percent of total dry weight. The concentration gradient from the soil solution to the plant cell exceeds 2,000-fold, with an average free P of 1 µM in the soil solution (Ragothama, 1999). This concentration is well below the $K_m$ for plant uptake. Thus, although bound P is quite abundant in many soils, it is largely unavailable for uptake (Giller, 2001).

### 2.5.5 Phosphorus and legume nutrition

Amongst the obvious outcomes of legume $N_2$ fixation are increased amounts of plant protein and a reduced depletion of soil N reserves. A deficiency in mineral N usually limits plant growth, thereby evolving a symbiotic relationship between plants and various $N_2$-fixing organisms (Freiberg *et al.*, 1997). At present, legumes are majorly grown as food and/or feeds (Lekberg and Koide, 2005a); their capacity to improve soil N fertility may, however, be distorted by low soil P (Buresh *et al*., 1997). A good nodulation/specific nodulation activity, and hence high rate of $N_2$-fixation, requires large amounts of P (Jakobsen, 1985; Giller, 2001). Nodules, as strong sinks for P, range from 0.72 to 1.2% in P content as reported by Hart (1989a, b). Nodule formation in such legumes as groundnuts is highly related to available soil P in many soils. This also contributes in increasing shoot N content, which further explains the importance of P in $N_2$-fixation (Ogoke *et al*., 2005). Also, experiments by Abbas *et al.* (1993) and Chien *et al*. (1993) have indicated a tremendous increase in $N_2$-fixation of legumes after applying P fertiliser to P-deficient soils. Almendras and Bottomley (1987) observed an acidic soil that received P, as $KH_2PO_4$ at 25 mg P $kg^{-1}$ soil, to significantly increase percent nodule occupancy of *Trifolium subterranean* by *Rhizobium leguminosaerium* Vv. Trifoli.

Nitrogenase activity (*i.e.* nodulation and consequent $N_2$-fixation) of *Trifolium* v*esiculosum* was significantly increased after an addition of P (at 100 mg $kg^{-1}$ soil) and K (at 3 mg $kg^{-1}$ soil); also, its activity was doubled after the P concentration was raised to 400 mg $kg^{-1}$ soil as reported by Lynd *et al*. (1984). An application of 20 and 40 mg $kg^{-1}$ phosphate improved growth and nodulation of chickpea (*Cicer arietinum*) in the presence of $Zn^{2+}$, at 5 mg $kg^{-1}$ and at 2 levels (4.34 and 8.3 dS $m^{-1}$) of salinity as reported by Saxena and Rewari (1991). Differences were observed between cultivars of some legume species, with regards to P requirements, as reported by Buresh *et al*. (1989).

### 2.5.6 Factors affecting P nutrition of legumes

As nodulating plants, legumes usually have lesser developed root systems than their non-nodulated counterparts. Their capacity for capturing nutrients, especially P is, therefore, highly decreased (Haque *et al.*, 1986). As such, most legumes heavily depend on mycorrhizas for efficient uptake of less mobile nutrients in the soil, including P. This is achieved by increasing the soil volume that can effectively be explored by the plants

(Giller and Wilson, 1991). Some trees and shrubs; and most herbaceous legumes are therefore infected by arbuscular mycorrhizas (AM). Other woody legumes form ectomycorrhizas, which are the most frequently acquired mycorrhizal associations consequent to multiple independent gains and some losses of mutualism (Tedersoo and Brundrett, 2017). Alexander (1989) observed that some species are capable of forming both AM and ectomycorrhizas. The efficiency and dependence of legumes on the AM for capturing and utilising P are partly dictated by root geometry/system of legumes, which are sometimes poorly-branched and less root haired.

### 2.5.7 Phosphorus-affected nitrogen cycle

Nitrogen has the most complex nutrient cycle among all the mineral nutrients. This is largely as N can exist as gas (both ammonia and nitrogen), whereas the other thirteen mineral nutrients do not exist, under normal soil circumstances, as gas (Jones and Jacobsen, 2005a). The N cycle interacts with carbon (C), sulphur (S) and P cycles. In their summary on the effects of P on N cycle, Cole and Heil (1981) have stressed that only biologically active P controls the N cycle and not the total P. They, therefore, further concluded that in terrestrial systems, microbial growth processes are the main points at which N cycling is adjusted to the P supply. Nitrogen cycling processes being affected by P may, therefore, according to them (Cole and Heil, 1981), be itemised as thus:

i. Multiplication and activity of Rhizobium
ii. Root infection and growth of nodules
iii. $N_2$-fixation and other biochemical processes within the plant
iv. Blue-green algal proliferation and influence on rice in paddy soils
v. Initial colonisation by $N_2$-fixing lichens
vi. Nitrogen mineralisation rate in some Andepts
vii. Nitrification in some soils
viii. The decomposition rate of organic N in systems where microbial death is an important return mechanism for available P.

### 2.5.8 Soil factors affecting P availability

Soils that fix large quantities of P are: Alfisols, Andepts, Inceptisols, Oxisols and Ultisols. Total and available P decrease with depth and the available P content of surface soils does not seem to be adequate for optimum crop production in most soil profiles. In acid soils, most of the P applied is sorbed by various constituents and P

sorption accelerates with soil depth within the profile due to increase in sesquioxides and clay contents. Soil erosion is also a serious catastrophe (El-Swaify and Dangler, 1982). If the surface soil is eroded, however, the optimum P requirement for plant growth, on most of these soils, would increase (Haque *et al.*, 1986). Such various soil properties as physical, chemical and biological, affect the P availability in soils in their various ways. Soil physical properties such as temperature have powerful effects. In that, some soils are known to respond to P application in early spring when their temperature permits for P mineralisation at an adequate rate to meet the plant requirement (Paul and Clark, 1989). Soil moisture content, which aids to for example, dissolve a particle, of say fertiliser, is also closely important in increasing the level of soluble phosphates to be found in the soil solution. This will make it possible to further react with other soil minerals which together will be relatively available to meet the crop demands (Busman *et al*., 2008). Soil structure and texture are also important in almost all the afore-said and many other related processes in all soil properties.

Based on chemical properties, also, microbial mineralisation of organic P is inevitably influenced by many environmental factors. A mild alkaline *pH*, for example, favours mineralisation. Calcareous soils would, therefore, be expected to have a lower organic P content than acidic soils (Jemo *et al.*, 2006). Most of the savannah soils are inherently high in low activity clays and hence contain crystalline low specific surface minerals (*e.g.* kaolin) as well as oxides and hydroxides of Fe and Al (Mokwunye, 1979). These oxides contribute in removing P from the soil solution by rendering a large proportion of, both inherent and applied, P unavailable for plant uptake (Nwoke *et al.*, 2007).

Biologically, most of the organotrophic members of the soil micro-flora produce microbial phosphatases as observed by Paul and Clark (1989). Microorganisms are accountable for microbial mineralisation of P, and which can be readily explained by the constancy in the amount of labile inorganic P during the season and which ensures P availability to the needing plants (Jemo *et al.*, 2006). Arbuscular mycorrhizal fungal (AMF) population of a soil is another microbial form which aids P acquisition in soils (Smith and Read, 1997).

### 2.5.9 Plant factors affecting soil P availability

Plant factors, on the other hand, also affect soil P availability, just like the characteristics of phosphate rock (PR) material, soil and environmental conditions do

(Hayes *et al*., 1999). It has, for long, been recognised that some plants are more efficient in utilising soil or applied P (*e.g.*, RP) than others. For example, in a study, by Li *et al.* (1992), radish, buckwheat and oil rapeseed were identified as highly efficient in terms of Chinese rock phosphate (CRP) utilisation in both field and greenhouse experiments. Hayes *et al*. (1999) observed that the key mechanisms that accounted for the high P efficiency in these plants have been speculated to include high Ca uptake, the exudation of protons and secretion of organic acids. Comprehensive analyses of responses to P-deficiency with these high P-efficient crop plants are, however, still not clear. It is also not clear why different plants utilise different mechanisms in their adaptation to P-deficiency (Nielsen, 1993).

Earlier however, Nielsen and Schjørring (1983), among others, and recent studies (*e.g.* Li *et al.*, 2003) have revealed that a net P uptake per unit weight of a plant is determined by root length, root length per unit weight of the plant, uptake kinetics and P movement by diffusion to the root cylinder (Tinker and Nye, 2000). Low-P soil is consequent to a very low P mobility, and that is why the P has to be very close to the root cylinder before becoming bio-available (Nielsen, 1993). Root hair exploitation of the soil, however, will increase the quantity of the bio-available P, as plant-available P in the root hair cylinder is very close to the root hair cell membranes that absorb the P (Gahoonia and Nielsen, 2004). More so, many root-induced processes in the soil-root interface, such as excretion of organic acids and/or phosphatases, changes in *pH* and increase in the transformation of non-available soil P to plant-available soil P, are highly paramount (Krasilnikoff, *et al.*, 2003). Mycorrhizal colonisation may also increase the P uptake of annual crops later in a given season (Smith and Read, 1997). Such legumes as the common bean (*Phaseolus vulgaris* L.) and pigeonpea (*Cajanus cajan* L.) have shown genotypic differences in terms of their ability to obtain P (Subbarao *et al.*, 1997). The amounts of phosphatases produced by the plant roots are also known to vary (Kamh *et al.*, 1999) because some plant species are known to produce more extracellular phosphatases, in response to low levels of available P, than others (Paul and Clark, 1989). Other important plant-root characteristics that can increase P-acquisition efficiency of plants are rhizosphere acidification (Marschner *et al.*, 1990), exudation of organic acid anions (Neumann and Römheld, 1999) and root morphology (Gahoonia and Nielsen, 2004).

#### *2.5.9.1 Phosphorus Uptake Mechanisms of Plants*

Various mechanisms, through which plants extract P, exist. Most of these mechanisms are usually root-dependent (Fohse *et al*., 1988). Depending on the capacity of plant roots to adsorb P, therefore, plants differ in their capability to extract P from the soil, their active lifetime and the amount of roots per individual shoot (Nielson *et al*., 2001). Some of the mechanisms of P uptake include: (i) soil P exploration by roots (Singh *et al*., 1997); and (ii) root interaction with such soil microorganisms as arbuscular mycorrhizal fungi (Abdelgadir, 1998). Root hair, as a mechanism for accessing nutrients, was studied by Omwega *et al*. (1988) in a growth pouch experiment. Cowpea genotypes (Melakh and IT 82E -18) were reported to produce longer root hairs under P-stressed conditions than other cowpea genotypes using the growth pouch technique. Also, in relevant experiments, pigeonpea root was observed to exudate a piscidic acid, which was later reported to facilitate for a P release from, usually, plant unavailable Fe-bound soil P (Ae and Otani, 1997), and the exudation of citric acid by white lupin (Gardner *et al*., 1981) and banksia (Grierson, 1992).

Arihara *et al*. (1991), in pot studies, also demonstrated this same ability, of pigeonpea, of releasing P from Fe-P that could result in an increased P availability to subsequent maize cultivated within the same pots. This indicated the possibility of pigeonpea to introduce, an otherwise unavailable, P into the nutrient cycles of cropping systems (Saidou, 2005). Size of the root system is, therefore, one of the factors determining P uptake. Phosphorus transport to the root surface is majorly governed by diffusion due to its low mobility nature in soils (Barber, 1995). An extensive root system with fine roots is beneficial for accessing a large soil volume.

Other factors are such root exudates compounds as daidzen, genistein, and coumestrol, which induce *rhizobial* genes and/or fungal development on cowpea as reported by Dakora *et al*. (1987). Phosphorus-starved plants exhibit a reduced shoot growth and an increased root-to-shoot dry weight ratio (Whiteaker *et al.*, 1976). This decreased shoot growth, of the P-deficient plants, is viewed as a direct result of a leaf expansion reduction and reduced initiation (Lynch *et al*., 1997), possibly due to decreased hydraulic conductance of root (Radin and Eidenbrock, 1984) and a reduced root to shoot transport of cytokinins (Hergro and Warelog, 1980). Plants' performance, when raised on low-P soils, is dictated by their P-efficiency. Efficiency, in this context, is defined as

plant growth and seed yield with suboptimal P availability (Lynch and Beebe, 1995). Many possible root-related mechanisms have been proposed for P-efficiency improvement in crop plants, including reduced P requirements and increased reserve (Lynch and Beebe, 1995), mycorrhizal symbiosis (Koide, 1991) and root architecture and plasticity (Vanvuuren *et al*., 1997). More so, a change of root system composition may also improve its P uptake efficiency (Saidou, 2005) as root systems are composed of various types with distinct properties, in terms of nutrient uptake (Eshel and Waisal, 1996) and construction cost (Eisenstat, 1992).

The P-efficient plants can, therefore, employ a number of potential adaptive mechanisms for a better growth on low-P soils. Some of such mechanisms are as thus:

*2.5.9.2 Root morphology and architecture*

Plant root hair formation, growth of its primary root and the lateral root formation are especially sensitive to alterations in internal and external nutrients' concentration, and which increases absorptive area and soil volume explorable. Average root hair length, root hair length per unit root and root hair density were found to differ among different genetic materials, mainly due to differences in P statuses (Wang *et al*., 2004). Root architecture is a benchmark that indicates the extent to which soil volume is or can be explored. This architecture includes, root growth plasticity, length and growth angle of basal roots and lateral root branching (Ajay *et al*., 2015). Plants characterised by shallow root architecture naturally have higher P-efficiency. This is attributable to higher nutrient availability in the topsoil. The high P availability in the top soil, therefore, causes shallower growth angles of axial roots and enhances adventitious root growth.

Greater dispersion of lateral roots is also known to be associated with P foraging from the top soil and, consequently, P acquisition. Bonser *et al*. (1996) and Liao *et al*. (2001) reported that a variation in root growth angle (RGA) among beans contributed to up to 600% increase in P acquisition and, consequently, 300% increase in yield. The RGA is known to be influenced by basal roots, which appear in distinct nodes/whorls. Ajay *et al.* (2015) stated that the basal root whorl number (BRWN) differs, from 1 to 4, among genotypes. Shallow basal RGA are, on one hand, found in the topmost whorls whereas the lower whorls produce steeper basal RGA. The RGA has been successfully used in breeding varieties suitable for low fertility soils (Lynch, 2007). Adventitious roots

grow, in dicotyledonous plants, from subterranean portion of hypocotyls horizontally through the top soil, and have an especial association with P acquisition in P-deficient soils. Metabolic cost of soil exploration by these roots is also less.

*2.5.9.3 Symbiosis*

Rhizobium:

Phosphorus addition has a significant impact on rhizobium symbiosis and, consequently, biological $N_2$ fixation (BNF) through increased nodule formation and nitrogenase activity on the upper parts of roots (Kuang *et al*., 2005). The shallow root systems increase P-uptake efficiency and, hence facilitate BNF. Improved N status, which results in an enhanced root growth, might be the mechanism at play which allowed soya bean's P uptake to increase in plants inoculated with effective rhizobium strains on acidic low-P soils (Ajay *et al*., 2015).

Azolla and blue green algae:

Blue green algae (BGA) inside Azolla, symbiotically, fix atmospheric nitrogen ($N_2$). The Azolla encompassed a BGA, *Anabaena azollae*, inside its leaves, where foliar or split dosed fertiliser P application, increased the growth of the Azolla and BGA and $N_2$-fixation; and consequently the growth and productivity of rice and fertility of the rice field (Singh and Singh, 1990; Singh *et al*., 1988).

Mycorrhizae:

Arbuscular mycorrhizal fungi (AMF) can increase P availability. This can be by setting phosphates free in much the same way as the ones exuded from the plant roots. It can also be by exudating various organic acids. Under P-deficient conditions, plants usually have more mycorrhizal infection rate and, therefore, contribute more P for subsequent uptake (Singh and Chaudhari, 1996, 2007). Plant growth response to AMF associations, termed: 'mycorrhizal growth response' (MGr), varies widely among plant species and, even, varieties. Beneficial fungal colonisation is known to improve P-access through the "extension" of rooting system of the crop with mycorrhizal hyphae (Bucher, 1971). This, indirectly, increases the root surface area for an optimal nutrient absorption and consequent crop growth. Shenoy and Kalagudi (2005), therefore, concluded that mycorrhizal hyphae work to improve the nutrient acquisition efficiency of crops by increasing their affinity for P ions and decreasing the concentration gradient required for

a more energy efficient absorption. Also, biodiversity of AMF is greater in a low-input production system compared to high-input one, possibly due to the availability of nutrients which makes microbial symbiotic relationships out of vogue and relatively more energy expensive to the crop (Oehl *et al*., 2004).

The AMF play vital roles in enhancing physical, chemical and biological soil quality. They are, therefore, known to maintain and improve soil structure, the uptake of such relatively immobile elements as P, among macronutrients, and Zn, among micronutrients, the alleviation of Al and Mn toxicities, the interactions with other beneficial soil organisms (such as $N_2$-fixing *rhizobia*), and improved protection against pathogens. Mycorrhizal associations ensure for a better use of sparingly soluble P pools, thereby increasing the efficiency of added P fertiliser and of the large, relatively immobile, P pools. Mycorrhizal management via agroforestry, reduced soil disturbance or crop rotation, is usually a better alternative than mycorrhizal inoculation, considering the noxious problems and costs of large-scale inoculum production. Research directions that are needed to increase understanding of mycorrhizal associations in tropical cropping systems and to increase mycorrhizal benefit are very critical.

Root exudates:

Root apex of crops exudes a variety of organic acids, known to possibly influence the crop nutrition and provides an easily degradable nutrient source for soil microbes (Rengel and Marschner, 2005). The roots, under P-deficient conditions, excrete such organic acids as citrate, malate and oxalate acids, which are the most effective organic acids known for the efficient mobilisation of soil P (Hinsinger, 2001; Ryan *et al*., 2001). These acids are good in releasing unavailable P from bound minerals, allowing for the chelation of $Al^{3+}$, $Fe^{3+}$ and $Ca^{2+}$, thereby consequently freeing phosphorus and helping to alleviate P stress (Marschner, 1995; Singh, 2000; 2008). Differences in exudation level of the organic acids can be seen between crops whether or not under P-deficiency (Neumann and Romheld, 1999; Yan *et al*., 2002). Exuded carboxylates, in addition to their role in improving access to otherwise previously unavailable phosphates through acidification of rhizosphere, they also promote microbial growth and potentially exploit beneficial microbial relationships that are correlated with the bioavailability of P (Rengel and Marschner, 2005). There are therefore, beneficial relationships between

crops and mycorrhizal fungi in improving the availability and uptake of P (Li *et al*., 2010).

Activation of high-affinity phosphate transporters:

The inorganic phosphate ($P_i$) concentration within the plant cells is approximately >10 mM (*i.e.* > 3 g $kg^{-1}$, on a dry-weight biomass basis), and yet the concentration in the soil solution is typically observed to be < 10 μM (Bieleski, 1973; Marschner, 1995). Plants have evolved different mechanisms to increase $P_i$ uptake from soil, due to low concentration of soluble P form P and its slow rate of diffusion. High-affinity $P_i$ transporters (PTs) are assumed to play a predominant role in $P_i$ acquisition by plant roots (Marschner, 1995; Raghothama, 1999). The genes that encode these PTs were first identified in Arabidopsis (Muchhal *et al*., 1996). Similar genes were also later identified in other plant species that included cereals, legumes and *solanaceous* species (Leggewie *et al*., 1997; Mitsukawa *et al*., 1997; Smith *et al*., 1997; Liu *et al*., 1998a,b; Chiou *et al*., 2001; Mudge *et al*., 2002; Paszkowski *et al*., 2002; Rae *et al*., 2003; Glassop *et al*., 2005; Nagy *et al*., 2005; Maeda *et al*., 2006; Javot *et al*., 2007; Xu *et al*., 2007). Most of the genes were expressed in roots and were induced due to low-$P_i$ supply or by AMF (Bucher, 2007), and few of them were also expressed in such other plant parts as stems, leaves, cotyledons, tubers and flowers (Karthikeyan *et al*., 2002; Mudge *et al*., 2002). At least two forms of PTs are known in vascular plants, and are classified based on the $P_i$ absorption kinetics and affinity to target $P_i$ (*i.e.*, high-affinity PTs, Km ($P_i$) = 3 – 7 μM; low-affinity PTs Km ($P_i$) = 50 – 330 μM) (Furihata *et al*., 1992; McPharlin and Bieleski, 1987).

The high- and low-affinity PTs belong to Pht1 and Pht2 families, respectively (Bucher et al., 2001). The former family members are induced under P-deficiency mostly exclusively in the root (Daram *et al*., 1998; Rae *et al*., 2003). On the contrary, the members of Pht2 family are mostly expressed constitutively in the aerial parts of the plant (Daram *et al*., 1999; Rae *et al*., 2003). High-affinity PTs are involved in regulating $P_i$ uptake and transcriptional control of PTs activity (Muchhal and Raghothama, 1999; Raghothama and Karthikeyan, 2005) and post-transcriptional regulatory mechanisms (Bucher *et al*., 2001). Hence, high-affinity PTs have been suggested as potential targets for improving $P_i$ uptake (Mitsukawa *et al*., 1997; Rae *et al*., 2003; Vance *et al*., 2003).

Studies have indicated that plasma membrane $H^+$ - ATPase is also involved in P uptake (Shen *et al*., 2006).

Secretion of organic acids and phosphatases into the rhizosphere:
A major portion of $P_i$ in soil may be present in organic forms. Organic P ($P_o$) complexes, such as phytic acid, may contribute to significant portions (20 – 80%) of P in soil (Jungk *et al*., 1993; Richardson, 1994). The $P_o$ complexes need to be broken down by enzymatic activity before the $P_i$ is released into the rhizosphere (Raghothama and Karthikeyan, 2005). Inoculation of food crops with plant growth promoting rhizobacteria (PGPR) or mycorrhizae can directly increase plant available P via mechanisms of solubilisation and mineralisation of fixed P from inorganic and organic forms (Rengel and Marschner, 2005; Hodge *et al*., 2009).

The release of protons, organic acids and phosphatases into the rhizosphere include some of the mechanisms. Pseudomonas and Bacillus bacteria; and fungi, notably in the *Penicilium* and *Aspergillus* genera are among the most powerful P solubilisers available. Another mechanism that may lead to an indirect increase in P acquisition by plants is the production of phytohormones, mainly in form of auxins, by rhizobacteria that stimulate root growth (Richardson *et al.*, 2001b; Jacobsen *et al*., 2005; Richardson *et al*., 2009a). Also, an inoculation with *Azospirillum*, which is known to produce large quantities of indole-3-acetic-acid (IAA), increases the density and length of root hairs. It also enhances the elongation rate and general appearance of lateral roots in many plants species (Fallik *et al*., 1994). This further increases the surface area for absorption of P.

### 2.5.10 Phosphorus Balances

The problem of low rate in the use of fertiliser, especially in sub-Saharan Africa (SSA) is well documented as reported by Bationo *et al*. (2006). About thirty years ago, Vlek (1993) raised concerns on noxious nutrient exports from sub-Saharan Africa. In that, export of stimulant crops alone, in the year 2007, removed about 50,000 tons of P from the region, this is one-fifth of the annual P use. Craswell *et al*. (2010) observed that this amounts to a doubled P exports against a stagnant P fertiliser use over the past two decades. Over three decades of ceaseless harvests, and without a commensurate fertiliser application, an estimated depletion of 75 kg P $ha^{-1}$ from 200 million ha of cultivated land in 37 African countries was the bitter outcome. This estimate was equivalent to 3.3 kg P $ha^{-1}$ $yr^{-1}$ as reported by Sheldrick and Lingard (2004), which was

consequently, forecasted to a hike of 6 kg P $ha^{-1}$ $yr^{-1}$ in 2020 in the depletion rates unless a 7% increase in growth of fertiliser P use is achieved per year. This poses a serious threat, which requires urgent attention to juxtapose the menace. Luckily, however, some of the countries in SSA enjoy inherent PR deposits that could be locally developed and used for direct application. This will assist in relatively solving the problem. On another hand, however, are such 'nutrient surplus' countries (Craswell *et al*., 2004) as Belgium, Denmark, and The Netherlands, in Western Europe, which import feed grains for livestock production and create excess nutrients into the environment, and hence face unprecedented pollution challenges. A similar scenario, as reported by Craswell *et al*. (2010), is in vogue in some intensive production systems of North America and Asia.

Super-abundant P use can cause eutrophication of waterways and, hence, toxic growth of algae that can pose a threat in form of red tides in coastal zones. A progress in the reduction of P surpluses in German agricultural lands by 60% in the last 10 years of the $20^{th}$ century was reported by Bach and Frede (1998). Low rates of P over extended crop and pasture fields have led to neutral or slightly positive P balances in Australia. Phosphorus balances are generally positive for plantation and cash crops in Latin America but negative in low yield subsistence cropping fields (Bach and Frede, 1998).

## 2.6 Phosphate Rock

Phosphate rock (also called phosphorites) refers to the mineral assemblage that occurs naturally with an exceptionally high concentration of phosphate minerals (RMRDC, 1995). It is a sedimentary rock composing of high phosphate minerals, especially apatite. It is directly used in fertiliser as a source of P compounds. Apatite includes 10 mineral species and has the general formula $X_5Y(PO_4)_3$, where X is usually $Ca^{2+}$ or $Pb^{3+}$ and Y is $F^-$, $Cl^-$ or $OH^-$ (chemical land, 2017). Most of the recovered phosphate rocks (PR) in the world are used for the manufacture of superphosphate fertilisers and phosphoric acid for the production of compound fertilisers (FAO, 2000). Phosphate mineral deposits are widespread the world over. Phosphate rocks have widely diverse mineralogical, chemical and textural characteristics, depending on their origin and the prevailing weathering conditions (Stewart *et al.*, 2005). Several common soil phosphate minerals that control P in soils and sediments include apatite (Ca-$PO_4$), hydroxyapatite ($Ca_5(PO_4)_3OH$), fluorapatite (also called fluoroapatite or calcium fluorophosphates,

($Ca_5(PO_4)_3F$), octacalcium phosphate (OCP, $Ca_8H_2(PO_4)_6.5H_2O$), strengite (Fe-$PO_4$), vivianite ($Fe_3(PO_4)_2 \cdot 8HO$), variscite (Al-$PO_4$) and wavellite ($Al_3(PO_4)_2(OH,F)_3 \cdot 5H_2O$.) as reported by Reddy *et al*. (1999) and Brady and Weil (2002).

Phosphate rocks (PRs) can be used either as raw materials in the industrial manufacture of water soluble phosphate (WSP) fertilisers or as P sources for direct application in agriculture. When fertilising for permanent pastures and/or soils where P levels are already high, such a slow P-releasing P source as PR can be applied. Research has indicated that finely ground sedimentary phosphate rocks are suitable for direct application as they consist of fairly open, loosely consolidated aggregates of microcrystals with a relatively large specific surface area (Zapata and Roy, 2004; Havlin *et al*., 2005). Direct application of PR has been identified to be a valuable source of nutrients, depending on the rock type, soil properties, climatic conditions, crops/cropping systems, and nutrient management practices (Rajan and Upsdell, 1981).

The rate at which the PRs dissolve is, however, very slow (Lewis *et al*., 1997; Rech *et al*., 2019), and modification of PR by appropriate chemical, physical, and biological technologies has also has been suggested effective than direct application of PR (Rajan and Chien, 2001). Meyer *et al*. (2011) stated that PRs generally work well when applied as a broadcast treatment to acid soils and has good residual P effects that often last into the fourth and fifth ratoon crops, but should initially be supplemented with an in-furrow application of about 30 kg/ha P as MAP. Another common agricultural practical means of speeding this up is by the addition of organic matter (Brady, 1974). It has been proposed that upon decomposition, the organic matter produces organic acids which help dissolve the insoluble rock phosphate (Troeh and Thompson, 1993).

Although low-cost direct application of phosphate rock has been used commercially in only a few countries, like Malaysia, Indonesia, Brazil, Colombia, and New Zealand among others, and despite hundreds of published research papers and several national/international conferences, information on the direct application of PRs is limited and conflicting results are still being reported (Rajan and Chien, 2001).

### 2.6.1 Origin of phosphate rocks

There are basically two major types of PR deposits, as thus: i. igneous phosphate deposits, mined mainly in Russia, the Republic of South Africa, Finland and Brazil, and

ii. sedimentary phosphate deposits, providing more than 80% of the total world PR production. Igneous ores are often low in grade but through processes of beneficiation can provide PR with up to 30% $P_2O_5$. Phosphate deposits are widespread the world over, occurring nearly on all continents. Igneous phosphate deposits are usually associated with alkalic and/or carbonates intrusions. Sedimentary phosphate deposits occur all over the geological time scale and most of them were formed offshore in marine conditions on continental shelves. Sedimentary PRs have a wide range of chemical compositions and large variations in their physical forms. Island deposits are a sedimentary deposits type that is associated with oceanic islands; they have been an important source of PR for more than 100 years but intensive exploitation resulted in the depletion of most of the deposits (Poswa, 2016).

### 2.6.2 Global phosphate rock production and reserves

Phosphate rock, a non-renewable natural resource, is popularly found in igneous and sedimentary deposits, as stated earlier on. A sustainable production and management of PR is of paramount importance. The vast majority of world's phosphate produced goes to agriculture. The remainder goes to chemical industries, mainly for the manufacture of detergents and such high tech products as sensors and lasers. An even smaller portion of RP is used to produce other phosphate-based products, which also play a vital role and key function in our everyday lives. About 95% of the PR mined is, therefore, used in the production of fertilisers, pesticides and animal feeds (Cisse and Mrabet, 2004). This large percent of phosphate being used in agriculture clearly indicates agricultural development as the driving force for PR production. China, Morocco and the US constitute two thirds of the global phosphate production (World fertilizer, 2017b, 2019).

### 2.6.3 Phosphate rock production and reserves

Commercial production of PR began in the mid-19$^{th}$ century. In 1847 for example, about 500 tonnes of PR were mined in Suffok (United Kingdom). The world production was then increased to over 10 million and over 100 million tonnes in 1928 and 1974 respectively. The world production of PR further increased to up to around 125 million tonnes in 2001 and 2002. About 93% of the PR produced is used in the production of such mineral fertilisers as diammonium phosphate (DAP), monoammonium phosphate (MAP), triple superphosphate (TSP), single superphosphate (SSP) and phosphoric acid and animal feed. The six member companies of 'IMPHOS' (CPG: Tunisia, OCP: Morocco, JPMC: Jordan, ICS: Senegal, FERPHOS: Algeria and IFG: Togo, currently

produce more than 30% of world's PR production, export nearly 50% of world's PR exports, and represent almost 70% of recoverable phosphate reserves. The USA, China, Russia and Morocco, on another hand collectively produce 70 to 75% of the world's total PR. The four countries, together with Tunisia, Jordan, Brazil, Israel, the Republic of South Africa, Syria, Senegal, Australia, India, Togo, Egypt and Algeria constituted the world's total PR producers to a level of 95% in 2001. Among those four major producers, the Morocco reserves accounts for about 50% of the world's total.

As a result of the growth in phosphate consumption to an estimated 1 – 2% per year, the global phosphate reserves extend, for all purposes, into the future centuries to come. Depletion of the most economically vibrant and exploitable reserves can be estimated to occur within a 100 - 130 years period. About 95% of the world's total PR production is used in agriculture through fertilisers, pesticides and animal feeds. Only about 5% are, therefore, used in products and/or applications other than agricultural.

### 2.6.4 The Sokoto phosphate rock

Sokoto, a north-western State in Nigeria, geologically represents parts of the south-eastern sector of the Iullemmedan basin that contains important phosphorite deposits (Albert *et al*., 2016). The phosphate rock (PR) varies both in size and colour, and occurs in beds and disseminations mostly in the Sokoto group of sediments. The Sokoto PR is ranked from highly suitable to highly unsuitable. A suitability map for PR in Sokoto State indicates that, Gwadabawa, Dange, Wurno, Shagari, Wamakko, Sokoto North, Sokoto South, Kware, Bodinga and Illela LGA's provides major sites for phosphates prospecting and therefore very suitable. Geochemistry indicates average phosphates ($P_2O_5$) contents to be 33.89%; a very acceptable grade for raw PR (Albert *et al*., 2016).

The Sokoto phosphate can, however, be beneficiated to 35% $P_2O_5$, which is a very acceptable grade for the manufacture of superphosphate fertilisers or the production of phosphoric acid for the manufacture of compound fertilisers. Okosun (1997) reported that the PR imported, from Togo, to feed the federal superphosphate fertiliser plant at Kaduna, Nigeria, was beneficiated to reach 34.88% $P_2O_5$ market grade. Data from analyses indicate Sokoto and Togolese phosphates to, geochemically, be similar. They also share similar origin and process of formation, although agronomic testing is paramount before application. Exploration and exploitation of this agro-geological

resource must be intensified as it will boost the growth of phosphate beneficiation plant in Nigeria and ultimately the manufacture of superphosphate fertiliser or phosphoric acid for the production of compound fertiliser. This will, ultimately, rescue national foreign exchange being expended on importation of RP (Albert *et al*., 2016).

The reserve of Sokoto phosphate deposit is estimated at five million tonnes (MSMD, 2000). The place of fertiliser, as an input in the agricultural sub-sector, cannot be over-measured if sustainable agriculture is to remain a key agenda of the Nigerian government at all levels. Field sampling leads to analysis which gives an insight on the geochemistry of the PR and thus the average $P_2O_5$ content. Exploration and exploitation of the fertiliser mineral resources will invariably boost agriculture and save Nigeria's foreign exchange, part of which is been expended on the importation of RP (Albert *et al*., 2016). The agronomic and economic effectiveness of PR can, in some circumstances, be equivalent to or better than water-soluble phosphorus (WSP) fertilisers. Unlike WSP fertilisers, which can be widely used, there are specific factors that must be taken into account in order to maximise the utilisation of PR. These factors include: crop species, reactivity of the PR sources, soil properties and management practices. Use of Phosphate Rock Decision Support System (PRDSS) model would also be an effective means of predicting the best use of this nutrient resource (Chien *et al*., 2010).

## 2.7 Phosphorus Fractions in Soils

The Saloid-bound-P, also variously called labile-, soluble- and desorbable-P, usually occurs as readily soluble, desorbable orthophosphate, or easily available P forms (Sarkar *et al*., 2014), which are available for plant uptake. After an application of fertiliser P to the soil, it must be converted into the orthophosphate forms, which may exist as either $H_2PO_4^-$ or $HPO_4^{2-}$, depending on *pH*, before plants can utilise it. The two orthophosphate forms can be found readily available for plant uptake when the soil *pH* is near 7.0. When the *pH* increases above 7.0, however, $HPO_4^{2-}$ becomes the dominant available-P form. Other than soil *pH*, P form also depends on such other soil factors as texture, temperature, moisture, organic matter content and crop residue incorporation. As the plant takes up water soluble orthophosphate from the soil, the concentration of phosphate in solution declines and is replenished from the labile pool (Busman *et al*., 2009). The labile pool is the main source of available P for crops because the water-

soluble P pool is very small and phosphate concentration becomes reduced as a plant takes it up.

## 2.8 Sorption and Precipitation Reactions

Phosphate retention in soils involves adsorption and precipitation reactions. The adsorption is, however, considered to be the most significant process controlling P availability in soils over a short period (Gichangi *et al*., 2008). Phosphorus sorption is, by definition, the removal of labile P from soil solution, due to the adsorption on, and absorption into the solid phases of the soil, mainly on to surfaces of more crystalline clay compounds, oxyhydroxides, or carbonates and/or magnesium as reported by Hollford and Mattingly (1975). Phosphate precipitation is a process in which P reacts with another substance to form insoluble P compounds, in form of a solid mineral, (Gichangi *et al*., 2008). As successive increments of soil are contacted by the moving front of the fertiliser solution that dissolves increasing quantities of Fe, Al, Mn, Ca, Mg, and cations derived from soil. The solution, then, becomes supersaturated relative to a variety of P compounds, resulting in the precipitation of P minerals (Sample *et al.,* 1980).

When soluble phosphatic fertilisers are applied to soils, they are initially dissolved to cause an immediate rise in the soil solution P concentration, which then participates primarily in the adsorption and precipitation processes (Prasad and Power, 1997). The reactions that occur are mainly *pH* dependent. In acidic soils, predominance of positive charges on Al- and Fe-oxides and hydroxides facilitates the attraction of negatively charged orthophosphate ($H_2PO_4^-$ and $HPO_4^{2-}$) ions to form compounds that are insoluble (Havlin *et al.,* 2005). Ligand-exchange, indicating a specific adsorption, occurs when P anions replace the hydroxyl groups on the surface of Al- and Fe-oxides and hydrous oxides (Haynes and Mokolobate, 2001). The solubility of these phosphates is known to increase with an increase in soil *pH* (Poswa, 2016).

### 2.8.1 Phosphorus sorption index

Phosphorus sorption index (PSI) is the P supplying capacity of soils. Hence, time estimate before fertiliser application would again be required and could best be made using PSI (Sims, 2000). It also predicts the possibility of an economic response to P, on

the basis of physical and chemical properties and to identify when the soil is sufficiently excessive in P (Sims *et al*., 1998).

## 2.9 Soil Iron and Aluminium Oxide Fractions

### 2.9.1 Forms of extractable Fe and Al

The fractionation among the various Fe and Al forms in soils can be realised by selective extraction methods. The acidified ammonium oxalate [$(NH_4)_2(COO)_2$] method extracts mainly the poorly crystalline amorphous forms of inorganic and organically-complexed Fe and Al from soils (Mehra and Jackson, 1960). The alkaline sodium-pyrophosphate ($Na_4P_2O_3.10H_2O$) extraction method, on the other hand, extracts organically-complexed fraction of Fe and Al. Total free oxides, including the major parts of organic complexes, can, however, be determined by a reductive dissolution procedure with dithionitecitrate-bicarbonate solution. This solution also extracts goethite and haematite and silicate minerals only slightly including silicate Fe and Al (Mehra and Jackson, 1960). The sodium citrate-sodium bicarbonate-sodium dithionite (CBD) solution, therefore, gives the approximate 'free' (non-silicate) forms. These procedures have, however, been proved to be more successful for fractionating Fe than Al in soils, as reported by Bascomb (1968) and McKeague *et al*. (1971).

The oxalate-extractable Fe ($Fe_o$) and Al ($Al_o$) give an estimate for the extent of amorphous products' accumulation in a recent weathering. This is even truer for soils formed from materials that widely differ in *pH*, organic matter, texture, colour and total oxides (McKeague and Day, 1966). Large quantities of $Fe_o$ and $Al_o$ are also related to soils with high *pH*-dependent charges and, hence, high P fixing potential (Saunders, 1965). The dithionite extractable Fe ($Fe_d$) largely accounts for the combined content of amorphous and crystalline Fe-oxides. Blume and Schwertmann (1969) reported that, $Fe_d$ is, quantitatively, not a useful measure of the extent of Fe release from primary minerals due to passive Fe migration in profiles. For this reason, therefore, $Fe_o$ seems more suitable for that purpose (Nartey, 1994).

The $Fe_o$ contents are generally more preponderant in surface than subsurface of soils (Gamble and Daniels, 1972; Juo *et al*., 1974; Moniz *et al*., 1982) due to decrease in organic matter with depth. Organic matter has been reported to inhibit Fe crystallisation in soils (Schwertmann, 1966; Huang and Violante, 1986). Juo *et al*. (1974) reported low

$Fe_o$ in well drained savannah soils, which they attributed to high temperature *vis-á-vis* prolonged dry season related to the environment. Some Ghanaian soils were, however, observed to contain an acidic ammonium oxalate Fe-oxides content of as high as 25%. Sherman *et al*. (1964) noticed that drying at high temperatures results in the dehydration, which subsequently leads to high rate of crystallinity, of amorphous Fe and Al oxides. This loss (crystallisation) of the amorphous oxides, due to high temperatures, also leads to decrease in cation exchange capacity in tropical soils.

The level of $Fe_o$ is, in most cases, less than the total free Fe (Alexander, 1970). The relative distribution of $Fe_o$ to $Fe_d$ ($Fe_o/Fe_d$) in soils is most commonly expressed as "active Fe ratio". This ratio is used as a relative measurement tool for the degree of aging/crystallinity of free Fe-oxides (Schwertmann and Taylor, 1977). Normally, the active ratio is less than one, as acidic oxalate extracts less Fe from mineral soils than does the dithionite-citrate, and it approaches zero in old tropical soils (Alexander, 1974). This active Fe ratio is authentic only when soils are characterised or compared with similar parent material; or in situations where significant amounts of primary Fe have been removed (Blume and Schwertmann, 1969). The active Fe ratio, like the $Fe_o$, is also generally higher in the surface than subsurface soils (Gamble and Daniels, 1972; Juo *et al*., 1974). Daugherty and Arnold (1982), however, related this trend to be more prevalent in well-drained soils than in soils where Fe concentration is due to fluctuations in water table. During the initial stages of weathering and soil development, Fe release, from primary minerals, may exceed the rate of crystallisation into secondary compounds, thereby causing the active Fe ratio to increase, but thereafter the ratio decreases with ageing. High ratios of $Fe_d$ to total Fe ($Fe_t$) of soils suggest a strong weathering condition in the landscape. As soil development continues, the ratio of $Fe_d$ to $Fe_t$ increases further (Schwertmann, 1985; Bigham *et al*., 1991).

Phosphate status, fractions and adsorption characteristics of soils are significantly influenced by the proportion and distribution of Fe and Al oxides of soils (Torrent, 1987; Torrent *et al.*, 1990; Agbenin, 2003; Abdu, 2006; Abdu, 2009, Abdu and Udofot, 2015). Understanding the amount, nature and distribution of these oxides in soils is, therefore, very necessary in understanding soil phosphate reactions.

#### *2.9.1.1 Iron*

Iron (Fe), the second most abundant metal in the Earth's crust, is found in such primary minerals as silicates, oxides and sulphides. It is an essential element for diverse organisms. The metal is only toxic when in very high concentrations compared to other metals (Khan and Nugegoda, 2007). Iron has a rather complicated chemistry in soils, and can exist in the environment in mainly two oxidation states: iron (II) and iron (III). The former form is stable in such reducing environments as anaerobic conditions (*e.g.*: low-oxygen sediments, *Fadama* soils, hypolimnetic lake water and ground water. The latter is, however, the stable form in aerobic soils. Organic matter and light are capable of reducing iron (III) to iron (II) as reported by Miles and Brezonik (1981). Iron (II) is generally present in the free hydrated ion form, as it does not bind strongly to organic matter (van Dijk, 1971). At significant concentrations, and in the presence of other ions, Fe can precipitate into various mineral forms such as vivianite ($Fe_3(PO_4)_2 \cdot 8HO$), siderite ($FeCO_3$) or amorphous iron sulphide (FeS) as reported by Davison (1993). Iron (III) has completely different chemistry. It also easily precipitates into various secondary oxides and hydroxides and has a very low solubility. Aluminium and Pb were associated with Fe, probably due to coprecipitation according to many authors including Pokrovsky and Schott (2002) and Vasyukova *et al*. (2010).

Studies have indicated that Fe minerals play a, consistently, dominant role in P sorption compared to Ca minerals (Matar *et al*., 1992; Hinsinger, 2001; Zhang *et al*., 2005). It has also been further confirmed that relative amounts of P occluded to Fe-oxides are not necessarily related to the level of P enrichment in soils (Dominguez *et al*., 2001). Smaller concentrations of either Fe or phosphates are, therefore, not valid criteria to negate P sorption in alkaline calcareous soils.

#### *2.9.1.2 Aluminium*

Aluminium is the third most abundant element and the most common metal in the Earth crust. It is present in granites and gneisses. So far, it has not been proved that aluminium is an essential element to any organism. Instead, it is toxic at large concentrations, especially to fish, but also to other aquatic organisms, for example, invertebrates and planktons (Gensemer and Playle, 1999). The major potentially toxic forms of Al are the inorganic cations, especially the free $Al^{3+}$ ion. Above *pH* 6, Al solubility is low in soils,

and it is controlled by a mineral phase with $Al(OH)_3$-type solubility (Tipping, 2005). The actual mineral form that is controlling Al solubility is, however, not confirmed yet. Suggestions in soils are amorphous $Al(OH)_3$, gibbsite (crystalline $Al(OH)_3$), and silica containing (proto)-imogolite or allophane (Gustafsson *et al*., 2001). The theoretical $Al(OH)_3$ phase has a higher log solubility product than $Fe(OH)_3$, at 25 °C it is estimated to be 8.29 in moderately acid Bs horizons of podzolised soils (Gustafsson *et al*., 2001). Temperature has a large effect on the $Al(OH)_3$ solubility, the colder the higher solubility product. When estimating the solubility of Al in soils, Gustafsson *et al*. (2001) used the heat of reaction determined for gibbsite as -105.0 kJ $mol^{-1}$ (Palmer and Wesolowski, 1992) whereas Tipping (2005) used a mid-range value from several studies of -107 kJ $mol^{-1}$ (Tipping *et al*., 2002).

## 2.10 Nitrogen

### 2.10.1 Nitrogen and agriculture

Nitrogen is the most important nutrient element that is limiting in agricultural lands universally. This is due to its unavailability although it is among the most abundant elements on earth (Graham and Vance, 2000). Sunlight and water are only more important. Principally, plants acquire their N from the soil and atmosphere. The soil provides N via commercial fertiliser, manure, and/or mineralisation of organic matter. Atmospheric contribution comes through biological $N_2$ fixation (Vance, 2001). Generally, plants can accumulate N in their vegetation for periods of up to hundreds of years, examples being in trees, or cycling it seasonally in annual crops (Paul and Clark, 1989). Agricultural contribution to global N must include the 45 to 50 Tg coming from symbiotic $N_2$-fixation (Socolow, 1999). Modern agriculture therefore, adds as much N to the global cycle as the pre-industrial $N_2$ fixing-unfixing cycle. It is predicted that addition of N by agriculture will surpass the pre-industrial equilibrium of 150 Tg by 140% in 2030 (Vance, 2001). Anthropogenic addition of N by agriculture matters, as a grain yield of 5 to 9 metric tonnes $ha^{-1}$ requires an addition of 200 to 300 kg N $ha^{-1}$ (Peoples *et al.*, 1995a).

Although the question of global N deposition on land due to intensive agriculture is controversial with ranges calculated between 2 to 45 kg $ha^{-1}$, current thought suggests that excess N from agriculture reduces biodiversity and ecosystem function (Tilman *et*

*al.,* 2001). Successful management of N is therefore, a requisite for maximizing crop quality and yield with mineral impact on the environment and natural resources (Vance, 2001).

### 2.10.2 Biological nitrogen fixation

Biological nitrogen fixation (BNF) is the process in which, in the presence of nitrogenase, atmospheric nitrogen (N=N) is reduced to ammonia. Nitrogenase is however, a biological catalyst that is found, naturally, only in certain microbes such as the symbiotic *Rhizobium* and *Frankia,* or the free-living *Azotobacter* (Brockwell *et al.,* 1995). Biological NF is the major source of N input into agricultural systems. *Rhizobia* (synonymously called nitrogen-fixing bacteria (Moreira *et al.,* 2008), are symbiotic bacteria that elicit on the roots of specific legume hosts the formation of new organs called nodules, within which the bacteria proliferate, differentiate into bacteroids and subsequently fix atmospheric nitrogen ($N_2$) into ammonia ($NH_3$) (Denarie *et al.,* 1992).

The BNF process is brought about by both free living soil microorganisms and symbiotic associations of microorganisms with higher plants. Groundnut, like other leguminous counterparts, fixes atmospheric nitrogen by working symbiotically with *Rhizobia* living in the root nodules. The *Rhizobia* infect root hairs of the legume and produce the nodules (Tate, 1995). The nodule becomes home for the bacteria, fromwhere they now obtain energy from their plant host and take free $N_2$ from the soil air and process same into combined N. In return, however, the plant receives the fixed-N from the nodules and fromwhich it produces food and forage protein. Biological NF is, therefore, an efficient source of N (Peoples *et al.*, 1995b).

An estimated 100 - 200 kg N per hectare, under a range of different field conditions has been reported by Boddey *et al.* (1990) as a biological $N_2$-fixed by groundnuts. Both, quantity fixed and proportion of total crop N derived from $N_2$-fixation, can, however, be dictated by cultivar (Giller *et al.,* 1987) and/or water stress (Peoples *et al.,* 1992). Some studies revealed that amount of $N_2$-fixed exceeded the N need for pod growth; hence, residual $N_2$-fixed was present in vegetative parts to be distributed to soil after pod harvest (McDonagh *et al.,* 1993). Other studies have, on the contrary, suggested that despite high levels of $N_2$-fixation, the net N-balance following pod harvest can be negative and so soil N reserves might as such be depleted due to *Arachis* cropping

(Peoples *et al.,* 1992). Some locally sourced soya bean varieties were observed to have obtained a larger percent $N_2$ derived from the atmosphere (% Ndfa) (65%) than Nasoko (53%), an 'improved' variety, in a study by van Vugt *et al*. (2018) in which variability in % Ndfa, $N_2$-fixed and grain yields were compared.

### 2.10.3 The nitrogen fixation process

The element nitrogen (N) or 'azote', meaning 'without life', as Antonie Lavoisier called it about 200 years ago, has proved to be anything but lifeless, as it is a component of poisons, explosives, food and fertilisers (Schoot Uiterkamp, 1990). The atmosphere contains about $10^{15}$ tonnes of $N_2$, and N cycle involves the transformation of some $3x10^9$ tonnes of $N_2$ $year^{-1}$ on a global basis as reported by Postgate (1982). However, transformations, like $N_2$-fixation, are not exclusively biological. Fertiliser industries provide very important quantities of chemically fixed nitrogen. Lightning also provides, probably, about 10% of the global fixed-N supply (Havlin *et al.,* 1999).

### 2.10.4 Measurement of biological nitrogen fixation process

There is no single "correct" method of quantifying $N_2$-fixation, as no single technique provides an accurate measure of $N_2$ fixation for all legumes cultivated in any soil, under varying environmental conditions (Peoples *et al.,* 1989). Biologically fixed nitrogen can, notwithstanding, be estimated using a number of simple techniques of BNF quantification: short-term and medium term BNF estimation methods, represented by Acetylene Reduction Assay (ARA) and N-Solute Analysis of Xylem Exudate, respectively, or a third method that involves, nodule counting, nodule weighing, or assessment of leghemoglobin, although less reliable than the two preceding methods (Takishima *et al.,* 1989). Peoples *et al.,* (1989), also explained those three methods as thus: (a). nitrogen-difference technique, (b). xylem-solute technique, and (c). $^{15}N$-isotopic technique.

#### *2.10.4.1 Principles of the N-difference method*

The N-difference method of quantifying biological $N_2$-fixaton is a, relatively, simple technique. It attempts to ensure (assume) that both the treatment legume and control plant have a similar amount of N derived from the soil in their shoots. The distribution of N between shoots and roots, of the two plant types should also be similar. The non-

fixing control plant could be: (a) a non-legume; (b) an uninoculated legume of the same species (requires soil to be devoid of effective *Rhizobium* species); and (c) a non-nodulating legume genotype (Peoples *et al.,* 1989). Although several methods of variation of the N-difference exist, the quantity of the legume N derived from $N_2$-fixation (Q) can be calculated as thus:

$Q = N\ yield_{treatment} - N\ yield_{reference}$

A modified procedure is usually used when the two crops, the legume and control, are not well matched as:

$Q = [N\ yield_{legume} - N\ yield_{control}] + [N\ soil_{legume} - N\ soil_{control}]$ (Evans and Taylor, 1987).

Advantages and disadvantages of the method:

It is a simple and direct method which adjusts for soil-derived N. It however requires a suitable non-$N_2$-fixing reference plant, preferably a non-nodulating legume which is usually very scarce especially in our part of the NGS of Nigeria, and for some crops. Another shortcoming of the method is the assumption that both the legumes and reference plants will take an equal quantity of soil N, which attainment is so difficult to ascertain for obvious reasons such as the noxious soil heterogeneity among others (Giller *et al*., 1986). A detailed review on the remaining methods of BNF quantification can be accessed from Gabasawa (2011).

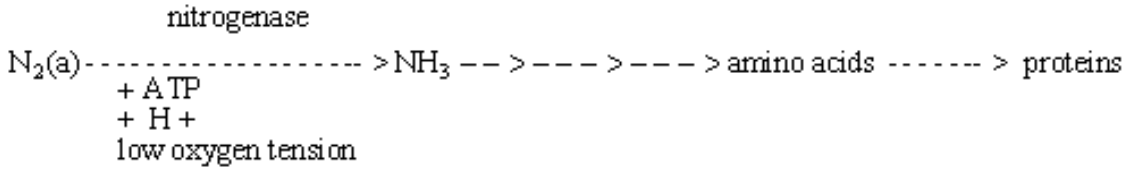
### 2.10.5 Significance of BNF to soil fertility

Much land has been degraded worldwide due to agronomic practices during tillage, bush burning, fertiliser and pesticides applications and other human influences (Balfour, 1977), and it is time to stop the destructive uses of land and to institutionalise a serious reversal of land degradation (Burris, 1994). Biological NF plays a key role in land remediation. The total annual terrestrial input of N from BNF, as given by Burns and Hardy (1975) and Paul (1988), ranged from 139 million to 175 million tonnes of N, with symbiotic associations growing in arable land accounting for 25 to 30%, representing 35 million to 44 million tonnes of N (Sprent and Sprent 1990). The symbiotic system of leguminous plants and *rhizobia* as associations has the greatest quantitative impact on the N cycle. A tremendous potential for contribution of fixed N

to soil ecosystems exists among the legumes (Tate, 1995). The plant's benefit from bacterial N fixation appears to be highest in symbiosis, for example, between legumes and *Rhizobia,* while associative bacteria do not form nodules but use plant exudates (Cristina *et al.,* 2007).

### 2.10.6 Nitrogen fixing organisms

Microbial $N_2$-fixation can take place in the free-living state and/or in symbiosis or association with higher plants (Jones and Jacobsen, 2005b). The mechanisms of $N_2$-fixation appear to be quite similar in most of $N_2$-fixing prokaryotes (Zahran *et al.,* 1995), however, the biochemical mechanism of $N_2$-fixation can be written in itssimplified form as follows:




This mechanism (above) indicates that $N_2$-fixing systems can survive in N-deficient soils. Adenosine triphosphate (ATP) is the source of energy necessary for the cleavage and reduction of $N_2$ into ammonia ($NH_3$). In *rhizobia*, for instance, ATP results from oxidative degradation of sugars and related molecules. These sugars are produced, during photosynthesis, by the host-plant, and then transferred to the root nodules. In general, therefore, for each gram of $N_2$ fixed by *Rhizobium*, the plant fixes 1 to 20 g of C, via photosynthesis. This is an indication that biological $N_2$-fixation (BNF) requires additional energy which can be used to produce more photosynthates in $NO_3$-fed plants. However, the extra energy cost of $N_2$-fixation can be safely carried by a majority of field-grown legumes, with little or no production loss (Takishima *et al.,* 1989).

All organisms capable of fixing $N_2$ (*i.e.*, converting the stable $N_2$ in the atmosphere into a biologically useful form) belong to a biological group named *prokaryotes*. A wide range of organisms can fix $N_2$, however, only a very small proportion of species are capable of doing so. About 87 spp in 2 genera of *Archaea,* 38 genera of bacteria and 20 genera of *cyanobacteria* have been identified as *diazotrophs* capable of fixing $N_2$ (Zahran *et al.,* 1995). This diverse variety of *diazotrophs* ensures that most ecological

niches contain one or two representatives and that lost N can be readily replenished (Sprent and Sprent, 1990).

### 2.10.7 Factors limiting BNF

Interactions between microsymbionts and plant are complicated by numerous environmental factors/conditions included in climatic, edaphic and managerial factors. A legume-*Rhizobium* symbiosis might be well performed in a loamy and not a sandy soil, sub-humid region but not in the Sahel, or under tilled but not zero-tilled plots, and/or vice-versa. These factors may either affect the microsymbionts, the host-plants or both, so that the level of crop production can be no higher than that allowed by the maximum limiting factor (Brockwell *et al.*, 1995).

#### *2.10.7.1 Physical constraints*

Temperature:

Surface soil temperature in some parts of the tropics can occasionally reach 65-70 $^0$C and that of the sub-surface (at 5 cm depth) can be above 50 $^0$C (Dudeja and Khurana, 1989). This temperature can be sufficiently high to inhibit seeds from germinating and kill many bacteria. Although many species of cyanobacteria can form spores called akinetes, which are highly desiccation-resistant, most of the heterotrophic free-living $N_2$-fixers and rhizobia do not resist the heat. This indicates that excessive soil temperatures can kill majority of the bacteria living in the surface layer, although all the same, some rhizobia can survive for some periods in dry soil temperature under 70 $^0$C (Marshal, 1964). Clay particles and SOM are however, helpful refuge for bacteria against the desiccative high temperature such that sandy soils are types commonly with high temperatures (Giller and Wilson, 1991). In Samaru, NGS of Nigeria, for example, rhizobial populations of only 4 - 40 cells $g^{-1}$ soil were found in the 5 cm surface depth of the soil, whilst populations of up to $10^4$ cells $g^{-1}$ soil were found at a depth of 20 - 25 cm below the surface by Day *et al* (1978). In general, therefore, bacteria are less tolerant to high temperatures in moist than in dry soil. High temperatures can prevent nodulation or can inhibit $N_2$-fixation activity of legumes even if the nodulation occurs (Day *et al.*, 1978) and even when soil insulates the root nodules against the highest temperatures (Giller and Wilson, 1991).

Soil texture:

As stated under temperature (above), depending on how finely textured a soil is, the piercing heat due to high temperatures can, more or less, be insulated from vulnerably reaching the bacteria such that clay soils are best at protecting the rhizobia against the harsh solar rays, whereas sandy soils are relatively the worst.

Drought:

Rhizobial population in a soil is proportional to soil moisture (Bushby and Marshal, 1977). Stressful drought affects $N_2$-fixation of legumes, negatively, as the $N_2$-fixation rate is more sensitive to soil moisture content reductions than such other processes as photosynthesis, transpiration or leaf growth. Deep rooting grain legumes, such as cowpea, relatively do well in water-stressed environments than their shallow rooting counterparts if they successfully penetrate deeply before the drought starts or becomes noxious (Sinclair et al., 1987).

Soil salinity and sodicity:

Saline soils are measured as having an electrical conductivity (EC) of > 4 dS $m^{-1}$ or due to mismanaged irrigation practices (Nortcliff, 1988), while sodic soils are those as sodium (Na)-rich as to constraint the growth of most plants, and they may or not be saline. The pH of both soils is usually > 8.5, which property can result in a reduced availability of P, iron (Fe), zinc (Zn), molybdenum (Mn) and boron (B) needed for plant growth. Water-stress, due to osmotic potential, is, however, the main problem with saline soils. Salinity-caused is more permanent than drought-caused as the former is always over when the drought is gone (Sprent, 1984). The legumes hosting the rhizobia are very much more sensitive to saline conditions than the rhizobia themselves, as some (rhizobial) strains are adapted to saline conditions, although they still are sensitive to salt stress in an alkaline pH; and chloride ($Cl^{-1}$) ions are particularly toxic to rhizobia (Elsheikh and Wood, 1989).

Groundnut nodulation is, however, not sensitive to salinity due, probably, to the direct mode of *rhizobial* infection as reported by Sprent (1984). A wild relative of pigeonpea (*Cajanus cajan*), *Atylosia platycarpa*, is also less sensitive to salinity such that there is no reduction in its nodulation at NaCl and $CaCl_2$ salinities of up to 8 dS $m^{-1}$ and effective nodules were still formed even at 12 dS $m^{-1}$, unlike the *C. cajan* whose number of nodules was reduced at 4 dS $m^{-1}$ (Subbarao *et al.*, 1990b). Once its initial

nodulation is successful, however, *C. cajan* can also grow in saline soil condition of up to 8 dS $m^{-1}$ without harmful effects on the following nodule development and/or functioning as observed by Subbarao *et al.* (1990a).

Waterlogging:

As rhizobia are normally aerobic, a waterlogged soil condition that necessitates for a rapid use of free oxygen by organic substrates, especially at high soil temperatures, threatens a habitable environment for the rhizobia. Nevertheless, some strains of Bradyrhizobium and Rhizobium meliloti possess an enzyme called dissimilatory nitrate reductase which can function as an electron acceptor. This enables the bacteria to survive under anaerobic conditions (Daniel *et al*., 1982). Lack of oxygen is also a major constraint to root respiration, as it can result in an immediate loss of nitrogenase activity (Witty et al., 1986). Even legumes that can grow in waterlogged conditions such as Aeschynomene and Sesbania some species, their root nodules do not develop in watered conditions. Stem nodules are, however, not affected even by submerged conditions, presumably, as oxygen is transported to the nodules via Lacunae within the shoot (Eaglesham and Ayanaba, 1984).

Some legumes can still, however, tranfer some oxygen from their shoot to the roots (de Willigen and van Noordwijk, 1989); while some roots respond, adaptively, to increase oxygen supply from shoot to themselves as their root porosity is increased. Nodules can also develop a thick cortex and enlarged “lenticels”, which can assist in gaseous exchange across nodule surface (Minchin and Summerfield, 1976). Toxic levels of Fe and Mn accumulation, that may inhibit *rhizobia* and plants, are among others, additional hitches related to water-logged environments (Giller *et al.*, 1989a).

*2.10.7.2 Chemical constraints*

Toxicities:

Soil acidity:

Low soil reaction (pH) is important, especially, in tropical soils, which are majorly acidic, and the problem can arise, either, from low pH survival medium troubles or that of chemical changes in soil, which is caused by high acidity, especially due to large amounts of Al or Fe and Mn in solution, on one hand, and decreased P and Mo; and the lack of Ca, in most acidic soils as reported by Giller and Wilson (1991). Bacterial

symbionts are usually affected by low pH, although those capable of regulating their internal *p*H were reported by O'Hara *et al*. (1989) to be having an increased survival rate at low *p*H. For example, some strains of Bradyrhizobium were tested to be more tolerant of Al than Bradyrhizobium japonicum strains (Johnson and Wood, 1990).

*Arachis hypogaea* and *Vigna unguiculata* are the most soil acidity tolerant legumes, to especially when compared to *Glycine max* or *Phaseolus vulgaris* (Munns, 1978), although *A. hypogaea* still indirectly suffers some problems, in the acid soil, due to the high need of pod for Ca, which is deficient in such (acid) soils. High available N levels can, in addition, greatly retard N fixation because the plant, automatically, stops releasing a chemical that attracts the bacteria to the roots, and the plant, consequently, disallows nodules formation (Jones and Jacobsen, 2005a).

Nutrient deficiencies:

Deficiencies in nutrients, essential for the growth of bacteria and/or plants, can cause tremendous reductions in the number and size of nodules that are to be formed, and consequently the quantity of $N_2$ to be fixed. In acid soils, that majorly highly weathered and leached, many essential nutrients (*e.g*., P and Mo) are deficient as they are bound into plant-unavailable forms, whereas other nutrients, like Fe and Zn, are inherently unavailable at a high soil reaction conditions. Deficiencies can, however, occur in soils of near-neutral pH due to leaching or continuous cropping (Giller and Wilson, 1991), and Guerinot (1991) reported that several such other nutrients as micronutrients (*e.g*., Co, B, Cu or Mo) can be deficient, thereby limiting nodulation and therefore constraining the BNF.

Pollution:

Edwards (1989) and Roberts (1991) reported that at least some of the myriad pesticides used in agriculture can have deleterious effects on the survival of rhizobia and/or nodulation of legumes. Graham et al. (1980), therefore, cautioned rhizobia inoculators to pay a unique attention while inoculating seed coats of legumes and while applying agro-chemicals to the seed surface. Polluting agricultural soils, with sewage sludges that are contaminated with heavy metals, has been shown to drastically and completely suppress $N_2$-fixation in, for example, white clover (Trifolium repens). This is as a result of the toxic characteristics of the heavy metals to Rhizobium (Giller et al., 1989b).

*2.10.7.3 Biological constraints*

The fixation process, in the $N_2$-fixing system, is strongly related to the the physiological state of host-plant, such that pruned and lopped leguminous plants, for example, have a decreased photosynthetic ability (Thies *et al.,* 1995). It impairs $N_2$-fixation and can cause nodule decay, which in turn results in shedding of a big number of root zone *rhizobia* as observed by Brockwell *et al.* (1995). Absence of the required *rhizobium*, presence of crop competition, nematodes and insects are some other biotic factors that drastically limit $N_2$-fixation in an otherwise efficient N-fixing legume as reported by Thies *et al.* (1995). According to Roughley (1985), competition and antagonism, from other organisms, are also highly influencial in the growth and survival of free-living $N_2$-fixing *rhizobia*.

## 2.11 Nitrogen-phosphorus Dynamics and Root Nodulation

The capacity of leguminous crops to improve soil N fertility may be hampered by low concentrations of inherently available soil P (Buresh *et al.,* 1997). This is because good nodulation and $N_2$-fixation levels, among which soil N fertility depends, require huge amounts of P (Giller, 2001). Knowledge of P dynamics in soil is, therefore, fundamental in predicting its bioavailability and the risk of its tranport from soil to water bodies (Zheng *et al.,* 2004). Lajtha and Harrison (1995) highlighted that plants adopt two main strategies to promote N and P acquisition and use, including: (a) those directed towards improved acquisition and/or uptake, and (b) those targeted to conserve use.

### 2.11.1 The root and root nodules

Nitrogenase, as earlier mentioned, is an oxygen sensitive enzyme. The low oxygen tension condition is realised through compartmentation in cyanobacteria (heterokysts in *Anabaena azollae*), active respiration (in *Azotobacter*), synthesis of *leghaemoglobin* is a macro molecule synthesised by the symbiotic partners (*i.e*, *rhizobia* and host plant). The *rhizobium* synthesises the '*haeme*' portion; and plant, the '*globine*'. Like the human *haemoglobin*, *leghaemoglobin* fixes $O_2$. It is responsible for the red or brown colour of active (*i.e,* $N_2$-fixing) nodules. Non-$N_2$-fixing nodules have a white or green nodule contents when the *globine* has degenerated as reported by Tripathl and Psychas (1992). Generally, therefore, nodules' effectiveness can best be evaluated by the degree of pink, brown or red colouration of $N_2$-fixing bacteroid and; would, consequently, not be

considered when classifying a currently active nodulation (Peoples *et. al.*, 1989; Tripathl and Psychas, 1992).

### 2.11.2 Chlorophyll content of plant leaf

Chlorophyll, one of the most vital plants' chelates, has capacity of directing solar energy into chemical energy through the photosynthesis process. In addition to being plant nitrogen status indicator, chlorophyll content (CC) is also an important leaf senescence indicator (Noodén *et al*., 1997). The chlorophyll content can also be adjusted due to response to possible stresses of the environment (Neufeld *et al*., 2006). Several CC examining methods exist, including the extraction method, which involves extraction of the chlorophyll in a solvent followed by spectrophotometric in vitro measurements. This method is, however, laborious, costly, destructive and time-consuming. Alternatively, however, use of chlorophyll meters (*e.g.*, the SPAD-502, from Spectrum Technologies, Plainfield, Illinois, USA), provides a quick, non-destructive and simple method for estimating the CC of a given leaf (Xiong *et al*., 2015). Chlorophyll metre, therefore, provides a non-destructive and rapid diagnosis of plant N status is easily applicable even in field experiments (Uddling *et al.*, 2007; Vollmann *et al*., 2011) and has widely been tested for many crops (Turner and Jund, 1991; Follett *et al*., 1992; Peterson *et al.*, 1993; Varvel *et al*., 1997). Chlorophyll metre measurements of a crop are correlated with its petiole nitrate-N, leaf N and yield and that they (the measurements) are less variable than petiole nitrate (Bronson *et al.*, 2001). An enhanced mineral nutrition is known to assist in an increased chlorophyll content of plants, and consequently helps in achieving a higher photosynthetic rate (Feng *et al.*, 2002). There is a close relationship between chlorophyll content of a plant and its nitrogen concentration (Richardson *et al.*, 2001a). This implies the possibility of using its measurement to compliment for $N_2$-fixation measurement (Vollmann *et al.*, 2010).

Using soil plant analysis development (SPAD) meter to assess leaf chlorophyll concentration has, relatively, become common, although calibrating SPAD meter readings into direct units of chlorophyll concentration still remains difficult. A comprehension of the relationship between these two parameters, as necessity is another hitch (Markwell *et al*., 1995). Diverse studies have estimated the SPAD readings and chlorophyll content relationships per leaf area in different plant species. This relationship (between SPAD readings and chlorophyll content per leaf area) has,

however, been found to differ widely among plant species, and even within same species in some cases (Uddling *et al*., 2007; Parry *et al*., 2014; Lin *et al*., 2015). This difference is presumed to be due to variation in conditions of measurement measurement (Hoel and Solhaug, 1998) and to leaves' structural differences that cause difference in reflection and/or scattering effects of light. About 80% of leaf N is attributed to chloroplasts and about 50% of the leaf N is utilised in photosynthetic proteins in leaves. Only 0.5 – 1.5% of the leaf N is, however, allocated to chlorophyll, depending on the growth environment and species of plant (Le Roux et al., 1999). An increased leaf N content allocated to chlorophyll–protein complexes, due to decreased irradiance has been reported for many plant species (Evans and Poorter, 2001). Moreso, the allocation ratio of leaf N to chlorophyll is reported to be affected by N supplementation conditions (Makino and Osmond, 1991). Comprehending the leaf characteristics and environmental factors effects on the SPAD readings, and the relationship between chlorophyll content and leaf N content per leaf area will be questions of critical importance when the SPAD-502 is used to guide N management practices in agriculture systems.

Jiang *et al.* (2017) observed a more significant interrelationship between SPAD-502 chlorophyll meter reading (SCMR) and chlorophyll a (Chl a) content values in tomato leaves than with chlorophyll b (Chl b) content. The SCMR, therefore, measures the Chl a content of the plants (Jiang *et al.*, 2017). The ratio of Chl a to Chl b in higher plants is about 3:1 (Rajalakshmi and Banu, 2015). Chlorophylls and carotenoids are the two primary classes of photosynthetically important pigments available in algae and plants. Each of the classes has numerous kinds of pigment molecules. Chlorophyll a (Chl a) absorbs light in the blue-violet portion, whereas chlorophyll b (Chl b) assimilates red-blue light (Rajalakshmi and Banu, 2015; Zielewicz *et al*., 2020).

## 2.12 Soil Enzymes

### 2.12.1 Soil enzymes and enzyme activity

Nutrient cycling in soils involves physical, chemical and biochemical reactions. The biochemical processes are mediated by microorganisms, plant roots and soil animals (Tabatabai, 1994b). All biochemical reactions are catalysed by enzymes, which are proteins with catalytic properties due to their power of specific activation. Enzymes are substances that, without undergoing permanent alteration, cause chemical reactions to

proceed at faster rates (Tabatabai, 1994b). All metabolic processes of all living materials (microbes, animals or plant roots) in the soil depend on these processes. Many classes of enzymes exist, such as respiratory (concerned with energy generation) and those concerned with cell synthesis. Soil enzyme production and its control on nutrient availability and soil fertility are controlled by the factors influencing soil microbial activity (Sinsabaugh *et al*., 1993). The contribution of microbial enzyme activity to hydrolysis of phytate in the Rhizosphere is negligible compared to the enzymatic cleavage mediated by root-derived enzymes (Martin, 1973). Availability of organic compounds for organisms present in soil is required in order to effectively decompose pesticides residue, and those processes are called cooxidation. Soil *pH* may affect sorption of enzymes and the effect of *pH* on sorption of enzymes has only recently been realized as being important in measurement of phosphatase activity (Li *et al*., 2004).

Enzyme activity in soil, on the other hand, provides information on its biochemical processes and is regulated by *pH* and microbial biomass (Dick *et al*., 1988). Soil enzyme activity is variable in time and limited by available substrate supply (Degens, 1998), and may provide useful linkage between microbial community composition and carbon processing (Waldrop *et al*., 2000). Information of soil enzyme activities used to determine soil microbiological characteristics are very important for soil quality and health, detecting changes occurring in soils (González *et al*., 2007) and are therefore "sensors" of soil degradation since they integrate information about microbial status (Aon and Colaneri, 2003), and also, physicochemical conditions (Baum *et al.*, 2003). They are involved in nutrient cycling and availability to plants and can be used as an index of soil functioning (Nannipieri *et al*., 2003).

### 2.12.2 Nitrogen cycle enzymes

Nitrogen cycle enzymes are called amidohydrolases and several amidohydrolases are present in soils. All are involved in hydrolysis of native and added organic nitrogen to soils (Tabatabai, 1994a) and is also essential to maintain soil fertility (Wick *et al*., 1998). They catalyse the hydrolysis of substrates with peptide bonds, using simple peptides and dipeptides (Pascual *et al*., 1997) and reflect the proteolytic potential of a soil and hence indicate the protein degradation capacity (Wick *et al*., 1998). Among these, amidase, urease L-asparaginase and L-glutaminase are the most important (Tabatabai, 1994a).

*2.12.2.1 Urease*

Urease enzyme is responsible for the hydrolysis of urea fertilisers applied to the soil into ammonia ($NH_3$) and carbondioxide ($CO_2$) ($NH_2CONH_2 + H_2O$ ----- > $2NH_3 + CO_2$) with an accompanying rise in soil *pH* (Tabatabai and Bremner, 1972; Andrews *et al*., 1989). This, in turn, results in a rapid N loss to the atmosphere through $NH_3$ volatilisation (Tabatabai and Bremner, 1972; Simpson and Freney, 1988). Due to this role, urease activities in soils have received a lot of attention since it was first reported by Rotini (1935), a process considered vital in the regulation of N supply to plants after urea fertilization. Soil urease originates mainly from plants (Polacco, 1977) and microorganisms found as both intra- and extra-cellular enzymes (Burns, 1986). On the other hand, urease extracted from plants or microorganisms is rapidly degraded in soil by proteolytic enzymes (Zantua and Bremner, 1977). This suggests that a significant fraction of ureolytic activity in the soil is carried out by extracellular urease, which is stabilized by immobilization on organic and mineral soil colloids. Urease activity in soils is influenced by many factors. These include cropping history, organic matter content of the soil, soil depth, soil amendments, heavy metals, and environmental factors such as temperatures (Krajewska *et al.,* 2003; Yang *et al*., 2006, 2016).

*2.12.2.2 Amidase*

Amidase is the enzyme that catalyzes the hydrolysis of amides and ammonia and the corresponding carboxylic acid. They act on C-N bonds other than peptide bonds in linear amides. It is specific for aliphatic and aryl amides and cannot act as substrates (Kelly and Clarke, 1962). This enzyme is widely distributed in nature. It has been detected in animals and microorganisms (Bray *et al*., 1949). Amidase is present in leaves of maize (*Zea mays L*.), sorghum (*Sorghum bicolor L*.), Alfalfa (*Medicago sativa L*.) and soya bean (*Glycine max L*.) (Frankenberger and Tabatabai, 1980a, b, 1982; Frankenberger and Dick, 1983). Microorganisms shown to possess amidase activity include bacteria (Clarke, 1970), yeast (Joshi and Handler, 1962), and fungi (Hynes, 1975). The substrates of this enzyme are sources of N for plants (Cantarella and Tabatabai, 1983).

*2.12.2.3 L-Asparaginase*

The activity was first detected in soils by Drobni'k (1956). This enzyme catalyses the hydrolysis of L-aspartic acid and ammonia. It is widely distributed in nature and has been detected in both plants and microorganisms (Wriston, 1971). Asparaginases have been shown to vary widely in different strains of microorganisms.

*2.12.2.4 L-Glutaminase*

It is among the amidohydrolases that play an important role in supplying N to plants. This hydrolase is specific and acts on C-N bonds other than peptide bonds in linear amides. The reaction catalysed by this enzyme involves the hydrolysis of L-glutamine yielding L-glutamic acid and ammonia. It has been detected in several animals (Sayre and Roberts, 1958), plants (Bidwell, 1974), and microorganisms (Imada *et al*., 1973). Plants and microorganisms are probable sources of L-glutaminase activity in soils but the main source is believed to be microbial in nature. (Roberts *et al*., 1972).

*2.12.2.5 Proteases*

Proteases in the soil play a significant role in nitrogen (N) mineralization (Ladd and Jackson, 1982), an important process regulating the amount of plant available N and plant growth. This enzyme in the soil is generally associated with inorganic and organic colloids (Nannipieri *et al*., 1996). The amount of this extracellular enzyme activity may be indicative not only of the biological capacity of soil for the enzymatic conversion of the substrate, which is independent of the extent of microbial activity, but might also have an important role in the ecology of micro-organisms in the ecosystem (Burns, 1982).

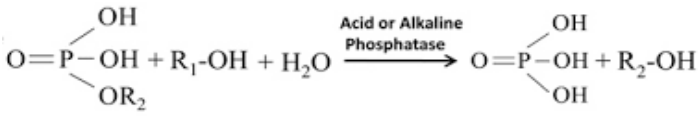
**2.12.3 Phosphorus cycle enzymes**

The general name phosphatases have been used to describe a broad group of enzymes that catalyse the hydrolysis of both esters and anhydrides of $H_3PO_4$ (Schmidt and Laskowski, 1961). The phosphatases include the phosphoric monoester hydrolases, phosphoric diester hydrolases, triphosphoric monoester hydrolases, enzymes acting on phosphoryl-containing anhydrides and enzymes acting on P-N bonds such as the phosphoamidase. The phosphomonoesterases (acid and alkaline phosphatases), have been studied extensively. They are classified acid and alkaline phosphatases because

they show optimum activities in acid and alkaline ranges, respectively (Speir and Ross, 1978). Plants have developed many structural and enzymatic adaptations to tolerate low phosphate availability. This includes transcription activity of acid phosphatases, which tends to increase under P-deficient conditions (Ndakidemi, 2006).

*2.12.3.1 Phosphomonoesterases*

The phosphomonoesterases are the most studied phosphatases in soil, as earlier stated. Such phosphomonoesterases as acid phosphatase (orthophosphoric monoester phosphohydrolase, EC 3.1.3.2) and alkaline phosphatases (orthophosphoric monoester phosphohydrolase, EC 3.1.3.1) are classified based on their optimum *p*H activities, which readily vary towards acid and alkaline ranges, respectively (Dick, 2011). The phosphomonoesterases are known to be hydrolysers of a variety of phosphomonoesters in the soil such as β-glycerophosphate, β-naphthyl phosphate, phenylphosphate, and *p*-nitrophenyl phosphate. The general equation involved in the hydrolysis of phosphomonoesters into orthophosphates in the presence of acid or alkaline phosphatase as catalyst is:




Where:
R represents either alcohol or phenol groups or nucleosides (Privat de Garilhe, 1967).

For phosphates to be available, from phytate to plants, it has to be hydrolysed by phosphatase (Richardson *et al*., 2000). The term *Phosphatases* is a general name, which has been used in describing a wide array of groups of enzymes capable of catalysing the hydrolysis of esters and anhydrites of hydrogen phosphate ($H_3PO_4$) (Schmidt and Laskowski, 1961). As earlier introduced, they are classified into five, as follows: i) phosphoric monoester hydrolases, ii) phosphoric diester hydrolases, iii) triphosphoric monoester hydrolases, iv) enzymes acting on phosphoryl-containing anhydrites, and v) such enzymes acting upon P-N bonds as the phosphoamidases (Florkin and Stortz, 1964). A phosphatase is generally, an enzyme that removes a phosphate group from its

substrate by hydrolysing phosphoric acid monoesters into a phosphate ion and a molecule with a free hydroxyl group as explained by Makoi and Ndakidemi (2008).

Specifically, the term (phosphatase) in soils is, however, used to denote a group of enzymes responsible for a hydrolytic cleavage of diverse ester-phosphate bonds of organic phosphates and anhydrides of orthophosphoric acid ($H_3PO_4$) into inorganic phosphate (Harrison, 1983). Yadav and Tarafdar (2003) reported that of such types of phosphatases as phytases can increase dephosphorylation (hydrolysis) rate in organic P ($P_o$). Phosphatases in the rhizosphere may either arise from soil microorganisms (Richardson *et al*., 2001a) or from plant roots (Hayes *et al.,* 1999). The hydrolysis of soil $P_o$ is chiefly mediated by the soil microbial activity (Li *et al*., 1997), although roots of plants also possess phosphatase and phytase activity (Tarafdar and Jungk, 1987). Phosphatases are believed to play critical roles in phosphorus cycles in soil ecosystems (Speir and Ross, 1978) as evidenced by their correlation with P stress and plant growth. Apart from being good indicators of soil fertility, phosphatase enzymes play a key role in the soil system (Eivazi and Tabatabai, 1977; Dick *et al*., 2000). For example, when there is a signal indicating P deficiency in the soil, acid phosphatase secretion, from plant roots, is increased to enhance the solubilisation and remobilisation of phosphate, thus influencing the ability of the plant to cope with the P-stressed conditions (Karthikeyan *et al*., 2002). These enzymes affect the P-acquisition and P-use efficiency in plants.

They also catalyse the hydrolysis of P-ester bonds from organic matter, resulting in the release of $P_i$, as reported by Garcia *et al.* (1995). They are the key enzymes in P cycling in soils (Pascual *et al.*, 1998). They show changes in the quantity and quality of soil phosphorated substrates (Rao and Tarafdar, 1992). These enzymes release phosphate from both cellular (Bariola *et al.*, 1994) and extra-cellular (Duff *et al.*, 1994) organic compounds at different stress levels. The activities of phosphate transporters are increased to optimise uptake and remobilisation of phosphate in P-deficient plants. The amount of acid phosphatase secreted by plants is genetically controlled, and differs with crop species and varieties as well as crop management practices (Wright and Reddy, 2001). Some studies have shown that the amount of enzymes secreted by legumes were 72% higher than those from cereals (Yadav and Tarafdar, 2001). Chickpea roots were able to secrete greater amounts of acid phosphatase than maize. The activity of acid and

alkaline phosphatases was found to correlate with organic matter in various studies (Aon and Colaneri, 2001).

*2.12.3.2 Acid and alkaline phosphatases*

Acid (Ac) and alkaline (Ak) phosphatases (Phases) particularly hydrolyse the ester bonds binding P to C (C-O-P ester bonds) in organic matter. During the process, $P_i$ is released from organically bound P such as leaf litter, dead root systems and other organic debris without concomitant release of C (Harrison, 1983). Organic P sources can be utilised by the plant after they are hydrolysed by phosphatase (George *et al*., 2002).

Acid phosphatase:

Acid phosphatase is a type of enzyme, used to free attached phosphate groups from other molecules during digestion. It is stored in lysosomes and functions when these fuse with endosomes, which are acidified while they function; therefore, it has an acid *pH* optimum (Baldwin *et al*., 2001). These enzymes are also used by soil microorganisms to access organically bound phosphate nutrients. An assay on the rates of activity of these enzymes may be used to ascertain biological demand for phosphates in the soil (Dick *et al*., 2000). Acid phosphatase secreted from roots was increased under P-deficient conditions (Hayes *et al*., 1999) and in hydroponic and soil cultures (Li *et al*., 2003; Li *et al*., 2007) and, consequently, the hydrolysis of phytate was also increased.

Alkaline phosphatase:

It is a hydrolase enzyme responsible for removing phosphate groups from many types of molecules, including nucleotides, proteins and alkaloids. The process of removing the phosphate group is called dephosphorylation. As the name suggests, alkaline phosphatases are most effective in an alkaline environment (Baldwin *et al*., 2001). Alkaline phosphatase has been ascribed to soil bacteria, as it is absent from the rhizosphere of plants grown axenically (Tarafdar and Claassen, 1988) and its activity was reported to be highest in soils that contained increased amounts of organic matter and it was least in soils with little or no organic matter addition (Joner and Jakobsen, 1995).

*2.12.3.3 Soil phosphatase activity*

The use of certain crop plants seems to enhance phosphatase activity as their roots secrete AcPhase and other exudates (Jones, 1998) the way cultivation of certain plant types might alter potential of phosphatase activity in soils (Neal, 1973). Studies indicated that in P-deprived soils, plants secrete enzymes actively into the rhizosphere (Ozawa *et al*., 1995). In a study, Yadav and Tarafdar (2001) reported that plants, especially in P-limiting soils, are known to secrete AcPhase immediately after roots emergence. Phosphatases are, probably, best known in terms of their capacity to degrade nucleic acids (Razzell and Khorana, 1959), and this explains their obvious potential role in soil P transformation and cycling. Acosta-Martinez and Tabatabai (2000) also considered inductive enzymes and soil *pH* as strongly affecting their synthesis.

Quality of soil organic matter (SOM) may, however, dictate the rate of extracellular phosphatase production, with the aid of arbuscular mycorrhizal fungi (AMF) hyphae as phosphate's activity is influenced by the $P_o$ availability to hydrolytic cleavage (Stewart and Tiessen, 1987; Joner and Jakobsen, 1995). Hence, roots' extracellular phosphatase activity may readily be stimulated in the presence of simply hydrolysable substrates (Tarafdar and Claassen, 1988), but may be repressed by non-hydrolysable $P_o$ forms as observed by Azcon and Elatrash **(**1997). Phosphatase activities may also be markedly influenced by the host plant (**A**zcon and Elatrash, 1997) and species of fungi available (Rao and Tarafdar, 1993). An even increased phosphates' activity is, however, more commonly observed in the rhizosphere as reported by Tarafdar and Jungk (1987). Plant roots, with a high phosphatase activity, have a greater potential of utilising soil $P_o$ (Helal, 1990). This activity does not, however, directly serve as a P-status measurement, it rather suggests for a potential release of P from organic sources as reported by McCallister *et al*. (2002). Phosphatase enzymes that majorly originate from microbes are widely distributed in nature and play a significant role in plant P nutrition (Tabatabai, 1994b). They are also very critical in chemical transformations aiding orthophosphate release from diverse $P_o$ compounds (Cookson, 2002). Phosphatases exhibit some persistence in soils, probably due to adsorption by humic materials, and hence they may represent a kind of "historical" soil property. Their assessment may suggest a cumulative estimate of potential in P mineralisation (McCallister *et al*., 2002).

Phosphatase is higher in the surface layer and rhizosphere, where majority of fresh and less humified organic matter is prevailing (Tarafdar *et al*., 2001) and playing a vital role in the plants and microbial P acquisition, and consequently, in its cycling within the soil environment as observed by Nadgórska-Socha *et al*. (2006).

# CHAPTER THREE

# 3 MATERIALS AND METHODS

## 3.1 Sites Location and Description

The experiment was conducted at two locations – Minjibir, in field on $12^{O}$ 8' 44.3" N and $8^{O}$ 39' 59.4" E, Sudan savannah agro-ecology; and Samaru, in Field in S2 ($11^{O}$ 10' 32.4" N and $7^{O}$ 36' 34.4" E), in northern Guinea savannah agro-ecological zone. The experimental sites, in these locations, were the Institute for Agricultural Research (IAR) Experimental Farms at Kano (at Wasai village (Figure 3.1) in Minjibir) and Samaru (Figure 3.2) Research Stations, respectively. Soils of Minjibir are Latosols, in their natural state, largely reflecting the influence of parent materials. There are alterations in the soils' profile characteristics - textural, structural and chemical, largely due to intensive use of the soils and addition of organic manures and inorganic fertilisers (Saidou *et al.,* 2012). Minjibir consists of the Sudan savannah vegetation, composing of farmed parkland, dotted with patches of savannah shrubs (Matlon, 1987). Minjibir experiences a monomodal pattern of rainfall, which begins in June and cease in late September, with a mean annual total in the range of 600 - 1000 mm. The mean daily temperature ranges from 26 $^{O}$C to 33 $^{O}$C (Saidou, 2005). Samaru soil is, on the other hand, largely classified as leached tropical ferruginous, an classed Typic Haplustalf (*i.e.*, ***hapl****ous* (a simple) ***ust****ic* (seasonally dry) ***Alf****isols*), in Soil Taxonomy, and Acrisol, in the FAO System or Alfisols in the United States Department of Agriculture (USDA) System (Tomlinson, 1965; Jones and Wild, 1975; Valette and Ibanga, 1984; Uyovbisere *et al.*, 2000). The soils are formed on loess materials overlying a basement complex, that covers an area of 43,000 km (Klinkenberg and Higgins, 1968), its clay content is predominantly kaolinitic (Gallez *et al.,* 1975; Ojanuga, 1979; Agbenin, 1996), typically high in iron (Fe)- and aluminium (Al)-oxides (Moberg and Esu, 1991), which are, agriculturally, of major importance (Agbenin, 1996). The high content of these (Fe and Al) oxides is certain to make applied and inherent P in them very susceptible and highly vulnerable to fixation against availability to crop plants.

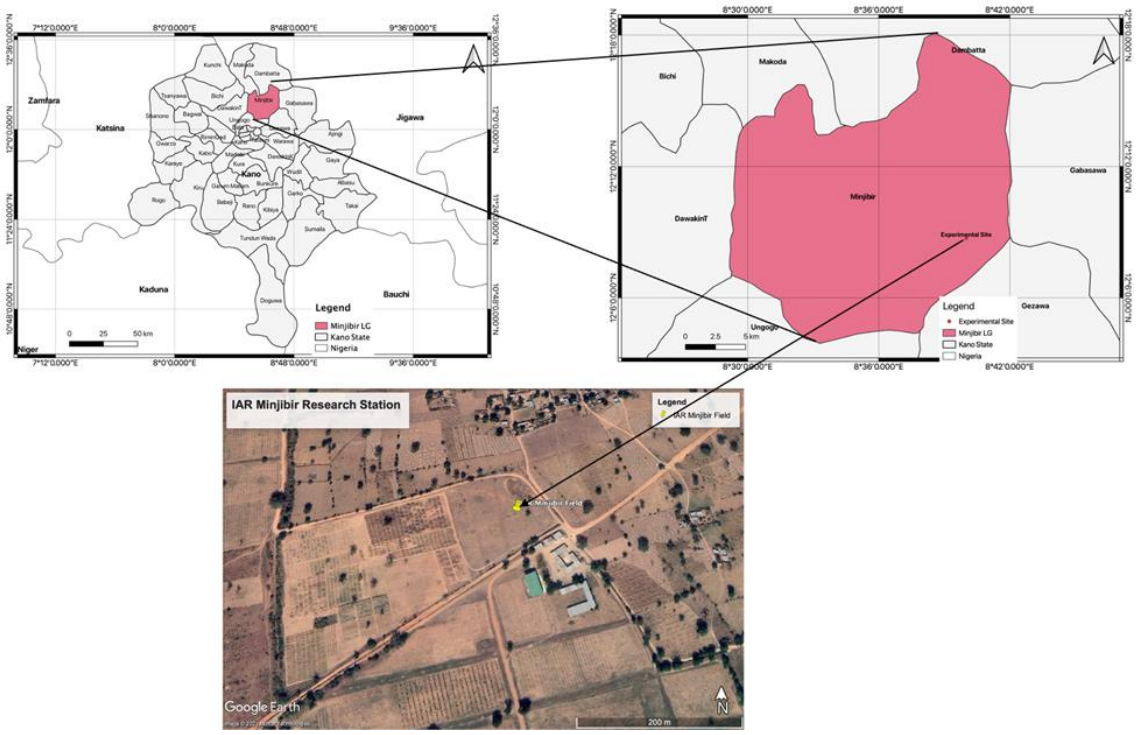



Figure 3.1: The experimental site at Minjibir, Sudan savannah agro-ecological zone of Nigeria

Rainfall period usually sets in May but, often, ceases in late September to early October. Dry season sets in by October and lasts into the month of May. Soil moisture and temperature regimes in the area are inferred to be ustic and isohyperthermic, respectively. Mean air temperature in the agro-ecology ranges between 25 $^{O}$C and 28 $^{O}$C during the rainy season (June to September) and decreases to less than 20 $^{O}$C in the months between December and February (Odunze, 2003; Odunze *et al.*, 2004; Oluwasemire and Alabi, 2004).

## 3.2 Sites' History

The relatively flat field, on which the trial was conducted in Minjibir has a very low Olsen P of 2.1 mg P kg$^{-1}$ soil (Saidou *et al.*, 2012) due, partly, to continuous cultivation and lack of commensurate nutrients replenishments. The field is now at a 14.18 mg Bray P kg$^{-1}$, due to agricultural activities now being taking place in the field. The field in Samaru was, on the other hand, a fallow for a period of over 25 years and hence, also, with a low Bray P status of 9.1 mg P kg$^{-1}$ (Figure 3.2).

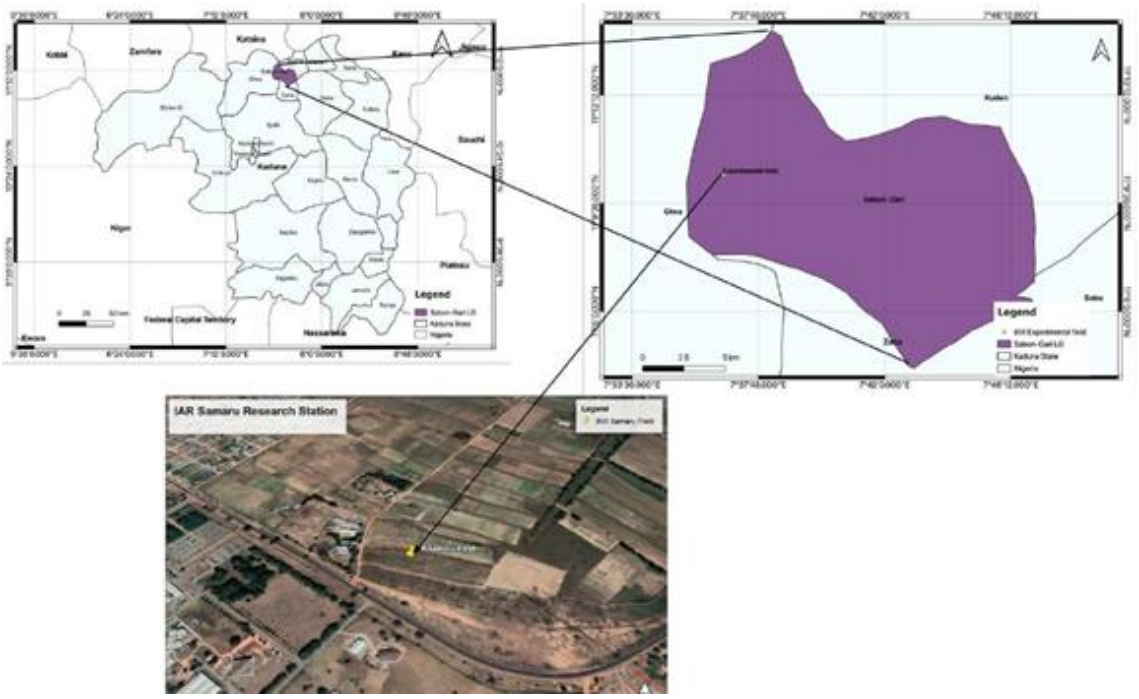



Figure 3.2: The experimental site at Samaru, northern Guinea savannah agro-ecological zone

## 3.3 Soil Samplings and Preparations

### 3.3.1 Soil profile pit and description

Two soil profile pits were dug in each of the two study sites and sampled from bottom upwards. This was to avoid possible contamination due to falling debris of soil materials within and across the horizons, in accordance to occurrence of natural horizon for soil characterisation. The profile pits were dug to the standard size of 200 cm long, 100 cm wide and a maximum depth of 200 cm, or when an impenetrable layer was encountered. One, deepest, pit per study site was, however, described about its full range of morphological characteristics according to international standards (FAO, 2006). These standards included soil depth, horizon thickness/boundary, matrix colour/mottles, texture/structure, consistence, porosity, roots, vegetation/landuse records, topography, slope, depth to water table and internal drainage status, *et cetera*. Following the descriptions, disturbed soil samples were collected from each genetic (natural) horizon for laboratory analyses.

Those soil samples, were air-dried, ground and sieved through a 2-mm mesh. The less than 2 mm fraction was analysed for some physical and chemical properties. In addition, some of the 2-mm sieved sample was further passed through a 0.5-mm mesh.

The less than 0.5 mm meshed fraction was then used for the determinations of organic carbon (OC), total nitrogen and micronutrients.

After crops' establishment, another set of soil samples, from the rhizosphere of each of the groundnuts plants were collected at flowering stage. This was done by carefully uprooting the plants sampled from the boarder rows. The soil directly attached to the roots within 0 - 5 cm proximity was then collected. These were separately bagged in labelled polythene bags, in their wet forms, and refrigerated, and were later used for the biochemical assays.

## 3.4 Physical, Chemical and Biochemical Analyses

The following soil analyses were conducted before the establishment of the field experiments and they included:

### 3.4.1 Physical analyses

#### *3.4.1.1 Particle size distribution*

Particle size distribution of the soils was determined using the hydrometer method as described by Gee and Bauder (1986).

Bulk density:

The bulk density of the soil was determined using the core-sampler technique (Jamison *et al*., 1950) in which undisturbed core samples were used for the determination based on a procedure by Blake and Hartge (1986).

Soil water characteristics:

Some soil water characteristics peculiar to the soils of the two study locations were observed using the Soil – Plant – Air – Water Field and Pond Hydrology software, version 6.02.75 (SPAW, 2007).

### 3.4.2 Chemical analyses

#### *3.4.2.1 Soil reaction*

The soil reaction (*pH*) of the sites was determined in the ratio of 1:2.5 soil to water and 0.01 M $CaCl_2$ suspensions, using glass electrode *pH* metre (Agbenin, 1995).

#### *3.4.2.2 Soil organic carbon/matter*

Soil organic carbon (OC) was analysed using wet oxidation method of Walkley and Black as described by Juo (1979). The organic matter content of the soils was, in turn,

computed therefrom by multiplying the % OC by a factor 2[1] (Nelson and Sommers, 1982; Van Reeuwijk, 2002; Pribyl, 2010).

#### *3.4.2.3 Total nitrogen*

The total nitrogen (TN) was determined by micro-Kjeldahl digestion procedure according to Jackson (1962).

#### *3.4.2.4 Carbon/nitrogen ratio*

The carbon/nitrogen ratio was calculated by dividing the percent organic carbon (OC) by percent total nitrogen (TN).

#### *3.4.2.5 Total phosphorus*

The total phosphorus was determined by acid digestion method as outlined by Murphy and Riley (1962).

#### *3.4.2.6 3.4.2.6 Available phosphorus*

Available phosphorus (Avl-P) was determined by Bray No. 1 acid fluoride method (Bray and Kurtz, 1945).

#### *3.4.2.7 Exchangeable acidity*

Exchangeable acidity of the soils was determined by shaking each soil sample in 1.0 M KCl and titrating the filtrate with 0.1 M NaOH according to procedure by McLean (1965).

#### *3.4.2.8 Exchangeable bases*

Exchangeable bases: calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) were extracted in 1 N sodium acetate ($NH_4OAc$) solution according to Chapman (1965). Calcium and Mg were, however, determined by ethylene di-amine tetra-acetic acid (EDTA) titration method (McLean, 1965). The K and Na were determined using flame photometry based on procedure according to Anderson and Ingram (1993).

[1] Published studies from the end of the 19th century have consistently shown that the van Bemmelen factor (1.724) is too low for most soils. The median value for the conversion factor was found to be 1.9 from experimental studies and applications that are more theoretical. A factor of 2, on the basis of the assumption that organic matter is 50 % carbon, would in nearly all cases be more accurate than the customary van Bemmelen factor of 1.724.

*3.4.2.9 Percent base saturation*

The percent base saturation was also computed by dividing the exchangeable bases (as summed) by the CEC multiplied by hundred (Hajek *et al*., 1972).

*3.4.2.10 Micronutrients*

Some of the micronutrients boron (B), iron (Fe), manganese (Mn) and zinc (Zn) contents of the soils were also determined according to procedures by Juo (1979) and Page *et al*. (1982).

*3.4.2.11 Phosphorus adsorption studies*

Determination of phosphorus adsorption isotherms:

Phosphate sorption experiment was conducted with the soils sampled from the two locations that represented the two agro-ecologies. This was in order to derive the relevant P sorption parameters (Fox and Kamprath, 1970a, b; Uyovbisere, 1994; Abekoe, 1996; Egwu, 2001; Okalebo *et al*., 2002). Three grams (3 g) of < 2 mm-sieved soil was placed in 50 ml centrifuge tubes which were equilibrated with 30 ml of potassium dihydrogen phosphate ($KH_2PO_4$) that contained varying amounts (0, 30, 90, 300, 600 and 1000 mg P $kg^{-1}$) of P using 0.01 M $CaCl_2$ as the background electrolyte. These concentrations were equal to the volumes of 0, 0.9, 2.7, 9, 18 and 30 ml, respectively. Three drops of toluene ($C_6H_5CH_3$) were added to each centrifuge tube contents. This was in order to suppress utilisation of P by microbes. The tubes were shaken for 30 minutes, two times per day, on an end-to-end shaker at room temperature for 6 days. The system was then centrifuged and the supernatant obtained. Phosphorus in the supernatant solution was determined by the blue colour method according to Murphy and Riley (1962). The difference between the P added and that remained in solution was regarded as the P adsorbed, which is the amount of P added minus P in the solution.

Determination of soil P sorption index (PSI):

Phosphorus sorption index (PSI) was obtained as the ratio of sorbed P and the logarithm of the equilibrium P concentration (Bache and Williams 1971), which was also adopted by Hughes *et al*. (2000) and Indiati and Sharpley (1997) as thus:

$$PSI = {}^{S}/_{\log Ct}$$

Where:

PSI is the P sorption index,

S is the P sorbed after equilibration period; and

Ct is the P concentration in solution after the equilibration period.

*3.4.2.12 Phosphorus fractionation studies*

Phosphate fractionation in soil:

Principles

The fractionation procedure, based on the differential solubilities of the various inorganic P (phosphate) forms in the soils, was used to fractionate the inorganic soil P into six fractions. The procedure of Chang and Jackson (1958), with some modifications by Chang (1962) and Peterson and Corey (1966), was used in this study. The forms determined included: Saloid-bound P, aluminium (Al)-P, iron (Fe)-P, Reductant soluble (Occluded-P), and Occluded Fe- and calcium (Ca)-P. The distribution and relative occurrence of the different P forms are of significant importance in studies that are relevant to genesis, chemistry and fertility of soils. Ammonium chloride ($NH_4Cl$) was initially used to remove the soluble and loosely bound P. This was followed by extraction with ammonium fluoride ($NH_4F$) to separate Al-P from Fe-P, sodium hydroxide (NaOH) extractant was then used in order to remove Fe-P. The sodium citrate-sodium bicarbonate-sodium dithionite (CBD) extraction method was employed in removing reductant-soluble P. The Ca-P was extracted with sulphuric acid ($H_2SO_4$), as Ca-P is insoluble in CBD.

The P fractionation procedure:

The following method, which is common for non-calcareous soils, was employed in the process of fractionation of inorganic P fractions in the soils, according to the procedure of Chang and Jackson (1958) as modified by Chang (1962) and Peterson and Corey (1966), and reported by Kuo (1996) as thus:

Saloid-bound P:

One (1) g of (< 2 mm) soil was placed in a 100-ml centrifuge tube after which 50 ml of 1 M $NH_4Cl$ was added. This was shaken for 30 min, to extract the soluble and loosely (Saloid)-bound P. The suspension was then centrifuged at 2,000 revolutions per minute (rpm) for 10 min. The supernatant liquid was then decanted and saved into a 50-ml

volumetric flask and brought to volume with deionized water (and labelled as extract A) for P determination.

Aluminium (Al)-P:

Fifty (50) ml of 0.5 M $NH_4F$ (*pH* adjusted to 8.2), was added to the residue from the step i (above) and shook for an hour, to extract aluminium phosphates. This was centrifuged and the supernatant decanted and kept, in a 100-mL volumetric flask (labelled extract B), for P determination.

Iron (Fe)-P:

The (step ii) residue was washed once with 35 ml of the saturated NaCl, by centrifugation at 2,000 rpm for 5 min, and decanted. Fifty ml of 0.1 M NaOH was then added to the soil residue and shaken overnight to extract iron phosphate. It was then centrifuged at 2,400 rpm for 15 min. This was decanted and the supernatant solution kept in a 50-ml conical flask (and labelled Extract C). Phosphorus in the supernatant was then determined.

Five (5) drops of concentrated $H_2SO_4$ was added to the solution (within the flask) and swirled so as to flocculate organic matter observed in the solution, where present. More $H_2SO_4$ was, also, added where the solution remained coloured, and when the colour was still not removed. In this case, the solution was then filtered through a P-free activated charcoal.

Reductant soluble (Occluded) -P:

The soil residue from iii (above) was, once again, washed with 25 ml saturated NaCl before it was suspended in 25 ml of 0.3 M sodium citrate ($Na_3C_6H_5O_7.2H_2O$). A gram of solid sodium dithionite ($Na_2S_2O_4$) was added and the mixture shaken for 5 min. This suspension was then heated for 15 min in a water bath adjusted at 85 $^0$C. The suspension was diluted to 50 ml with distilled water, shaken for another 5 min and centrifuged at 2,000 rpm for 10 min. the P in the supernatant was then determined.

Occluded Fe- and Al-P:

The soil residue (in iv above) was washed with 25 ml NaCl, 50 ml of 0.1 M NaOH added and the mixture shaken overnight. This suspension was then centrifuged for 15 min at 2,400 rpm. Concentrated $H_2SO_4$ was added to the suspension, in case of

colouration, so as to remove the colour. The P was then determined from the resultant supernatant.

Calcium (Ca)-P:

The Ca-P was determined from soil residue (from step v above) by; firstly, washing the soil with 25 ml NaCl before 50 ml of 0.25 M $H_2SO_4$ was added to it and shaken for an hour. The suspension was then centrifuged at 2,000 rpm for 10 min before the supernatant P was determined.

Residual P:

Calcium carbonate ($CaCO_3$) fusion method, based on a procedure by Udo and Ogunwale (1986), was used in the residual P determination. The dried soil residue (from vi above) was transferred into a platinum crucible before an addition of about a gram of solid $CaCO_3$. These were thoroughly mixed in the crucible and placed into a muffle furnace set at 800 $^0$C for 2 hr. The heated mixture was removed from the furnace and allowed to cool before 25 ml, of 0.01 N, hydrochloric acid (HCl) was added. The suspension was thoroughly stirred and filtered through a No. 1 v-folded Whatman filter paper. The P in the filtrate was then determined.

It is noteworthy here that where fractionation of the P fractions was terminated before going through the entire procedure, the soil was preserved in 25 ml saturated NaCl solution.

Determination of P in the extracts:

The P in the extracts was determined by the blue colour method of Murphy and Riley (1962). An aliquot of 5 ml was used in developing the colour as earlier described. The determination of P in $NH_4F$ (ammonium fluoride), NaOH and sodium citrate-sodium bicarbonate-sodium dithionite (CBD) extracts were pre-treated based on methods by John (1970) and Weaver (1974) before the colour development, as thus:

i $NH_4F$ extract: 0.5 g of boric acid ($H_3BO_3$) was added per 50 ml of the extract before taking the aliquot.

ii NaOH extract: After precipitating the organic matter, using the concentrated $H_2SO_4$, the *pH* of the extract was adjusted to 12 with NaOH using 2,4-dinitrophenol ($C_6H_4N_2O_5$) indicator. An aliquot of the clear solution was taken into a 50-ml

volumetric flask. Three (3) drops of NaOH was added until the colour changed from colourless to yellow. Water and the solution B were then added to develop the colour.

iii Dithionite-citrate-bicarbonate (DCB) extract: Reductant soluble P

Ten (10) ml of the extract was pipetted into a test tube. One ml of perchloric acid ($HClO_4$) was added and boiled to destroy the dithionite ($Na_2S_2O_4$). This was transferred into volumetric flask and the test tube rinsed into the flask. Three (3) ml of 5% ammonium molybdate [$(NH_4)_6Mo_7O_{24}$] solution was added. Some distilled water was added to make up the solution to 40 ml. Absorbance was read after 30 min. The colour was stable for up to 4 hours. A separate calibration curve was, however, prepared for this.

*3.4.2.13 Soil aluminium, iron and manganese fractionation studies*

The Sodium-citrate sodium-bicarbonate sodium-dithionite (CBD)-extractable Al, Fe and Mn were determined based on procedures described by Juo (1979), as thus:

The extraction procedure:

One (1) gram of < 0.2 mm sieved soil was weighed into 50-ml plastic centrifuge tubes, before 40 ml of sodium citrate and 5 ml of sodium bicarbonate solutions were added. The tubes were then heated in water bath adjusted to 75 $^0$C. A gram of sodium dithionite salt was added and stirred continuously for a minute, and occasionally for 15 minutes. The suspension was then centrifuged, and the clear supernatant solution decanted into a 200-ml volumetric flask.

The treatment, with sodium citrate-sodium bicarbonate sodium dithionite (CBD) was repeated once. The soil was, afterwards, washed twice each with 40 ml of sodium-citrate, centrifuged and the clear supernatant solution added to the extract in the 200-ml volumetric flask. The flask was finally made to the 200-ml mark with distilled water. It was then thoroughly mixed before the Fe and Al contents of the extract were determined atomic absorption spectrophotometer (AAS) at a wavelength of 248.3 nm in cases where concentration of the 10-times diluted extract was below 15-20 mg Fe $ml^{-1}$. A wavelength of 373.9 nm was, however, used for higher concentrations.

Ammonium oxalate extractable Al, Fe and Mn:

For the ammonium oxalate [$(NH_4)_2(COO)_2$] extraction method, the following procedure was employed, as thus:

The extraction procedure:

In this extraction, 0.5 g soil was weighed into a 50-ml centrifuge tube, before 25 ml of acidified $(NH_4)_2(COO)_2$ extraction solution was added. The tube was stoppered and shook in darkness for 4 hours. This was then centrifuged for 5 min and the clear supernatant solution decanted into a small screen-capped plastic bottle. Ten (10) ml of the extract was transferred into a 100-ml volumetric flask and diluted to mark, with distilled water, before Fe in the extract was measured.

Sodium Pyrophosphate-extractable Al, Fe and Mn:

For the sodium pyrophosphate ($Na_4P_2O_3.10H_2O$)-extractable Fe and Al extraction method, the following procedure was employed, as thus:

The extraction procedure:

In this extraction, 2.0 g of < 250 µm (0.25 mm) soil was weighed into a 500-ml bottle. 200 ml of 0.1 M $Na_4P_2O_3.10H_2O$ was then added with pipette and the suspension shook overnight. After this, 25 ml of the shaken suspension was transferred into a 50-ml centrifuge tube and centrifuged at 12,000 rpm for 30 min. The Fe content in the supernatant solution was later determined with AAS after 10-times dilution with distilled water.

### 3.4.3 Biochemical analyses

#### *3.4.3.1 Leaf chlorophyll content*

The soil plant analysis development (SPAD) meter, widely employed in both agricultural and research settings (Songsri *et al*., 2009), was used to determine the chlorophyll content (CC) of the groundnut genotypes. The SPAD readings were computed on the basis of two transmission values: red light transmission (at 650 nm), which chlorophyll absorbs, and infrared light transmission (at 940 nm), which chlorophyll doesn't absorb (Xiong *et al*., 2015). The SPAD chlorophyll metre reading (SCMR) of sampled plants, in each plot, was recorded based on a procedure by Songsri *et al*. (2009). The unit µmol of chlorophyll per $m^2$ of leaf surface (µmol $m^{-2}$ leaf surface) is simply indicated as the SCMR (Parry *et al*., 2014). There was no need for any special preparation for the SPAD Chlorophyll metre determination apart from its calibration (Süß *et al*., 2015), which is necessary whenever the metre is switched on. During the calibration, two light-emitting diode (LED)s emit light sequentially without any sample leaf in the measuring head. This received light is then converted into electrical signals

and the ratio of their intensities is calculated per leaf by the equipment (Süß *et al*., 2015) and the number of leaves sampled averaged per plot, and which is recorded.

### *3.4.3.2 Determination of biological $N_2$ fixation and N uptake*

At 6 weeks after sowing (WAS), plant and soil samples were collected with which some biochemical analyses were carried out in order to assess the low P tolerance, yield and BNF of the genotypes. The samples were collected from border rows of the plots, following standard procedure in each case. Out of the various methods of quantifying the $N_2$-fixation by legumes (Peoples *et al*., 1989) available, however, the total N-difference (TND) method was employed in this work, for convenience. Therefore, the amount of $N_2$ fixed by the groundnut genotypes, in each treatment, was estimated using the TND method. This was through a comparison of total N of the nodulating groundnut treatments with that of a non-nodulating groundnut isoline (ICGL 5), according to Peoples *et al*., (1989) and Hanssen (1994). Hence, the quantity of $N_2$ fixed was computed by subtracting total N of the non-nodulating reference (ICGL 5 isoline) from that of the nodulated groundnut genotype. The difference was recorded as an assumed N derived from BNF (*i.e.*, the $N_2$ fixed).

Thus,

$$\text{N2 fixed} = \text{Total N in nodulating legume} - \text{Total N in non} - \text{nodulating legume}$$

Where: the total plant N is derived from plant dry matter and % N, as thus:

$$\text{Total N in the crops} = \frac{(\text{Dry matter weight (kg/ha) x \% N in crops})}{100}$$

and;

$$\text{Ndfa (\%)} = \frac{(\text{Total N in nodulating legume} - \text{Total N in reference crop})\ x\ 100}{\text{Total N in legume}}$$

Where % Ndfa is the percentage of $N_2$ derived from the atmosphere (Herridge and Giller, 2016).

### *3.4.3.3 Assays for soil enzymes activities*

Assays for the activity of three soil enzymes were conducted such that one N- cycle and two P-cycle soil enzymes were, specifically, considered in this study. The N-cycle enzyme assayed was urease, one of the Amidohydrolases, while the P-cycle enzymes were acid and alkaline phosphatases, together termed as phosphomonoesterases.

Assay method for the amidohydrolase (urease):

The method of assay for the determination of urease activity in the soils of the study sites was by the determination of ammonium ($NH_4^+$-N), using steam distillation method based on procedures by of Tabatabai (1994a) and Mulvaney (1996).

Calculations involved for the $NH_4^+$-N liberated:

To calculate the amount of N liberated by steam distillation, the following expression was employed:

(S - C) x T

Where:

S = the volume of $H_2SO_4$ used in titration of the sample,

C = the volume used in titration of a control (obtained by steam-distilling an aliquot of soil suspension) and

T = the titre of the titrant (for the 0.0025 M $H_2SO_4$, T = 70 µg $NH_4^+$-N $ml^{-1}$). This value was, however, converted into mg $NH_4^+$-N $l^{-1}$, for convenience.

Controls performed in the urease assay:

Controls were performed in each series of assays to allow for $NH_4^+$-N not derived from urea through urease activity. While performing the controls, procedure described for the urease assay activity was vividly followed, but for the addition of 1 ml of 0.2 M urea solution, after the addition 35 ml KCl-$Ag_2SO_4$ solution, instead of the addition of 0.2 g of MgO.

Assay for acid phosphatase (AcPhase):

The method of assay for the determination of the acid phosphatase (AcPhase) activities in the soils of the study sites was based on procedures by Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977).

The procedure for AcPhase assay:

The following procedure, for the AcPhase assay was employed, as thus:

One (1) g of < 2 mm soil was placed in a 50-ml Erlenmeyer flask, and 0.2 ml of toluene ($C_6H_5CH_3$), 4 ml of MUB (*pH* 6.5), 1 ml of *p*-nitrophenyl phosphate solution, made in the same buffer (MUB *pH* 6.5) were added and the flask swirled for a few seconds to mix the contents. The flask was stoppered and placed in an incubator at 37 $^0$C for 1

hour. After the 1 hour, the stopper was removed and 1 ml of 0.5 M $CaCl_2$ followed by 4 ml of 0.5 M NaOH, was added, the flask swirled for a few seconds and the soil suspension in the flask filtered through a Whatman No. 2 v-folded filter paper. The yellow colour intensity of the filtrate was then measured with a spectrophotometer (Spectrumlab 23A®) at 410 nm.

Calibration curve for p-nitrophenol standard:

The *p*-nitrophenol content of the filtrate was calculated with reference to a calibration graph plotted from the results obtained with standards that contained 0, 10, 20, 30, 40 and 50 µg of *p*-nitrophenol. To graph was earlier prepared by diluting 1 ml of the standard *p*-nitrophenol solution to 100 ml in a volumetric flask and mixing the solution thoroughly. Then, 0-, 1-, 2-, 3-, 4-, and 5-ml aliquots of this standard solution were respectively, transferred into 50-ml Erlenmeyer flasks using pipette. The volumes, in each case, were adjusted to 5 ml by addition of distilled water (*i.e.*, 5, 4, 3, 2, 1 and 0 ml, respectively). The procedure, as described in the enzyme assay protocol, after incubation of the soil sample (*i.e.*, addition of 1 ml of 0.5 M $CaCl_2$ and 4 ml of 0.5 M NaOH, mixing and filtering the resultant suspension) was also followed here. The yellow colour intensity of the filtrate was also measured with a spectrophotometer at the same wavelength as for the soil enzyme assay (*i.e.*, - 410 nm). A calibration curve (of *p*-nitrophenol concentration versus absorbance) was then prepared.

Assay for alkaline phosphatase (AkPhase):

The method of assay for the determination of the alkaline phosphatase (AkPhase) activities in the soils of the study sites was also based on procedures by Tabatabai and Bremner (1969) and Eivazi and Tabatabai (1977). It is noteworthy, however, that the only difference between the two (AcPhase and AkPhase) assay procedures is in *pH* of the prepared modified universal buffer (MUB), which was *pH* 11 for the AkPhase. as presented below:

The AkPhase assay procedure:

One (1) g of < 2 mm soil was placed in a 50 ml Erlenmeyer flask, and 0.2 ml of toluene ($C_6H_5CH_3$), 4 ml of MUB (*pH* 11), 1 ml of *p*-nitrophenyl phosphate solution, made in the same buffer (MUB *pH* 6.5) were added and the flask swirled for a few seconds to mix the contents. The flask was stoppered and placed in an incubator at 37 $^0$C for 1 hour. After the 1 hour, the stopper was removed and 1 ml of 0.5 M $CaCl_2$ followed by 4

ml of 0.5 M NaOH, was added, the flask swirled for a few seconds and the soil suspension in the flask filtered through a Whatman No. 2 v-folded filter paper. The yellow colour intensity of the filtrate was then measured with a spectrophotometer (Spectrumlab 23A®) at 410 nm.

Calculating the phosphomonoesterases activities of the soils:
The phosphomonoesterases (acid and alkaline phosphatases) activities of the soils were calculated using the following formula:

$$y = mx + c$$

Where:
y = absorbance
m = slope
x = concentration
c = intercept = 0

Finally, the activity of each of the two soil phosphomonoesterases was calculated by multiplying the value of absorbance (y) calculated earlier by the dilution factor (10.2 ml), derived from the procedure, and divided by weight of the soil (1 g) used as follows: y x $10.2/1$.

## 3.5 The Field Experiments

The field experiments were concurrently conducted at the two agro-ecological locations: the Sudan savannah (SS) in Minjibir and northern Guinea savannah (NGS) in Samaru in both (2015 and 2016) rainy seasons.

### 3.5.1 Planting materials, density and spacing

Sixteen (16) groundnut genotypes (Table 3.1), including a non-nodulating isoline (ICGL 5) were used for the experiments. All the genotypes were sourced from the groundnut gene bank of the Department of Plant Science, Ahmadu Bello University, Zaria (ABU), except ICGL 5, which was only available with the Soil Microbiology Unit of the Department of Soil Science, ABU. The non-nodulating isoline (ICGL 5) was used as control and, therefore, used in the N-difference method of quantification of atmospheric nitrogen ($N_2$) fixed by the nodulating genotypes. Two seeds were hand-dibbled at an intra- and inter-row spacing of 0.20 m and 0.75 m respectively. This gave a total population of 133, 333 groundnut crop plants per hectare.

### 3.5.2 Experimental treatments

The treatments were composed of the sixteen (16) groundnut genotypes, as indicated in Table 3.1, and three (3) phosphorus (P) sources (from zero, single superphosphate (SSP) and Sokoto rock phosphate (SRP) sources). The SSP and SRP were applied at 30 and 90 kg $P_2O_5$ $ha^{-1}$, respectively. The SRP was first analysed in the laboratory from which thrice the rate of application of the SSP, calculated as the 90 kg $P_2O_5$ $ha^{-1}$ was considered. This was on the basis of considerations in the solubility difference between the two P sources. Experimental information from The International Atomic Energy Agency (IAEA) revealed that the relative effectiveness of rock phosphate, which is sparingly soluble, is about 3 - 5 times lower than the relatively readily soluble SSP as reported by Zapata (1986). Accompanying the treatments was a basal application of potassium (K) at 20 kg $K_2O$ $ha^{-1}$, as muriate of potash (MOP).

Table 3.1: Genotypes used in the experiment at the two (Minjibir and Samaru) agro-ecological locations

| S/No. | Genotype | S/No. | Genotype |
|---|---|---|---|
| 1. | ICGV-IS 07815 | 9. | Kwankwaso |
| 2. | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 10. | SAMNUT 10 |
| 3. | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 11. | SAMNUT 11 |
| 4. | ICGL 5* | 12. | SAMNUT 14 |
| 5. | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 13. | SAMNUT 21 |
| 6. | ICGV-IS 07083 | 14. | SAMNUT 22 |
| 7. | ICIAR 6AT | 15. | SAMNUT 23 |
| 8. | ICIAR 7B | 16. | SAMNUT 24 |

*A non-nodulating groundnut isoline used in computing $N_2$-fixation of the genotypes using N-difference method

### 3.5.3 Experimental design and plot arrangement

A split plot design was employed in which P source was imposed into the main plot; and the genotype into the sub-plot (Figure 3.3). This was replicated four (4) times where each replicate comprised of three (3) blocks, one for each of the three (3) P sources. Each block contained 16 plots thereby arriving at 48 (gross) plots per replication. The gross plot had an area of 13.5 $m^2$ that comprised of 6 ridges of 3 m each (*i.e.* 0.75 m x 6 ridges of 3 m each). The 4 innermost ridges were used as a net plot that had an area of 9 $m^2$.

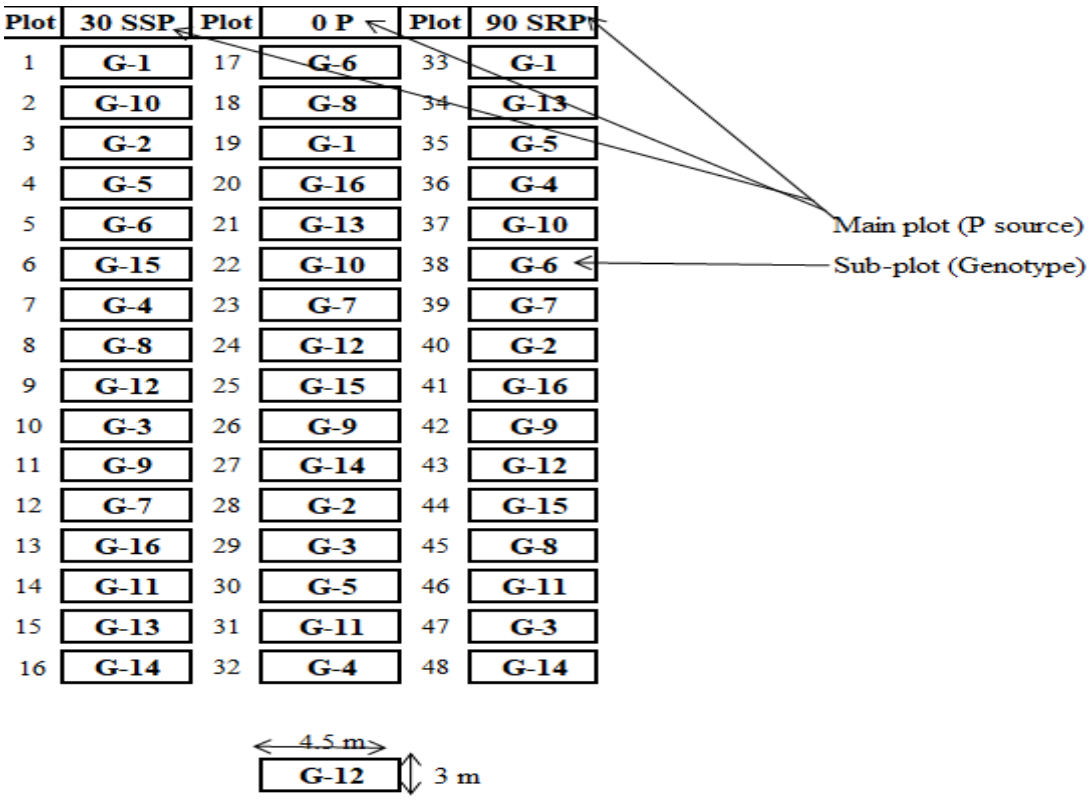



Figure 3.3: Showing field layout of one of the 4 replicates

## 3.6 Observations and Measurements

### 3.6.1 Data collection, preparations and analyses

The data were collected on per plot basis. The SPAD chlorophyll content was determined through the plants' leaves using a digital (SPAD-502Plus) chlorophyll meter (Konica Minolta Inc., 2017). Plant biomass (dry haulms) and pods data were also recorded. The dry haulms and pods were earlier air-dried to constant weights before been measured with a Mettler weighing balance. The dried haulms were ground and sieved, through a 500 µm mesh, for subsequent plant tissue total N determination. Nitrogen uptake was computed from the analysis results of the < 500-µm meshed samples. The quantities of atmospheric nitrogen ($N_2$), fixed by the genotypes, were also determined therefrom. The element N was earlier analysed following the micro-Kjeldahl method, according to a procedure by Jackson (1962).

## 3.7 Partial Economic Analysis

Partial economic analysis, for the field experiments, was performed, using the partial budget procedure, to determine the P source that would ensure a worthwhile return to the farmer, and at lower risk (CIMMYT, 1988). The economic analysis of the data was performed on the premise of the prevailing market price of

inputs and farm gate prices of operations and the outputs. The concepts used for the partial budget analysis were defined as follows: i. Gross Revenue (GR, in ₦ ha$^{-1}$), was the product of average price of groundnut and total yield for each P source; ii. Total variable cost (TVC, in ₦ ha$^{-1}$); was the cost of labour and inputs, which included groundnut seeds and fertilisers (Table 3.2 and Table 3.3, respectivelyly or Minjibir and Samaru); iii. Gross Margin (GM, in ₦ ha$^{-1}$), was the difference between GR and TVC; and iv. Gross Margin per ₦ invested (GM ₦ invested $^{-1}$), was the GM divided by TVC.

Table 3.2: Total variable cost (TVC, ₦ ha$^{-1}$) for Minjibir in 2015 and 2016 cropping seasons

| S/No. | Item | Quantity | | Unit price (₦) | | Price (₦ ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| | **Input** | | | | | | |
| 1 | Seed (kg kernel) | 30 | 30 | 600 | 600 | 18,000 | 18,000 |
| 2 | SSP (bags) | 3.4 | 3.4 | 3,500 | 3,500 | 11,900 | 11,900 |
| 3 | SPR (50 kg bags) | 5 | 5 | 1,750 | 1,750 | 8,750 | 8,750 |
| 4 | MOP (bags) | 2.7 | 2.7 | 6,800 | 6,800 | 18,360 | 18,360 |
| | **Labour (Mandays)** | | | | | | |
| 5 | Land Preparation | 68 | 72 | 250 | 250 | 17,000 | 18,000 |
| 6 | Sowing | 17 | 16 | 250 | 250 | 4,250 | 4,000 |
| 7 | Weeding | 52 | 58 | 250 | 250 | 13,000 | 14,500 |
| 8 | Fertilizer application | 5 | 6 | 250 | 250 | 1,250 | 1,500 |
| 10 | Harvesting | 18 | 16 | 250 | 250 | 4,500 | 4,000 |
| | **Total** | - | - | - | - | **97,010** | **99,010** |

SSP = Single superphosphate, SPR = Sokoto phosphate rock and MOP = Muriate of potash

Table 3.3: Total variable cost (TVC, ₦ ha-1) for Samaru in 2015 and 2016 cropping seasons

| S/No. | Item | Quantity | | Unit price (₦) | | Price (₦ ha$^{-1}$) | |
|---|---|---|---|---|---|---|---|
| | | 2015 | 2016 | 2015 | 2016 | 2015 | 2016 |
| | **Input** | | | | | | |
| 1 | Seed (kg kernel) | 30 | 30 | 600 | 600 | 18,000 | 18,000 |
| 2 | SSP (bags) | 3.4 | 3.4 | 3,500 | 3,500 | 11,900 | 11,900 |
| 3 | SPR (50 kg bags) | 5 | 5 | 1,750 | 1,750 | 8,750 | 8,750 |
| 4 | MOP (bags) | 2.7 | 2.7 | 6,800 | 6,800 | 18,360 | 18,360 |
| | **Labour (Mandays)** | | | | | | |
| 5 | Land preparation | 72 | 76 | 250 | 250 | 18,000 | 19,000 |
| 6 | Sowing | 18 | 16 | 250 | 250 | 4,500 | 4,000 |
| 7 | Weeding | 48 | 48 | 250 | 250 | 12,000 | 12,000 |
| 8 | Fertilizer application | 6 | 5 | 250 | 250 | 1,500 | 1,250 |
| 10 | Harvesting | 18 | 16 | 250 | 250 | 4,500 | 4,000 |
| | **Total** | - | - | - | - | **97,510** | **97,260** |

SSP = Single superphosphate, SPR = Sokoto phosphate rock and MOP = Muriate of potash

### 3.8 Statistical Analysis

The data generated from the field experiments were subjected to analysis of variance (ANOVA) using the General Linear Model (GLM) tool of the statistical analysis system (SAS) computer package (Steel and Torrie, 1980; SAS, 2014). Means that were significantly different at 5% ($P \leq 0.05$) level of probability were compared using Tukey's honest significant difference (HSD) (Steel and Torrie, 1980; Tukey, 1949) was employed in comparing the means observed in the field experiment. Parameters with coefficient of variability (CV) above the acceptable limit were transformed following the square root transformation procedure (Kozak *et al*., 2013; McDonald, 2014) before the statistical analyses were run. Magnitude and type of relationships between the parameters were assessed by running a simple correlation analysis (Little and Hill, 1978). Statistix10 statistical software was, however, used in comparing the means of all significant interactions observed in all the trials conducted (Statistix, 2016).

# CHAPTER FOUR

# 4 RESULTS AND DISCUSSION

## 4.1 Physical and Chemical Properties of the Soil from the Experimental Sites

### 4.1.1 The physical properties of the soil from the experimental sites

Particle size distribution, as determined for soils of Minjibir (in Sudan savannah, SS) and Samaru (in northern Guinea savannah, NGS) study locations was as shown in Table 4.1. Distribution of sand, silt and clay fractions was used to classify the Minjibir soils as sandy while those of Samaru as predominantly loam. This textural property will influence both the fertiliser use efficiency and cultivability of the soils. The loamy sand nature of Minjibir soils allowed for easier mechanical workability of the soil, however, with a somewhat resultant damage to the soil structure and hence an expected structural deterioration with continuous cultivation. The observed loamy texture of the Samaru soil, on the other hand, contributed to its moisture retention capacity, as also confirmed in Table 4.2, and also suggests leaching of fertiliser nutrients from these soils to be relatively low especially as clay content was relatively appreciable at pedal depth. Also, Malgwi and Abu (2011), in a study, attributed an observed reduced moisture retention capacity to a continuously cultivated than fallowed soils.

High sand content (> 700 g $kg^{-1}$) recorded for the Minjibir soils may be attributed to the granitic parent material from which the soils were developed because its composition directly influenced the distribution of fine earth fractions. The dominance of quartz ($SiO_2$), known to be highly resistant to weathering in basement complex (Adiela *et al*., 2018) and low in plant nutrients (Brady and Weil, 2013) could imply the enrichment of the sand content across pedal depth, since quartz is found essentially in sand fraction and often constitutes a significant portion of the silt fraction. The higher sand fractions observed in Minjibir could also partly be attributed to the more continuous cultivation of the soils than that of Samaru, which was fallowed for over 25 years (as earlier explained under sites' history). Although also influenced by changes in landscape positions, Malgwi and Abu (2011) in a study concluded the predominance of sand to be as a result of continuous cultivation. Silt content decreased from 100 g $kg^{-1}$ in the surface to 60 – 80 g $kg^{-1}$ in the subsurface. Clay content was, however, observed to increase from 80 g $kg^{-1}$ at the surface to 140 g $kg^{-1}$ at sub-surface horizons, thereby implying the occurrence of an argilluviation process.

Similarly, sand dominated the mineral fraction (480 - 680 g $kg^{-1}$) of the Samaru soils which may be partly attributed to parent material rich in quartz and gneiss minerals (Shobayo, 2010), and partly to pedogenic processes involving sorting of soil materials by biological activities. It can also be inferred that the contrasting agro-ecological zones, differing especially in precipitation and temperature conditions, contributed to higher biological activity observed in Samaru. Nutrient cycling and improved soil structure, due to the relative thicker vegetation in Samaru against the Minjibir study locations are some examples. Silt (140 - 320 g $kg^{-1}$) and clay (180 - 320 g $kg^{-1}$) contents were relatively high in this soil which contributed to its good structural and textural aggregation. It was also observed that this soil had some drainage impairment attributable to its slope position and hence it's imperfect drainage condition.

The silt/clay ratios (Table 4.1) for the Minjibir soil varied between 0.43 and 0.57 in the subsurface soils while the surface soil recorded a ratio of 1.25; thus, implying that the subsurface soils were significantly weathered, compared to the surface soil. This decrease in silt/clay ratio with pedal depth has been reported by many researchers, including Ayodele *et al*. (2012) and Sharu *et al*. (2013). Surface soil of Samaru recorded a ratio of 1.60 while the subsurface soils ranged from 0.67 to 1.20. The difference between the surface and subsurface values indicates a moderate differential weathering. Silt-clay ratio differentials between surface soils of Minjibir and Samaru soils further buttressed the characteristic influence of higher temperature on weathering in a typical Sudan agro-ecology. Values of silt/clay ratios of the soils (Minjibir and Samaru) were higher than the 0.15 critical value considered to be intensively weathered (Shobayo, 2019). Both soils from the study locations are deep as they are more than 100 cm in depth, this will allow for root proliferation and elongation by crops. There was a greater silt proportion than clay soil separates in the top soil of both Minjibir and Samaru, although a higher silt/clay ratio was evident in the Samaru soil (Table 4.1). The soil texture of both locations was, therefore, quite suitable for sustainable groundnut production (Raemaekers, 2001). Soil texture has a significant influence on soil physical conditions through its effect on pore continuity and pore-size distribution. This, in turn, controls gas diffusion due to a controlled soil water availability, and hence the soil organisms' activity (Hassink *et al*., 1993). An interaction between these processes, therefore, dictates the optimum soil moisture content for microbial biomass activity and its consequent distribution.

Table 4.1: Soil physical and chemical properties of the experimental sites

| | Location | | | | | | |
|---|---|---|---|---|---|---|---|
| | Minjibir | | | Samaru | | | |
| Horizon | Ap | B | BCx | Ap | Bt | Btv | $Btv_2$ |
| Depth (cm) | 0 – 15 | 15 – 32 | 32 – 100 | 0 – 21 | 21 – 69 | 69 – 108 | 108 – 165 |
| **Particle Size Distribution (g $kg^{-1}$)** | | | | | | | |
| Sand | 820 | 800 | 780 | 480 | 340 | 680 | 600 |
| Silt | 100 | 60 | 80 | 320 | 360 | 140 | 160 |
| Clay | 80 | 140 | 140 | 200 | 300 | 180 | 240 |
| Textural Class | LS | LS | LS | Loam | CL | SCL | SCL |
| Silt/Clay | 1.25 | 0.43 | 0.57 | 1.60 | 1.20 | 0.78 | 0.67 |
| **Soil Reaction (pH)** | | | | | | | |
| $H_2O$ | 5.86 | 5.94 | 6.05 | 5.87 | 5.55 | 5.95 | 6.21 |
| $CaCl_2$ | 4.43 | 4.51 | 4.95 | 4.78 | 4.75 | 5.29 | 5.57 |
| ΔpH | -1.43 | -1.43 | -1.10 | -1.09 | -0.80 | -0.66 | -0.64 |
| Exch. Acidity (cmol $kg^{-1}$) | 0.60 | 0.40 | 0.20 | 0.80 | 0.4 | 1.00 | 0.80 |
| ECE ($dSm^{-1}$) | 0.08 | 0.05 | 0.02 | 0.09 | 0.01 | 0.05 | 0.05 |
| **Exchangeable Bases and CEC (cmol (+) $kg^{-1}$)** | | | | | | | |
| Ca | 1.25 | 1.33 | 1.94 | 2.62 | 3.90 | 2.10 | 7.21 |
| Mg | 0.68 | 0.68 | 0.68 | 0.77 | 1.48 | 0.70 | 0.78 |
| Na | 0.35 | 0.32 | 0.35 | 0.48 | 0.59 | 0.43 | 0.53 |
| K | 0.25 | 0.15 | 0.17 | 0.34 | 0.67 | 0.26 | 0.33 |
| TEB | 0.63 | 0.62 | 0.79 | 1.05 | 1.66 | 0.87 | 2.21 |
| CEC | 4.80 | 4.80 | 3.90 | 5.20 | 5.30 | 4.80 | 4.10 |
| BS (%) | 13.18 | 12.92 | 20.13 | 20.24 | 31.32 | 18.18 | 53.96 |
| Org. C (g $kg^{-1}$) | 0.23 | 0.07 | 0.26 | 0.18 | 0.12 | 0.14 | 0.09 |
| *Org. M (g $kg^{-1}$) | 0.46 | 0.14 | 0.53 | 0.35 | 0.25 | 0.28 | 0.18 |
| Total N (g $kg^{-1}$) | 0.11 | 0.11 | 0.11 | 0.11 | 0.07 | 0.11 | 0.07 |
| C/N Ratio | 2.18 | 0.67 | 2.51 | 1.68 | 1.76 | 1.34 | 1.26 |
| Avl. P (mg $kg^{-1}$) | 29.42 | 27.53 | 25.645 | 29.04 | 26.78 | 18.86 | 25.65 |
| **Micronutrients (mg $kg^{-1}$)** | | | | | | | |
| Cu | 2.64 | 2.94 | 2.65 | 4.36 | 3.54 | 4.50 | 6.55 |
| Fe | 20.00 | 13.00 | 16.00 | 23.00 | 14.00 | 18.00 | 35.00 |
| Mn | 19.90 | 12.20 | 19.90 | 26.50 | 5.49 | 10.10 | 8.96 |
| Zn | 5.24 | 2.60 | 4.47 | 3.37 | 4.58 | 5.99 | 3.88 |

LS = Loamy sand; CL = Clay loam; SCL = Sandy clay loam; TEB = Total exchangeable bases; BS = Base saturation; Org. C = Organic carbon; Org. M = Organic matter; *Org. C x 2 (Nelson and Sommers, 1982; Van Reeuwijk, 2002).

More so, the size, distribution and continuity of pore spaces determine the available soil space for microbial activities and maybe protection of soil organic matter (SOM) from mineralisation as suggested by Zibilske and Bradford (2003). Typically, organic matter decomposes in sandy soils more rapidly than in clay soils, where the amount of soil

microbial biomass is more, thereby suggesting a greater physical protection of SOM in the more fine textured soils (Franzluebbers and Arshad, 1996). Specific respiratory activity is, however, higher in coarse-textured soils, thereby providing plant available nutrients more quickly than in fine-textured ones as reported by Hassink (1994) and Franzluebbers *et al*. (1995). Soil separate (texture) also affects availability of such nutrients as N and P by influencing the accumulation of total SOM (Schimel *et al*., 1985) and microbial activities (Hassink *et al*., 1993). Some researchers, like Scott *et al*. (1996) have, however, found no effects of texture on litter decomposition. Although the soil texture effect on SOM fractions' stabilization has been investigated by some authors, for example, Stevenson (1994) and Rosell and Galantini (1997), little information is handy on its effect on the properties and distribution of SOM components and related mobility and availability of, especially, N in the fine-textured (silt and clay) soil fractions, especially in the semiarid regions. It has also been reported that the higher the clay soil content, the more the stabilization of a given surface soil and the organic matter content is readily enhanced (Balesdent *et al*., 2000).

The soil texture can also be related to changes in P fractions and transformation. In that, it was reported by O'Halloran *et al*. (1985) that up to 90% of the spatial variance in total P content of a *Mollisols* was attributed to soil texture. A similar study indicated significant proportions of all P fractions variability, but for Brown Chernozemic loam $H_2SO_4$-P, to be attributable to sand content changes (O'Halloran *et al*., 1987). An increased silt, vis-à-vis, clay content, has also been significantly correlated with higher soil $NaHCO_3$-$P_i/P_o$, resin-P, and NaOH-$P_i/P_o$ pools. Positively correlated with sand content was HCl-P pool (O'Halloran *et al*., 1987). Evidence has it that soil P transformations were closely attached to C dynamics and microbial activity. These affect mineralization and immobilization of P as observed by Hedley *et al*. (1982a). A loamy soil, for example, enhanced higher microbial biomass than sandy and sandy loam soils (Cooper and Warman, 1997). Huffman *et al*. (1996) reported soil texture as having a higher effect on P transformation than the effects of residue addition, residue placement and nutrient addition combined. This is because the soil texture was observed to have affected labile inorganic ($P_i$,) labile organic ($P_o$) and microbial P pools. Therefore, soil texture affects availability of N and P by affecting soil microbial activity (Hassink *et al*., 1993), physicochemical equilibriums (McDowell *et al*., 2003) and SOM accumulation (Schimel *et al*., 1985; Kuhn *et al*., 2012). Different SOM pools are,

however, diversely affected by soil texture (Kuhn and Armstron, 2012) as soil texture affects SOM storages through direct and indirect mechanisms (Plante *et al*., 2006). The precise nature of soil texture impact on P equilibrium and dynamics on its (P) availability is still obscure (Salas *et al*., 2003; Kooijman *et al*., 2005). Phosphate diffusion towards crop roots is lower in sandy soils (Bolland and Allen, 2003); fixation can be higher in loamy soils, thereby decreasing the available P pool. There is, however, a little information on the influence of texture on different P forms distribution (Makarov *et al*., 2004), its physicochemical equilibria (Salas *et al*., 2003) and on its availability to crops.

The bulk density of the soils were observed to range from 1.46 to 1.50 Mg $m^{-3}$, with a mean of 1.49 Mg $m^{-3}$, in Minjibir; and 1.41 to 1.50 Mg $m^{-3}$, with a mean of 1.47 Mg $m^{-3}$, in Samaru locations (Table 4.2). The relative higher mean bulk density recorded in the Minjibir than Samaru could readily be due to the continuous cultivation of the former than the latter location. In a study by Malgwi and Abu (2011), differences in bulk density was observed between three landuses where the highest bulk density was conclusively attributed to continuous cultivation. This was in addition to the influence of changes in landscape positions. All the bulk densities observed in this study have generally, however, indicated that the soils are agriculturally good, as soils in both agro-ecological locations were lower than 1.65 Mg $m^{-3}$. Soils with bulk density higher than 1.65 Mg $m^{-3}$ are considered not agriculturally good (Vickers, 1979). Changes in soil bulk density are known to affect the amount of P-forms (kg $ha^{-1}$) and not its concentration (µg $g^{-1}$) as reported by Suñer and Galantini (2017). The ability of soils to supply and/or utilise fertiliser nutrients, thereby improving its productivity differs with location and period. These potentials are significantly affected by crop type and such soil physical properties as depth, texture and structure (Bolland and Gilkes, 1989; Aduayi *et al*., 2002). He *et al*. (2005) observed a consistent increase in percentage dissolution of PR with a decrease in soil particle sizes.

### 4.1.2 The Soil Chemical Properties of the Experimental Sites

### 4.1.3 Soil reaction (pH), exchangeable acidity and electrical conductivity (ECe) of soils of study locations

The result showed that the soil reaction (*p*H, in water) was moderately acidic for Minjibir and Samaru alike. The *p*H values, in Samaru, were observed to have irregularly decreased with increasing soil depth (Table 4.1). This could be attributable to

inconsistent distribution of basic cations within the soil profiles (Table 4.1.3). Although a *p*H range of 5.5 – 6.0 is regarded as satisfactory for most crops, a range of 5.5 – 6.5 is specifically regarded as optimum for groundnuts (Chude *et al.*, 2004; Chude *et al.*, 2011). Higher mean values of 4.6 (very strongly acidic) and 5.1 (strongly acidic) of *p*H in salt (0.01 M $CaCl_2$) were respectively recorded for the soils of Minjibir and Samaru agro-ecological locations. This implied that the higher clay content, recorded in the Samaru soil (Table 4.1), influenced the adsorption of more basic cations (*e.g*., total exchangeable bases of 5.79 cmol (+) $kg^{-1}$) to the exchange sites. This resulted into the higher soil base saturation (mean, 31%) observed in Samaru against the 15% average recorded for Minjibir (Table 4.1). Measurement of soil *p*H by salt gives a more realistic picture of soil reaction under field conditions (Agbenin, 1995); however, their mean *p*H values in $H_2O$ were similar. All the soil *p*H values measured in salt were lower than those measured in water. The delta (Δ**,** *i.e.*, change in) *p*H value [given as *p*H ($CaCl_2$) – *p*H ($H_2O$)] were, therefore, negative in soils of both locations (Minjibir and Samaru). This surmised that the soils had a net negative charge on their colloids (Breeuwsma, 1973). This could also imply that the soils were relatively dominated by such variable charge minerals as haematite as reported by Shobayo (2019) in a study.

The soils require liming due, additionally, to their calcium (Ca)-deficient nature, more especially that the *pH* in $CaCl_2$ in the soils of thetwo locations were in the very strongly (4.5 – 5.0) and strongly (5.1 – 5.5) acidic *pH* ranges (Soil Survey Staff, 1993), respectively in Minjibir and Samaru locations. Agbenin (1995) explained that measuring *pH* in a soil to 0.01 M $CaCl_2$ solution ratio is generally more preferred to same measurement in (distilled) water, for many advantageous reasons. Some of these reasons include provision of a more reasonable approximation of *pH* under field conditions by the former than the latter method. Also, the *pH* being measured under the former technique is independent of dilution and soluble salt concentration in non-calcareous and/or non-saline soils.

The electrical conductivity (ECe) was found to vary from 0.017 - 0.080 $dSm^{-1}$ and 0.007 - 0.085 $dSm^{-1}$ respectively, in Minjibir and Samaru soils. The values of soil ECe of the saturation extract were less than 4 $dSm^{-1}$ in all horizons of the profiles (Table 4.1) indicating that the soils were, predominantly, non-saline. Salinity problem is, in addition, not likely to develop in these soils if the current land use system were to be maintained. The ECe values obtained are also considered very low and would constitute

negligible effects on both crop growth and microbial populations (Peoples *et al*., 1989; Giller, 2001). These soils are therefore good for even saline sensitive crops. Values of exchangeable acidity revealed that Minjibir soils (mean, 0.40 cmol (+) $kg^{-1}$) and Samaru soils (mean, 0.75 cmol (+) $kg^{-1}$) were generally low, for their being less than 1 cmol (+) $kg^{-1-}$ (George, 2009). However, the higher mean value obtained in the Samaru soil (mean value tending towards a moderate rating) may be attributable to the improved soil textural property (due to the increased loamy nature) that influenced build-up of exchangeable acidity through reduced leaching of exchangeable aluminium (Al) and hydrogen (H) in the solum. The exchangeable acidity contents of soils at both locations were, therefore, within limits that posed no threat to crop production (George, 2009).

Dissolution of phosphate rock (PR) depends, strongly, on the chemistry and mineralogy of the source materials (Hammond *et al*., 1986). It is also established that the PR dissolution extent increases with carbonate substitution level and Ca: P ratio of apatite in the PR (Bolland *et al*., 1997). The dissolution of PR is also known to increase soil pH, resulting from the protons consumption during the reaction (Lewis *et al*., 1987; He *et al*., 2005). The dissolution also results in Ca and Mg release as reaction products proportionate to the P release rate. As such, changes in pH (in water or salt) and exchangeable (Ca + Mg) can be used as indirect means of estimating PR dissolution extent. Such soil properties as pH; and exchange Ca and Mg are, therefore, among the main factors closely related to PR dissolution in soil (He *et al*., 1996). Recently, Khalil *et al*. (2019) observed a suggested release of P from phosphate rock due to *p*H, and that *p*H, EC and $H_2O$-soluble P values also increased with increased rock phosphate.

### 4.1.4 Exchangeable bases, cation exchange capacity and base saturation of soils of study locations

The exchangeable Ca content was found to range from 1.25 to 1.94 cmol (+) $kg^{-1}$ (mean, 1.56 cmol (+) $kg^{-1}$) and 2.10 to 7.21 cmol (+) $kg^{-1}$ (mean, 3.96 cmol (+) $kg^{-1}$) respectively for Minjibir and Samaru soils. The mean value of exchangeable Ca was rated low for Minjibir soils while soils of Samaru rated moderate (FMAWRRD, 1989; FMANR, 1990) as in Appendix III. Exchangeable Ca distribution was irregular with pedal depth assuming the distribution of clay content (soil exchange site) with high Ca affinity. Exchangeable Ca content was, however, still the highest in proportion to other bases examined (*i.e.*, Ca > Mg > Na > K). Exchangeable Mg was similar in both, surface and subsurface, soils of Minjibir with similar values of 0.68 cmol (+) $kg^{-1}$ in

each of the horizons across the pedal depth. This implied no any corresponding movement of Mg with pedogenic processes. The mean value of Mg content (0.88 cmol (+) $kg^{-1}$) within this soil is indicative of a moderate level status. The exchangeable Mg content, however, varied between 0.70 to 1.48 cmol (+) $kg^{-1}$ (mean, 0.93 cmol (+) $kg^{-1}$) in soils of Samaru, which was also rated moderate (FMAWRRD, 1989; FMANR, 1990). The highest Mg content was, however, recorded in the subsurface soil horizon suggestive of increased moisture content that influenced leaching of exchangeable Mg from the surface soils and this also could have aided its irregular distribution across the horizons.

The mean values of exchangeable Na of 0.34 cmol (+) $kg^{-1}$ and 0.51 cmol (+) $kg^{-1}$ respectively for the Minjibir and Samaru soils. This rated them as moderate (FMAWRRD, 1989; FMANR, 1990). The Minjibir soil recorded an exchangeable Na that did not decrease with increase in depth. The exchangeable base, in Samaru soils, on the other hand, was irregularly distributed; which could be associated with the rainfall pattern (Appendix VI) which could have encouraged leaching and capillary translocation of the Na content. Exchangeable K values, as shown in the same Table 4.1, were also inconsistently distributed with pedal depth in soils of both locations. The values varied between 0.15 and 0.25 cmol (+) $kg^{-1}$ (mean, 0.19 cmol (+) $kg^{-1}$ - low), and 0.26 and 0.67 cmol (+) $kg^{-1}$ (mean, 0.40 cmol (+) $kg^{-1}$ - moderate) (FMAWRRD, 1989; FMANR, 1990) respectively for the Minjibir and Samaru soils. The high value (0.25 cmol (+) $kg^{-1}$) observed at the surface soil horizon of Minjibir might not be unrelated with its OM content. Perceived similarity of the exchangeable bases (Ca, Mg, Na and K) between the soils of Minjibir and Samaru may be suggestive of the similarity in land use, leaching pattern and/or crop uptake within both study agro-ecological locations. However, it can be surmised that soil organic matter (Table 4.1) contributed significantly to the exchangeable bases recorded in the Minjibir soils. Inheritance, from parent material, may, however, be attributed to the Samaru soil conditions. Generally, as shown by the total exchangeable bases (TEB), low to moderate levels of Ca, Mg, Na and K were of tremendous advantage to the soils and, consequently, the crops that were grown on it in the study locations. Such soil properties as pH; and exchange Ca and Mg are among the main factors closely related to PR dissolution in soil (He *et al*., 1996).

Change in soil management and land use practices is generally known to have a significant effect on organic matter content of soils. Many works have attached nutrients' depletion and serious soil erosion to ill soil management, continuous cultivation of tropical soils, deforestation, and so on (Tilhun, 2015). Land use practice is also known to affect the supply and distribution of soil nutrients by a direct alteration of soil properties and influence on root zone biological transformations (Bezabih *et al*., 2016). This is, for example, in the case of land conversion which repeatedly leads to nutrient losses when it upsets surface and mineral horizons (Semahugne, 2008). Cation exchange capacity (CEC) of the soils ranged from 3.90 to 4.80 cmol (+) $kg^{-1}$ (mean, 4.50 cmol (+) $kg^{-1}$) and 4.10 to 5.30 cmol (+) $kg^{-1}$ (mean, 4.85 cmol (+) $kg^{-1}$) respectively for Minjibir and Samaru soils. Although relatively better in Samaru, the mean values recorded for both soils were generally in the low CEC rating. The higher SOM content (Table 4.1) observed for Minjibir soils may not have influenced their CEC. Similarly, the soil parent materials (basement complex) could not have, considerably, influenced the CEC status of both soils due to their granitic origin.

The low CEC could also be attributable to the extensive cultivation of the soils. The values were generally an indication of low nutrient retention of the soil as reported by other findings in the areas (Shobayo, 2010; Gabasawa, 2011; Yau, 2015; Shobayo, 2019). Similarly, even lower values recorded in subsurface soils of Minjibir were an indication of a very low lessivation. The relatively higher CEC content recorded in the surface soils of Samaru as against the subsurface soils is suggestive of possible contribution from OM. The low CEC content in solum of both soils was also suggestive of dominance of low activity clay of the soils. Generally, Nigerian soils are light in texture, and consequently low in CEC (Agboola, 1986). In that, the clay texture ranges only between 9 to 43% (*i.e.*, 90 – 430 g $kg^{-1}$) in more than 60% of the country while that of CEC is between 2.40 to 5.95 mg $kg^{-1}$ of the soils with the value being less than 5 in most parts of the area (Agboola, 1986). Typically, soils with low CEC, like sandy soils, are very prone to quickly becoming acidic than their counterparts with high CEC (Efretuei, 2016).

The base saturation (BS), by ammonium acetate ($NH_4Ac$) method, calculated for the soils shows values with an irregular distribution with increase in depth down the soil horizons. The soils were rated low in BS, for being less than 50% (FAO, 1999). The highest percentage of BS observed for Minjibir soils was 20.13 which, and considered

very low (FAO, 1999, Shobayo *et al*., 2019). It also further reflected the distribution of the corresponding total exchangeable bases (TEB), as depicted in the same Table 4.1. Percent BS in the Samaru soils, on the other hand, varied between 18.18 and 53.96%, with an average of 30.93%, however rated low, but higher than the average observed (15.41%) for Minjibir soils. This difference could also be attributable to the observed relatively humified loamy textural characteristic of the Samaru surface soils (Table 4.1), which might have influenced its macronutrients (Bajgiran, 2013).

### 4.1.5 Organic carbon, total N and available P of soils of the study locations

The organic carbon (OC) and, consequently, organic matter (OM) contents were higher at the surface soils of Minjibir and Samaru than their mean contents in the subsurface soils. It could be attributed to deposition of biomass on soil surfaces. Researches indicated that presence of organic residues in soil increase its urease (Özdemir *et al*., 2000) and phosphomonoesterases (Reddy *et al*., 2020) activities. This is re-confirmed in this work, as shown in Table 4.11. The distribution of OC across the soil horizons, however, decreased consistently except in the BCx and Btv horizons of Minjibir and Samaru, respectively. This might be due to pedoturbation process within the respective soil solums. Generally, the values observed for soils of the study agro-ecological locations were rated low according to Esu (1991). The low content has been attributed to high mineralisation of organic matter, majorly due to high temperature within the study locations, as reported in other studies (Odunze, 2006; Eche *et al*., 2014; Yau, 2015; Aliyu, 2016). Continuous cultivation have also been attributed to depleting OM and, consequently low, OC status (Malgwi and Abu, 2011; Shobayo, 2019).

The same Table 4.1 reveals the distribution pattern and content of total nitrogen (TN) and available phosphorus (AP) of soils of the study locations. Highest TN (of 0.105% in all horizons, in Minjibir, and Ap and BtV horizons, in Samaru soils) was observed. The highest AP (of 29.416 mg $kg^{-1}$, in Minjibir, and 29.039 mg $kg^{-1}$, in Samaru) was observed in the Ap horizon of each location. The nutrient element P was, however, also observed to steadily reduce with depth in Minjibir but irregularly in Samaru. Conversely, the OM in the Minjibir soil was observed to irregularly increase with depth (from surface to subsurface) but irregularly decreased with depth in Samaru soil. This, in part, implied that the TN and AP were not considerably contributed from the organic constituents of the soils. Nitrogen availability due to biological fixation, especially in soil reaction range between 6 and 8, the most favourable *p*H range for symbiotic $N_2$-

fixing microbes, and precipitation could contribute some N to soils (Foth, 1990). Phosphorus release from (desorption of precipitated) mineral deposits is, for example, also deemed important, although much of the plant-available P is supplied through mineralisation of organic materials. The quantity of plant-available P here is, however, not much in any one growing season (Hopkins, 2015). A decreasing particle size is also reported by Bolland and Gilkes (1989) to, usually; increase the rates of dissolution and agronomic effectiveness of PR. To reaffirm this, Bolland and Allen (2003) also reported lower phosphate diffusion towards roots of crops in sandy soils. A steady content distribution down the profile was, however, observed; a trend that indicated that its distribution was controlled by a co-translocation process with clay. This was with especial reference to Minjibir. Moderate and low total N contents were respectively observed for Minjibir and Samaru locations (Table 4.1; FMAWRRD, 1989; FMANR, 1990).

The ratio of carbon to nitrogen (C/N) observed in the surface soil, of Minjibir and Samaru locations, was higher than the average C/N ratio of each subsurface soil counterpart of Minjibir (1.59) and Samaru (1.45) as depicted in the sameTable 4.1. This, however, generally indicated a good C/N ratio for the soils in both locations and all horizons, especially in Samaru soils. The C/N ratio of a soil depicts its suitability to supply nutrients and capability of its carbon storage and the lower the ratio the better (Swangjang, 2015). Higher C/N ratio is indicative of an affected decreasing N pool as reported by Callesen *et al*. (2007). The C/N ratio in arable soils, of arid regions, is reported to, usually, range between 8:1 and 15:1, with between 10:1 and 12:1 being the median (Brady and Weil, 2008; Persson and Kirchmann, 1994). A ratio of about ≤ 20:1 is, however, generally considered an approximate threshold between net mineralisation and net immobilisation of soil N (Killham, 1994; Swangjang, 2015). Management practice must have influenced this perceived reversed observation as the higher mineralisation rate is expected to be more pronounced in the Minjibir soils.

Similarly, numerically higher values of available phosphorus (AP) were observed for soils in Minjibir, although both soils (*i.e.*, of Minjibir and Samaru) had AP contents that qualified them of being of high AP rating (> 20 mg $kg^{-1}$) as according to Aduayi *et al.* (2004) and Chude *et al.* (2011). Since the organic matter (OM) levels in the study locations were low, a negligible AP contribution is expected from organic matter. It is reported that the residue of plants contains a moisture of up to 60-90% and the dry

matter left contains many nutrient elements, including C, O, H and small quantities of S, N, P, K, Ca and Mg. Although these nutrients are present in minute quantities, they are very vital in soil fertility management (Bot and Benites, 2005). Therefore, parent materials would have been the major contributor, as soils that are developed from such an inherently rich material as basalt have higher fertility potentials than those of granitic origin, which have lesser nutrients as also explained by Bot and Benites (2005). It was also observed that the AP content decreased irregularly with depth, and higher values were recorded for the soils at the surface than the subsurface. This observation could be a part contribution by the relatively higher OM in the surface soil horizons. This suggests a need for additional N and P supplies to the soils of both locations from all sources possible, including biological $N_2$-fixation, in case of N.

### 4.1.6 Micronutrients levels in soils of the study locations

Values of micronutrients determined in the soils of the study locations are presented in Table 4.1. Values of extractable micronutrient levels ranged from 2.64 to 2.94 mg $kg^{-1}$ (mean, 2.74 mg $kg^{-1}$), 13.00 to 20.00 mg $kg^{-1}$ (mean, 16.33 mg $kg^{-1}$), 12.20 to 19.90 mg $kg^{-1}$ (mean, 17.33 mg $kg^{-1}$) and 2.60 to 5.24 mg $kg^{-1}$ (mean, 4.10 mg $kg^{-1}$) respectively for copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) in the Minjibir soils. Similarly, it ranged from 3.54 to 6.55 mg $kg^{-1}$ (mean, 4.74 mg $kg^{-1}$), 14.00 to 35.00 mg $kg^{-1}$ (mean, 23.00 mg $kg^{-1}$), 5.49 to 26.60 mg $kg^{-1}$ (mean, 12.80 mg $kg^{-1}$) and 3.37 to 5.99 mg $kg^{-1}$ (mean, 4.46 mg $kg^{-1}$) respectively for Cu, Fe, Mn and Zn in Samaru soils. Copper (Cu) in both soils varied irregularly down the profile and was attributed to leaching and capillary effect on Cu; similar occurrence was observed for extractable Fe. Both micronutrients (*i.e.*, Cu and Fe) had their mean values higher in the soils of Samaru. This implies that they were released through weathering of parent materials/pedogenic processes. However, their mean values show they are high in both soils (*i.e.*, of Minjibir and Samaru). Copper values were higher than the critical levels of (1.00 to 2.00 mg $kg^{-1}$ soil) as submitted by Sims and Johnson (1991) for 0.1 *M* HCl extractable Cu. Content of 0.1 *M* HCl extractable Mn in the soils was distributed inconsistently with depth in Samaru soils, a pattern that could be attributable to the distribution of *p*H in the soil horizons; but followed a regular pattern with depth in Minjibir soils.

Availability of Mn increases as soil *p*H decreases (Shobayo, 2019). Both soils were rated very high in Mn content, being generally > 5 mg $kg^{-1}$ (Appendix IV; Enwezor *et*

*al*., 1989). The higher mean values obtained in Minjibir soils were suggestive of contributions from OM. Extractable zinc (Zn) contents of the Minjibir and Samaru soils were irregularly distributed down the soil profiles. Their values were also rated as high (> 2 mg $kg^{-1}$). The highest values observed at surface soils were attributable to an association of Zn with soil organic matter. Conversely, the high values observed in the subsurface soils could be the tendency of Zn been adsorbed on clay size particles (Alloway, 2008). The micronutrients (Cu, Fe, Mn and Zn), so far analysed, were in sufficient supply. The groundnut genotypes grown in the study locations were, therefore, not vulnerable to any, let alone exhibiting, deficiency symptoms and/or requiring external supplementary applications of these nutrient elements.

Micronutrient deficiencies usually occur when sufficient quantities in the soil are insoluble and, hence, not available to the crop, and not due to insufficient amounts in the soil (Ayele *et al*., 2014). There are many factors, soil and environmental, affecting micronutrients' availability to plants. Among the major factors are: soil reaction, soil organic matter content, temperature, soil texture, which affects leaching, soil water content and nutrient interactions (Genc *et al*., 2005; Ayele *et al*., 2014).

### 4.1.7 Classification of the soils

Soils of both study locations were classified according to the United States Department for Agriculture (USDA) Soil Taxonomy (Soil Survey Staff, 2014). Soil moisture regime, important physical and chemical properties outlined by the USDA Soil Taxonomy (Soil Survey Staff, 2014) were taken into account for the classification to the Gre6at-group level. Soil moisture regime of the areas under study had the ability to supply water to crops without irrigation in a normal year (as could be inferred from the rainfall data in Appendix V, Appendix VI and Appendix VII. It has at least 90 consecutive days when moisture is available, but more than 90 cumulative days when water is not available in the rooting zone. It is therefore classified as having an *Ustic* soil moisture regime (Table 4.2). Ochric epipedon was diagnostic for soils at both Minjibir and Samaru agro-ecological locations.

The subsurface horizon met the particle-size class criteria for coarse-loamy and fine-loamy respectively, for Minjibir and Samaru soils (Table 4.1), and was greater than 7.5 cm thickness with evidence of clay illuviation; therefore, argillic endopedon was diagnostic for the soils. Base saturation (BS), by $NH_4OAc$, was less than 50%

(Table 4.1). The soils, therefore, fitted into the Order *Ultisols*. At the Sub-order level, both soils were classified into *Ustults* because they had *Ustic* soil moisture regime. The soils of Minjibir and Samaru were classified as *Haplustults* at the Great-group level. This is because they did not possess any of the special features in the profile that distinguished the other Great-groups. Soils of both locations were, therefore, observed to be *Haplustults*, which are *haplous* (simple) *Ultisols* with an *ustic* soil moisture regime (Tel and Hagarty, 1984; Soil Survey Staff, 2014).

If well managed, *Ultisols* (also called *Acrisols*) can support agriculture. In climates with marked dry season, however, this soil class can become very hard to prepare, especially by hand. Although incapable of holding large quantities of nutrients, this soil could still be productive with small doses of, but regular, fertilisers applied in the vicinity of crop plants. Low nutrients requiring plants can do well on this soil type. This soil type is, however, also very susceptible to capping and erosion problems, especially when left exposed.

## 4.2 Soil Water Characteristics of Soils in Minjibir and Samaru Study Locations

The Minjibir soil was observed as having contained a lower soil available water and higher hydraulic conductivity, as indicated in Table 4.2. This may, invariably, lead to higher water and, consequently, nutrient losses from the soil environment. The Samaru soil was, on the other hand, observed as having contained higher available water, lower hydraulic conductivity and slower unsaturated hydraulic conductivity (Table 4.2). Soil hydraulic properties are important in determining water storage and fluxes, and hence a number of critical biogeochemical cycling on critical zone of the earth (Lin, 2010). Hydraulic conductivity, of soil surface layers, at and near saturation is, in particular, a vital parameter that regulates the distribution of rainwater between groundwater recharge, surface runoff, plant water uptake and growth, biogeochemical cycling rates in soil; and pollutants risk impacts on ground and surface waters (Jarvis *et al*., 2013). The low conductivity status of soils of both locations (Table 4.2) indicated tendencies of more soil water availability and its lesser loss potentials. The level of soil compaction observed for the soils of both locations was within the normal rating. This suggested for an agriculturally normal and viable bulk density (Shaver *et al*., 2002; van Donk *et al*., 2008), which was also corroboratively observed at both agro-ecological locations (Table 4.2).

Table 4.2: Soil water characteristics of soils in Minjibir and Samaru study locations

| Location | Minjibir | | | Samaru | | | |
|---|---|---|---|---|---|---|---|
| Horizon | Ap | B | BCx | Ap | Bt | Btv | $Btv_2$ |
| Depth (cm) | 0 – 15 | 15 – 32 | 32 – 100 | 0 – 21 | 21 – 69 | 69 – 108 | 108 – 165 |
| Wilting Point (% Vol) | 6.80 | 10.30 | 10.30 | 13.70 | 19.10 | 12.60 | 16.00 |
| Field Capacity (% Vol) | 13.20 | 16.90 | 17.30 | 26.40 | 33.20 | 21.40 | 26.20 |
| Saturation (% Vol) | 45.10 | 43.50 | 43.60 | 45.10 | 46.90 | 43.50 | 43.50 |
| Available $H_2O$ (in $ft^{-1}$) | 0.76 | 0.79 | 0.83 | 1.52 | 1.69 | 1.06 | 1.22 |
| Saturated Hydraulic Conductivity (in $hr^{-1}$) | 3.02 | 1.70 | 1.66 | 0.67 | 0.26 | 1.00 | 0.50 |
| Matric Bulk Density (Mg $m^{-3}$) | 1.46 | 1.50 | 1.50 | 1.46 | 1.41 | 1.50 | 1.50 |
| Organic Matter (% Wt) | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 |
| Salinity (dS $m^{-1}$) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Gravel (% Vol) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Compaction | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Moisture Content (% Vol) | 19.50 | 19.50 | 19.50 | 13.80 | 19.50 | 19.50 | 19.50 |
| Matric Potential (bar) | 0.27 | 0.30 | 0.31 | 14.55 | 13.26 | 0.67 | 3.28 |
| Matric + Osmotic (bar) | 0.27 | 0.30 | 0.31 | 14.55 | 13.26 | 0.67 | 3.28 |
| Hydraulic Conductivity (in $hr^{-1}$) | 1.43E-5 | 5.99E-7 | 9.80E-7 | 1.92E-8 | 1.02E-7 | 8.85E-7 | 1.74E-7 |

### 4.3 Phosphorus Fractions of Surface Soils of the Experimental Sites

The result of the P fractionation studies conducted on soils of the two agro-ecological sites is presented in Figure 4.1. Other than aluminium-bound P (Al-P, 3.0 mg $kg^{-1}$) and iron-bound P (Fe-P, 5.0 mg $kg^{-1}$), which were observed to be lower in Minjibir soil, compared to Samaru's (4.0 and 7.0 mg $kg^{-1}$, respectively), all the other P fractions, including the saloid- (*i.e.*, easily available) P forms (Sarkar *et al*., 2014), were relatively higher in the Samaru soil (Figure 4.1). It was observed in a recent study by Ahmed *et al*. (2018) that despite a low $NaHCO_3$-extractable P, 2 - 3 mg $kg^{-1}$, observed in soils of central Sudan, many crops revealed an unpredictable response to P fertilisation as also earlier reported by Dawelbeit *et al*. (2010). The Soil Science Society of America had, however, set a limit of 5 mg P $kg^{-1}$ between sufficiency and deficiency of soil P (Olsen and Sommers, 1982). In a study by Nishigaki *et al*. (2018), $Al_o$ was suggested to have possibly caused an accumulation of Al-P. Also, $Fe_o$ and $Fe_d$ were observed generally to be responsible for the high Fe-P ($NaOH\text{-}P_i$) and residual P contents, respectively (Nishigaki *et al*. (2018). The $Al_o$ played a role in organic P and Al-P accumulation in three Tanzanian geological groups (Lair *et al*., 2009; Nishigaki *et al*., 2018). There was, therefore, an observed diversity and abundance of soil P forms that greatly varied among sites having different soil-related geological conditions. Values of $Fe_o/Fe_d$ within a range of 0.3 – 0.8 are considered high (Lair *et al*. 2009). There was, therefore, a similarly observed high $Fe_o/Fe_d$ values for both [Minjibir (0.26) and Samaru (0.29)] locations. This, generally, indicated a relative less predominance of such crystalline forms of Fe as goethite and haematite (Agbenin, 2003). The $Fe_o/Fe_d$ is indicative of the degree of crystallinity of Fe oxides (Lair *et al*. 2009).

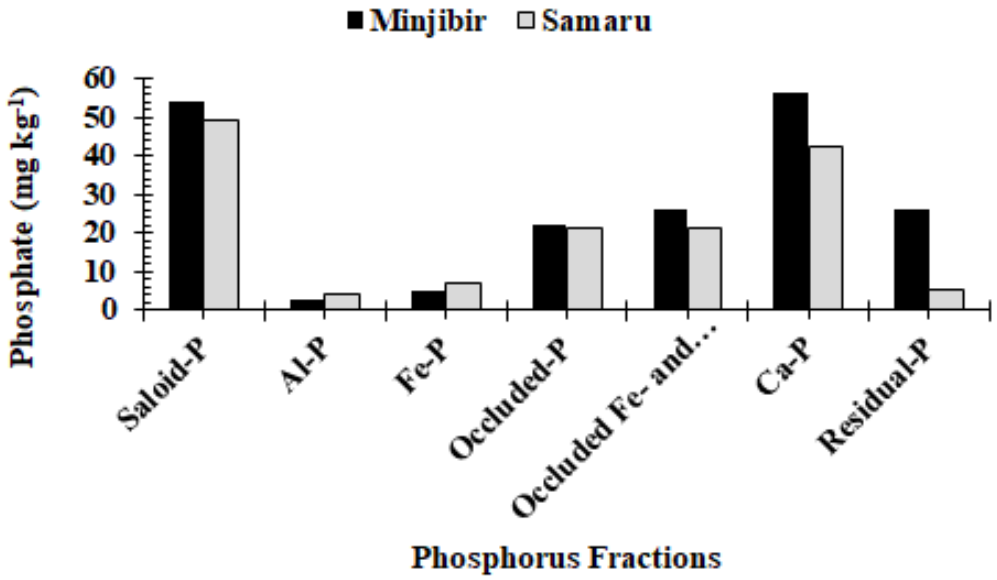



Figure 4.1: Phosphorus fractions of soils of the experimental sites

Similarly, Minjibir had the highest sodium-pyrophosphate extractable Al ($Al_p$) value (2500 mg $kg^{-1}$) than what was observed for Samaru (166.0 mg $kg^{-1}$). Also, the values for Na-pyrophosphate oxides of Fe and Mn ($Fe_P$ and $Mn_P$) were higher in Samaru (634.7 and 16.5 mg $kg^{-1}$, respectively) than in Minjibir (235.3 and mg $kg^{-1}$, respectively). The sodium citrate-sodium bicarbonate-sodium dithionite (C-B-D)-extractable $Al_d$, $Fe_d$ and $Mn_d$ were predominantly highest in Samaru (150.0, 2479.2 and 137.0 mg $kg^{-1}$, respectively) than in Minjibir (84.0, 1929.8 and 21.0 mg $kg^{-1}$, respectively) as also depicted in Figure 4.2 below.

Variations of the two locations, in terms of soil texture and climatic conditions, notably precipitation, might be part of the reasons behind the disparity observed in terms of preponderance of the metal oxide fractions. For example, soil water from precipitation may turn an insoluble ferric ($Fe^{3+}$) into a more soluble ferrous ($Fe^{2+}$) iron form, which is prone to leaching. Solid phase $Fe(OH)_3$ precipitates out of soil solution. Also, fresh $Fe(OH)_3$ precipitates is reported to have overwhelming P sorption capacities. They can also cause the soluble P levels to be reduced by orders of magnitude within a few minutes (Moore and Reddy, 1994; Graetz and Nair, 2000). It may have also co-migrated with clays or consequent to difference in soil organic matter contents of the two sites (Table 4.1).

Phosphate sorption, by iron (Fe) and aluminium (Al) oxides, and amorphous materials in soils, is a major factor that readily contributes to a reduced effectiveness of added phosphates which necessitates larger fertiliser P applications before achieving a good crop yield (Warren, 1994). Roles of amorphous Al and Fe oxides on P sorption have been well recorded (Janardhanan, 2007). An active amorphous Al per mole can adsorb almost twice as much P as an active amorphous Fe (Darke and Walbridge, 2000). This indicated that the soil in Samaru was relatively more vulnerable to higher capacity for P-fixation than that of Minjibir. This is basically because aluminium oxides have been reported to be much more effective in adsorbing phosphates in soils when compared to iron oxides (Borggaard, 1986). The amorphous form of both Al and Fe were, however, reported to be important predictors of soil P-sorption capacity in peaty, clayey and sandy soils (Borggaard *et al*., 1990; Freese *et al*., 1992). Amorphous Al and Fe correlated well with the soil organic matter in a study by Darke and Walbridge (2000).

### 4.4 Soil Al, Fe and Mn Fractions in the Surface Soils of the Experimental Sites

The result of Al, Fe and Mn fractionation are presented in Figure 4.2. The results indicated that the ammonium-oxalate extractable Al ($Al_o$) for Minjibir (997.0 mg $kg^{-1}$) was higher than that observed for the Samaru (805.50 mg $kg^{-1}$). Conversely, the $Fe_o$ and $Mn_o$ were observed to be higher for the Samaru (714.0 and 63.7 mg $kg^{-1}$, respectively) than Minjibir (503.9 and 25.8 mg $kg^{-1}$) locations.

### 4.5 P Sorption Characteristics of Surface Soils in the Experimental Sites

The result of P sorption studies for the surface soils of the experimental sites is presented in Table 4.3. The experimental soils were observed to substantially differ in their P sorption characteristics. It indicated that Samaru soil had a relatively higher integral P sorption capacity when compared to Minjibir soil. The P that remained in the soil solution was comparatively different after the experimental soils were spiked with the same amount of P as also indicated in Table 4.3. One of the most critical factors determining the rate of P diffusion in soils is the concentration of P in the solution. Hence, there must be an adequate amount of P in the soil solution for the provision of the required movement gradient P from the soil solution to root tips. A given quantity of an applied P in dissimilar soils will result in arriving at different soil P quantities as soils have differences in their characteristic P sorption capacity.

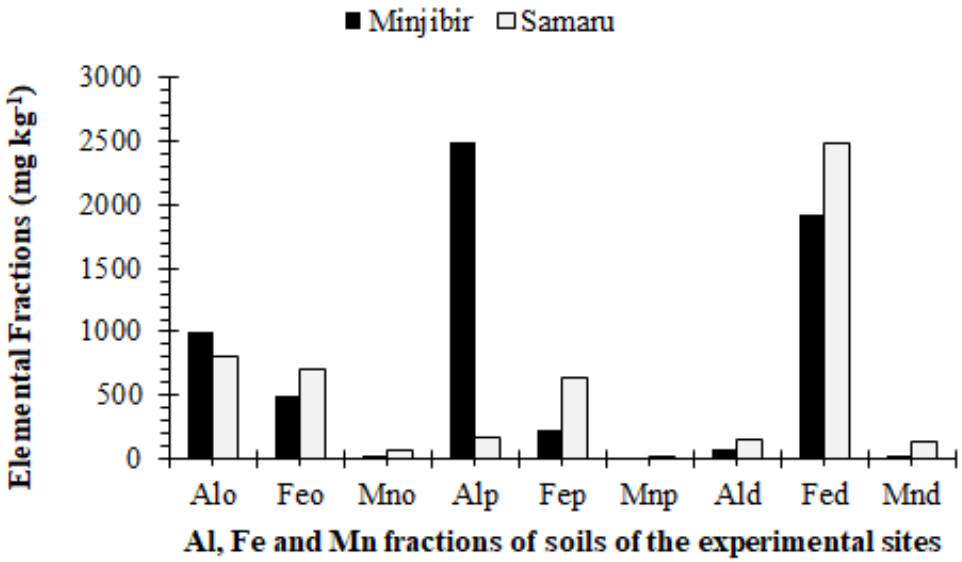



Figure 4.2: Al, Fe and Mn fractions of soils of the experimental sites

Table 4.3: Result of surface soil P sorption studies of the experimental sites

| S/No. | Quantity of P added (mg $kg^{-1}$ soil) | Sudan Savannah (Minjibir) | | | Northern Guinea Savannah (Samaru) | | |
|---|---|---|---|---|---|---|---|
| | | P in soln. (mg $kg^{-1}$) | P sorbed (mg $kg^{-1}$) | PSI | P in soln. (mg $kg^{-1}$) | P sorbed (mg $kg^{-1}$) | PSI |
| 1 | Control | 0.01 | - 0.09 | 0.05 | 0.28 | - 0.28 | 0.18 |
| 2 | 0.00 | 0.07 | 32.68 | -27.59 | 2.43 | 30.90 | -50.29 |
| 3 | 30.00 | 0.64 | 60.22 | -315.81 | 3.55 | 63.12 | -140.34 |
| 4 | 90.00 | 2.72 | 72.81 | 167.64 | 9.34 | 90.66 | -3069.30 |
| 5 | 300.00 | 4.27 | 90.64 | 143.78 | 52.97 | 80.36 | 110.99 |
| 6 | 600.00 | 5.33 | 113.41 | 156.15 | 57.36 | 109.30 | 144.08 |
| 7 | 1000.00 | 6.35 | 136.47 | 169.96 | 69.98 | 130.02 | 153.89 |

soln. = Solution; PSI = Phosphorus sorption index

A considerably higher P sorption index (PSI) was observed in soils of Minjibir when compared to Samaru, which fact was further stressed by the relatively lower P in solution observed in the Minjibir soil (Table 4.3). This clearly indicated that the Minjibir soils were of higher P buffering capacity (Moody and Bolland, 1999). Phosphate sorption index, being a reliable standard of soil P sorption potential (Bruland and Richardson, 2004) has reaffirmed the P sorption observed for the soils. Furthermore, the higher extractable amorphous (*i.e.*, $NH_4$-oxalate extractable) Al and Fe recorded for Minjibir soil were also corroborative of the different P sorption capacities

observed for soils of the two locations. This is because the amorphous Al and Fe have been reported to closely predict PSI (Darke and Walbridge, 2000; Bruland and Richardson, 2004).

Comparison between P application effects on two different soils, having different sorption capacities, is as such, very bothersome. A logical resolution to this problem is to make comparisons based on the P concentration that remained in the soil solution not on the quantity added. The interrelation between the quantity of P added to a soil and that remaining in the solution phase is best portrayed by developing the P-sorption isotherm of that particular soil. In this study, the amount of P sorbed was observed to gradually increase with increased P application to soils of both locations. A similar increase in P sorption with increased P in solution was also reported in a study by Naseri *et al*. (2010) and Hossain *et al*. (2012).

Phosphorus (P) sorption, commonly defined as P buffering capacity (PBC), which is the capacity of soil to moderate solution-P concentration changes when P is removed from or added to the soil (Ozanne, 1980), is an important phenomenon. It describes soil P partitioning between the sorbed and solution phases. Soil PBC has critical implications for management of P fertiliser from both environmental and productivity perspectives. It (PBC) affects P sorption extent and precipitation reactions that decrease fertiliser P availability (Moody and Bolland, 1999), thereby influencing the P fertiliser quantity required to improve the availability of fertiliser P for plant growth and development (Dear *et al*., 1992; Burkitt *et al*., 2001; Burkitt *et al*., 2008; Burkitt *et al*., 2010). A PBC estimate is also needed for certain soil P tests so as to adjust critical soil test concentrations for different soil types (Moody and Bolland, 1999). The use of PBC, in addition to improving P fertiliser accuracy of recommendations, may also prevent excessive application of P fertiliser and off-site movement of P, a major cause of eutrophication and algal blooms in waterways (Sharpley *et al*., 1987). Phosphorus sorption index, as suggested by Dear *et al*. (1992), is needed to predict PBC accurately.

## 4.6 Effects of Location, Genotype and Phosphorus on Dry Haulm and Pod Yields of the Groundnut Genotypes

### 4.6.1 Dry haulm yield of the groundnut genotypes

Location, genotype and P source significantly ($P \leq 0.05$) influenced dry haulm yield in the 2015 and 2016 seasons and mean across the seasons (Table 4.4). All the interactions on the parameter, in the two seasons and their mean, were statistically significant ($P \leq 0.01$). In that, SAMNUT 21 and SAMNUT 10, which were statistically similar to SAMNUT 22, outperformed all other genotypes in the 2015 trial season in terms of dry haulm yield. These were followed by ICIAR 7B, which was statistically similar to ICIAR 6AT and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, whereas ICGX-SM 00010/5/$P_{15}$/$P_1$ had the lowest dry haulm yield, although statistically not different from SAMNUT 14 (Table 4.4). In the 2016 season, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ outperformed all other genotypes. It was followed by ICGV-IS 07815, ICIAR 7B and ICIAR 6AT. SAMNUT 10, which was statistically similar to SAMNUT 24, and even SAMNUT 23, had the significantly lowest dry haulm yield record of the season. In the mean of 2015 and 2016 seasons, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ also outperformed all other genotypes but its dry haulm yield was statistically similar to that of ICGV-IS 07815. These were followed by each of the statistically similar ICIAR 7B and ICIAR 6AT, which were, in turn, significantly higher than the overall least-yielded SAMNUT 23. SAMNUT 23 was, however, statistically not different from ICGX-SM 00010/5/$P_{15}$/$P_1$, ICGV-IS 07083 and SAMNUT 11 (Table 4.4).

The significantly ($P \leq 0.05$) highest dry haulm yield was recorded under SSP in 2015 (1254 kg $ha^{-1}$), 2016 (1381 kg $ha^{-1}$) and the mean across the seasons (1318 kg $ha^{-1}$). The source was followed by SRP (1187, 940 and 1064 kg $ha^{-1}$, respectively in 2015, 2016 and the mean across the seasons). The lowest dry haulm yields of 1051 and 783; and 917 kg $ha^{-1}$ were recorded under the control P source in the 2015 and 2016 cropping seasons; and mean across the seasons respectively. Also, the highest dry haulm yield was generally recorded for the genotypes in Minjibir (Sudan savannah) than Samaru (northern Guinea savannah), in all the seasons, as also indicated by Table 4.4.

A study by Gabasawa and Yusuf (2013), however, showed that SAMNUT 21 and SAMNUT 22 produced the highest dry haulm yields in Samaru. Earlier, Kamara *et al.* (2011) also observed SAMNUT 21 and SAMNUT 22 as having outperformed other

genotypes tested on a P-deficient Alfisols in the northeastern Nigeria. SAMNUT 10 and SAMNUT 11 were reported to significantly ($P \leq 0.01$) produce the lowest dry haulm yields (Gabasawa and Yusuf, 2013). Immediately in the following season, Yusuf and Dianda (2014) reaffirmed these findings. In that, in addition to SAMNUT 22, they observed ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and SAMNUT 24 as having produced the highest dry haulm yield in these two agro-ecological zones of Nigeria.

### 4.6.2 Pod yield of the groundnut genotypes

The treatments also significantly ($P \leq 0.05$) influenced pod yield of the groundnuts in 2015 and 2016 trial seasons. Kwankwaso and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ had the lowest pod yield (256 and 264 kg $ha^{-1}$, respectively) record (Table 4.4). All treatment interactions on the parameter were also significant ($P \leq 0.01$) in the two seasons and their means. In that, SAMNUT 24 outperformed all the other genotypes, in terms of pod yield in the 2015 season and was followed by SAMNUT 22 and SAMNUT 14 (Table 4.4). In the 2016 cropping season, two genotypes (ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-IS 07083), which were statistically similar, outperformed all the other genotypes. They were followed by ICIAR 6AT, which was also at par with ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ and SAMNUT 14. ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-IS 07083 outperformed all other genotypes in terms of the dry pod yield recorded in the mean across the seasons. Exceptions were, however, ICIAR 6AT, SAMNUT 14 and SAMNUT 24, which were similar to the highest dry pod yield records of the mean across the seasons (Table 4.4). The lowest dry pod yield was recorded, in the 2015 cropping season, by Kwankwaso and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, although at par with ICGX-SM 00010/5/$P_{15}$/$P_1$, ICIAR 6AT, ICIAR 6AT and SAMNUT 11. SAMNUT 22 had the least pod yield record of the 2016 cropping season, as indicated by Table 4.4 below.

The control (424 kg $ha^{-1}$) and SRP (424 kg $ha^{-1}$) P sources outperformed SSP P source (393 kg $ha^{-1}$) in terms of pod yield in the 2015 cropping season. Conversely, SSP (1315 kg $ha^{-1}$) outperformed each of the two other P sources in the 2016 cropping season. It was followed by the SRP (1074 kg $ha^{-1}$) and lastly by the control (9561 kg $ha^{-1}$). Significantly highest pod yield was also recorded in Minjibir than Samaru in both the seasons and mean across the seasons (Table 4.4).

SAMNUT 14 was reported to be higher than SAMNUT 10, in terms of pod yield, in a study by Musa *et al*. (2015). This corroborated with the current finding in terms of the two genotypes, which were the only genotypes tested in that work. Also in corroboration with this study, in terms of pod yield, is a finding in an earlier work by Gabasawa *et al*. (2009) in which no significant difference was observed between SAMNUT 10, SAMNUT 11, SAMNUT 21 and SAMNUT 22, in terms of the parameter.

Table 4.4: Effects of genotype, P source and location on dry haulm and pod yields of the groundnuts in 2015 and 2016 trial seasons and mean across the seasons

| Treatment | Dry Haulm Yield (kg ha$^{-1}$) | | | Pod Yield (kg ha$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | 2015 | 2016 | Mean across the seasons | 2015 | 2016 | Mean across the seasons |
| **Genotype (G)** | | | | | | |
| ICGV-IS 07815 | 1315c | 1393b | 1354ab | 382de | 1097c-e | 735b |
| ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 1303c | 1547a | 1425a | 446cd | 1744a | 1095a |
| ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 1185d | 1114c | 1150ef | 264g | 1224b-d | 737b |
| ICGX-SM 00010/5/$P_{15}$/$P_1$ | 786f | 969de | 878ij | 327e-g | 880fg | 613b |
| ICGV-IS 07083 | 925e | 898ef | 911ij | 497c | 1731a | 1114 a |
| ICIAR 6AT | 1268cd | 1315b | 1292bc | 273fg | 1329b | 805ab |
| ICIAR 7B | 1353bc | 1318b | 1335b | 303e-g | 1092c-e | 695b |
| Kwankwaso | 921e | 1130c | 1026gh | 256g | 985e-g | 621b |
| SAMNUT 10 | 1499a | 652h | 1075fg | 428cd | 886fg | 662b |
| SAMNUT 11 | 930e | 896ef | 913ij | 302e-g | 850g | 578b |
| SAMNUT 14 | 881ef | 1028c-e | 954hi | 618b | 1243bc | 921ab |
| SAMNUT 21 | 1509a | 833fg | 1171de | 370d-f | 868g | 619b |
| SAMNUT 22 | 1445ab | 1034cd | 1240cd | 630b | 668h | 652b |
| SAMNUT 23 | 961e | 724gh | 843j | 369d-f | 1078de | 727b |
| SAMNUT 24 | 1178d | 673h | 9261i | 740a | 1034ef | 887ab |
| SE± | 20.9 | 27.5 | 17.3 | 20.1 | 33.5 | 74.0 |
| **Phosphorus (P, kg $P_2O_5$ ha$^{-1}$)** | | | | | | |
| 0 P | 1051c | 783c | 917c | 424a | 956c | 689b |
| 30 SSP | 1254a | 1382a | 1318a | 393b | 1315a | 852a |
| 90 SRP | 1187b | 940b | 1064b | 424a | 1074b | 751ab |
| SE± | 9.3 | 12.3 | 7.7 | 8.9 | 14.9 | 33.1 |
| **Location (L)** | | | | | | |
| Minjibir | 1456a | 1331a | 1393a | 458.98a | 1238.93a | 848a |
| Samaru | 872b | 739b | 806b | 368.40b | 991.20b | 680b |
| SE± | 7.6 | 10.0 | 6.3 | 7.323 | 12.225 | 27.0 |
| **Interactions** | | | | | | |
| G x P | ** | ** | ** | ** | ** | ** |
| G x L | ** | ** | ** | ** | ** | ** |
| P x L | ** | ** | ** | ** | ** | ** |
| G x P x L | ** | ** | ** | ** | ** | ** |

SSP= Single Superphosphate SRP= Sokoto Rock Phosphate, **=Significant at 1% level of probability; Means followed by same letter(s) within a treatment in a column do not differ significantly according to Tukey's honest significant difference (HSD).

Some previous studies were also in conformity with the findings of this study in terms of the significant role of Sokoto rock phosphate (SRP) in influencing the pod yield of groundnuts, and some other legumes. For example, Aliyu *et al.* (2007) and Musa *et al.* (2015) also observed a significant increase in pod yield of groundnuts due to the influence of SRP over that of SSP. In the present study, however, the SRP was statistically at par with the control, which contradicts many established findings on the role of P on pod yield, including Kamara *et al.* (2011)'s. This may, however, possibly be due to secretion of phosphomonoesterase, specifically acid phosphatase (AcPhase), amongst other possibilities. Reports from P-deficient soils studies have indicated that plants growing on such (P-deficient) soils actively secrete enzymes (Ozawa *et al*., 1995) and other exudates (Jones, 1998) into their rhizosphere. This will aid the degradation of nucleic acids (Razzell and Khorana, 1959) and, eventually, soil P transformation and cycling (Razzell and Khorana, 1959; Acosta-Martinez and Tabatabai, 2000). More specifically, for example, Richardson *et al*., 2001a and Yadav and Tarafdar (2001), in their works, observed that plants in P-limited soils are secreting AcPhase into their rhizosphere immediately following the emergence of their roots.

This is further reaffirmed in this work, as the control was observed to immediately follow the highest SRP, in terms of AcPhase activity. This, interestingly, implied that there would not necessarily be a pressing need for SRP, let alone SSP, for a good pod harvest to be accomplished. However, many factors responsible for this amazing potential should be seriously investigated, including more in-depth studies on AcPhase's role. Minjibir, in the Sudan savannah, had an edge over Samaru (in the northern Guinea savannah) primarily due to the disparity in weather conditions of the two locations as depicted in Appendix V, Appendix VI and Appendix VII. This can also be attributable to the relatively higher soil organic matter content associated with Minjibir (Table 4.1), which is known to encourage the phosphomonoesterases activity in soils (Rao *et al*., 1995; Reddy *et al*., 2020).

### 4.6.3 Genotype by phosphorus versus location interactions on dry haulm and pod yields in the 2015 and 2016 cropping seasons and mean across the seasons

*4.6.3.1 Genotype by phosphorus interaction on dry haulm yield in the 2015 field trial*

Generally, the genotype by P source interaction on dry haulm yield of the genotypes showed that SAMNUT 24 (1675 kg $ha^{-1}$), grown under SSP P in 2015, had the

significantly ($P \leq 0.05$) highest dry haulm yield amongst most of the genotypes (Figure 4.3). However, SAMNUT 10 under the control (1485 kg $ha^{-1}$), SAMNUT 21 (1513 kg $ha^{-1}$) and ICGV-IS 07815 (1482 kg $ha^{-1}$) each under the SSP; and SAMNUT 21 (1599 kg $ha^{-1}$), SAMNUT 10 (1554 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1542 kg $ha^{-1}$), SAMNUT 22 (1518 kg $ha^{-1}$) and ICIAR 7B (1511 kg $ha^{-1}$) all under SRP were statistically at par with the SAMNUT 24 (1675 kg $ha^{-1}$). The same SAMNUT 24 under the control P source (657 kg $ha^{-1}$), however, had the significantly lowest dry haulm yield. It was statistically at par with Kwankwaso (792 kg $ha^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (755 kg $ha^{-1}$) and SAMNUT 14 (660 kg $ha^{-1}$) under the same control P source; and SAMNUT 14 (830 kg $ha^{-1}$), Kwankwaso (801 kg $ha^{-1}$) and ICGX-SM 00010/5/$P_{15}$/$P_1$ (743 kg $ha^{-1}$), under SRP sourced P (Figure 4.3).

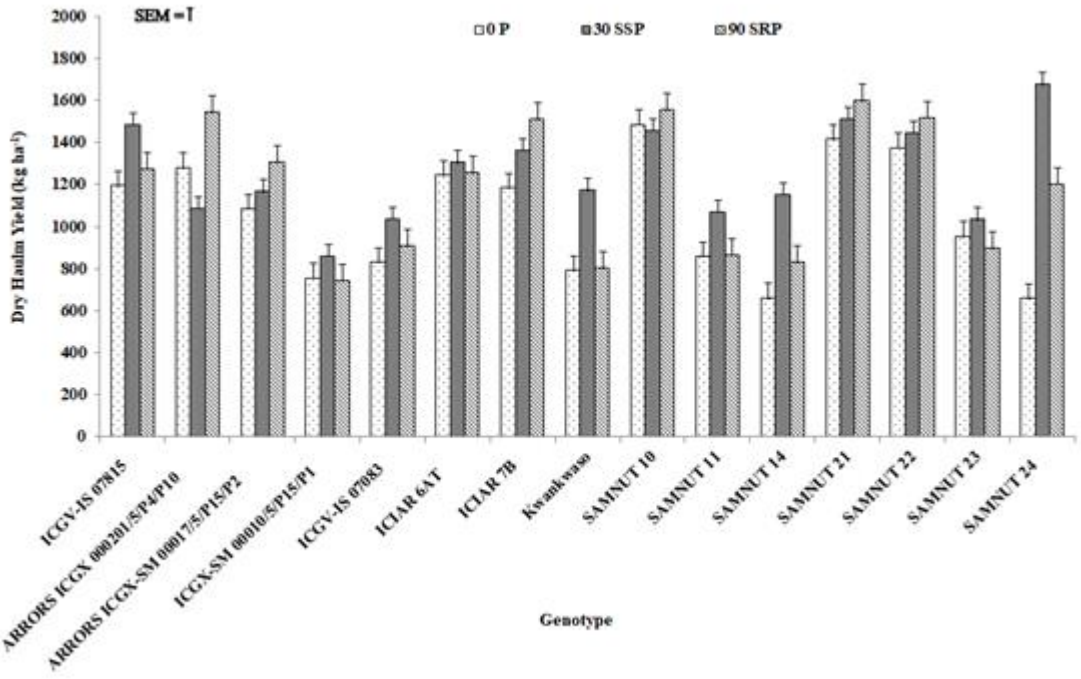



Figure 4.3: Genotype by phosphorus interaction on dry haulm yield in the 2015 field trial

SAMNUT 10 under the control treatment was, therefore observed to be statistically at par with such genotypes under SSP as SAMNUT 24, SAMNUT 21 and ICGV-IS 07815; and SRP as SAMNUT 21, ARRORS ICGX 000201/5/$P_4$/$P_{10}$, ICIAR 7B, SAMNUT 10 and SAMNUT 22. SAMNUT 10 was, therefore, more farmer-friendly than all the other genotypes, as they were lower in terms of the yield.

*4.6.3.2 Genotype by phosphorus interaction on dry haulm yield in the 2016 field trial*

In the 2016 trial, the result of the genotype by P source interaction on dry haulm yield indicated that ICIAR 7B, under SSP (2708 kg $ha^{-1}$), had significantly ($P \leq 0.05$) the highest dry haulm yield. It was followed by ICIAR 6AT (2244 kg $ha^{-1}$), which was statistically similar to ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (2067 kg $ha^{-1}$), Kwankwaso (1910 kg $ha^{-1}$) and ICGV-IS 07815 (1850 kg $ha^{-1}$). Generally, however, SAMNUT 10 (256 kg $ha^{-1}$) under SRP, although was at par with SAMNUT 24 (425 kg $ha^{-1}$) under the control, had the significantly ($P \leq 0.05$) lowest record of the dry haulm yield of the genotypes during the season (Figure 4.4).

The difference in the total (decadal) rainfall and rain days between the two seasons (Appendix VI and Appendix VII), might partly be the reason behind the variation in performance of SAMNUT 10 in the seasons. Generally, the dry haulm yield of groundnuts was reported to be higher in SSP than in SRP by Musa *et al.* (2015) in a study. This reaffirmed the finding of this study and indicated SSP as a more readily plant-available source for biomass development than SRP, and hence the translated differences in the dry haulm yield.

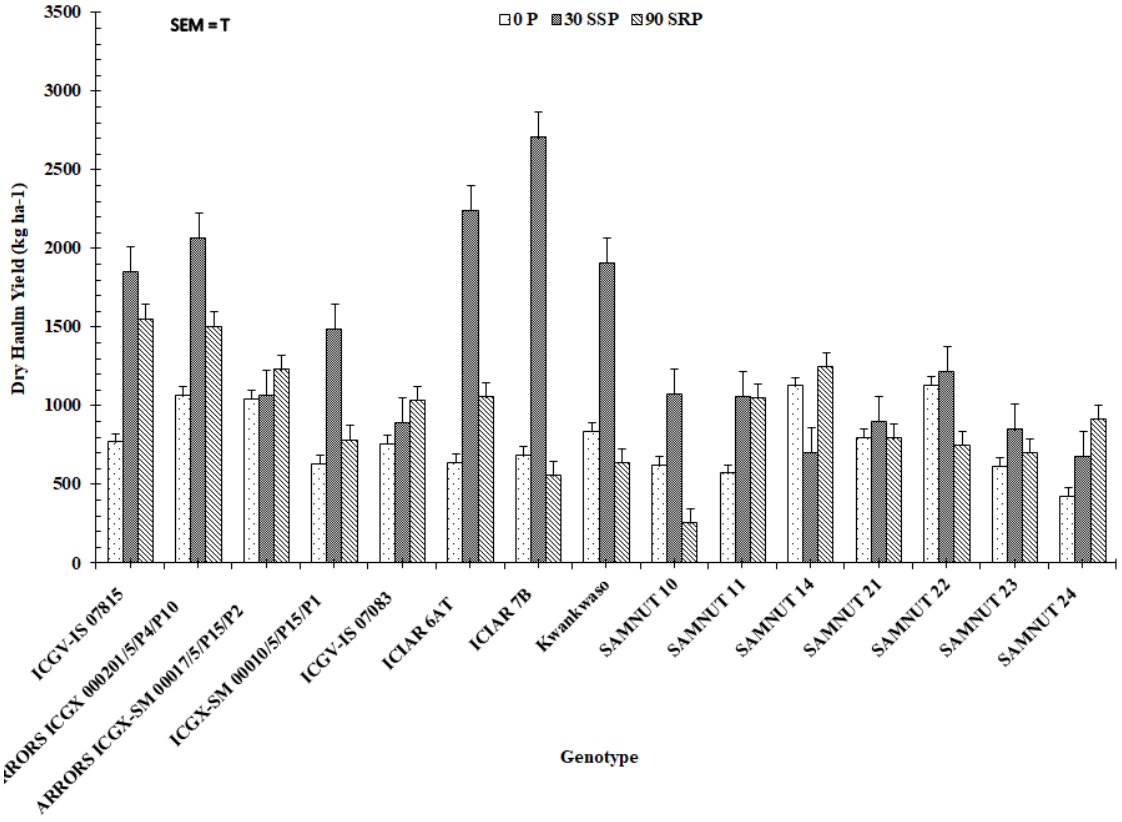



Figure 4.4: Genotype by phosphorus interaction on dry haulm yield in the 2016 field trial

The result of the genotype by P source interaction on dry haulm yield (DHY) of the genotypes in the mean of 2015 and 2016 trial seasons (Figure 4.5) was significant ($P \leq 0.01$). It indicated that although ICIAR 7B, under SSP (2036 kg $ha^{-1}$) P source outperformed most of the other genotypes across all the P sources, it was still statistically at par with about 27% of other genotypes under the same (SSP) P source. This was comprised of ICIAR 6AT (1775 kg $ha^{-1}$), ICGV-IS 07815 (1666 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1576 kg $ha^{-1}$) and Kwankwaso (1541 kg $ha^{-1}$). ARRORS ICGX 000201/5/$P_4$/$P_{10}$ under SRP P source (1525 kg $ha^{-1}$) was also statistically at par with these. The lowest DHY was recorded for SAMNUT 24 under the control P source (541 kg $ha^{-1}$). This was, however, statistically at par with many other genotypes grown across all the P sources (*i.e.*, about 67%, 26% and 60% under the control, SSP and SRP P sources, respectively) (Figure 4.5).

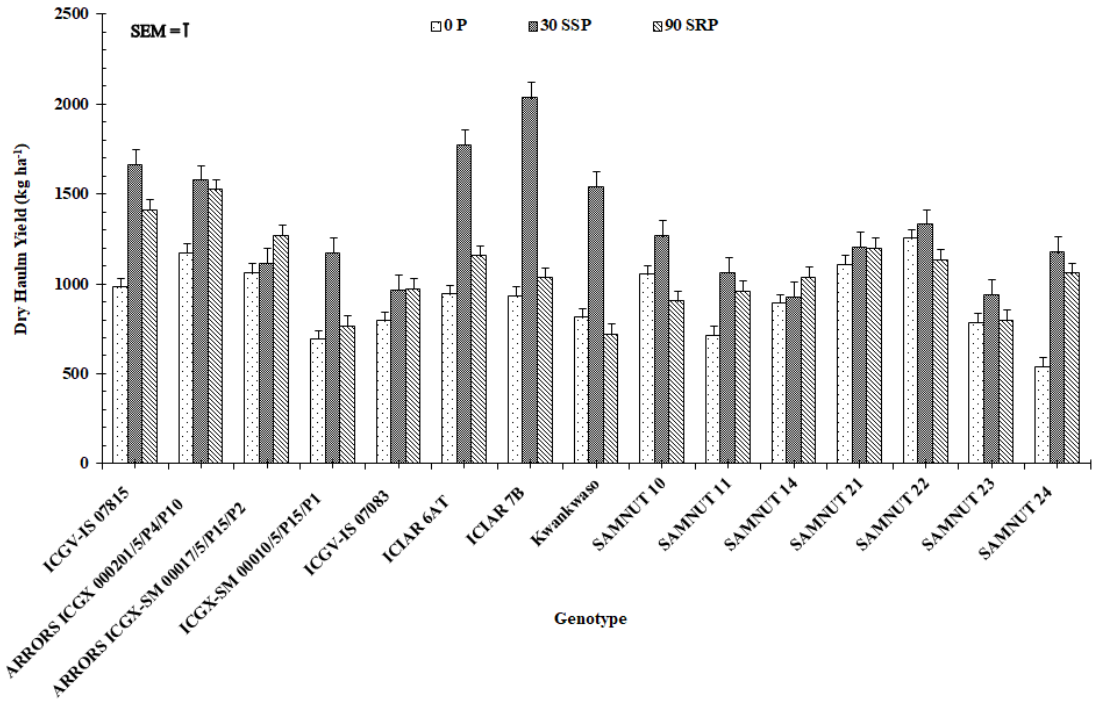



Figure 4.5: Genotype by phosphorus interaction on dry haulm yield in the field trials mean across the seasons

This indicated that about 80% of the genotypes can produce a relatively good quantity of DHY under SSP, and about 67% under SRP, P fertiliser sources. The significance of SSP on DHY was further made very clear during the mean across the seasons.

*4.6.3.3 Genotype by location interaction on dry haulm yield in the 2015 field trial*

The result of the genotype by location interaction on dry haulm yield of the genotypes was significantly ($P \leq 0.01$) different as indicated by Figure 4.6 below. In that, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1809 kg ha$^{-1}$) and SAMNUT 21 (1804 kg ha$^{-1}$) have the significantly ($P \leq 0.01$) highest dry haulm yield at the Sudan savannah Minjibir location, and have outperformed all the other genotypes grown in both locations. These were, however, followed by SAMNUT 24 (1613 kg ha$^{-1}$) in Minjibir, which was statistically similar to SAMNUT 14 (1492 kg ha$^{-1}$), SAMNUT 22 (1479 kg ha$^{-1}$) and SAMNUT 10 (1471 kg ha$^{-1}$) also in Minjibir, and SAMNUT 10 (1526 kg ha$^{-1}$) in Samaru locations (Figure 4.6). Significantly ($P \leq 0.01$) lowest dry haulm yield was recorded in Samaru for SAMNUT 14 (270 kg ha$^{-1}$), which was at par with ICGX-SM 00010/5/$P_{15}$/$P_1$ (561 kg ha$^{-1}$) at the same location (Figure 4.6).

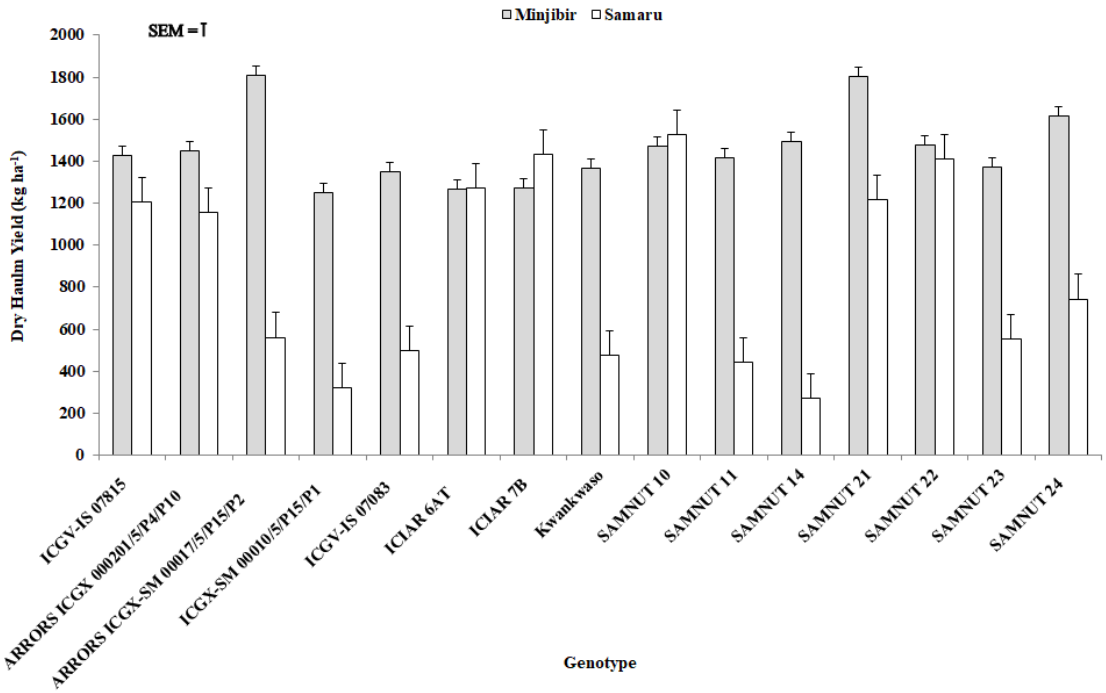



Figure 4.6: Genotype by location interaction on dry haulm yield in 2015 field trial

Although most of the highest yielded genotypes were observed in Minjibir for the 2015 trial season relative to Samaru, only about 13% of the genotypes significantly outperformed the others in terms of the parameter under discussion. About 20% of the genotypes outperformed other genotypes in the Samaru location (Figure 4.6).

*4.6.3.4 Genotype by location interaction on dry haulm yield in 2016 field trial*

Also, significantly highest dry haulm yield, due to the significant ($P \leq 0.01$) genotype by location interaction, was recorded for the genotypes grown in Minjibir. Hence, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (2096 kg ha$^{-1}$) and ICGV-IS 07815 (1911 kg ha$^{-1}$), at the agro-ecological location, were statistically similar and out-yielded all other genotypes in both locations. These were followed by statistically similar ICIAR 6AT (1654 kg ha$^{-1}$) and SAMNUT 14 (1673 kg ha$^{-1}$). These were also at par with some other genotypes in the location such as SAMNUT 22 (1528 kg ha$^{-1}$) and ICIAR 7B (1493 kg ha$^{-1}$). The significantly overall lowest dry haulm yield was recorded in Samaru for each of SAMNUT 14 (383 kg ha$^{-1}$), ICGV-IS 07083 (404 kg ha$^{-1}$) and SAMNUT 23 (441 kg ha$^{-1}$). These were statistically at par with about 27% of the remaining genotypes grown in Samaru, including SAMNUT 24 (524 kg ha$^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (532 kg ha$^{-1}$), SAMNUT 22 (541 kg ha$^{-1}$) and SAMNUT 10 (578 kg ha$^{-1}$) (Figure 4.7). SAMNUT 11 was, however, observed to be relatively more versatile than all other genotypes, as

there was no difference in terms of its DHY record in the two locations (Figure 4.7). It can, therefore, be grown in both agro-ecologies without fear of yield variability given a proper management. According to the individual agro-ecologies, however, 13% of the genotypes in Minjibir outperformed all other genotypes, irrespective of location. However, the highest yielded genotype in Samaru (ICIAR 7B, 1143 $ha^{-1}$) was statistically similar to only ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1225 kg $ha^{-1}$) and SAMNUT 23 (1007 kg $ha^{-1}$), rated 4$^{th}$ in Minjibir.

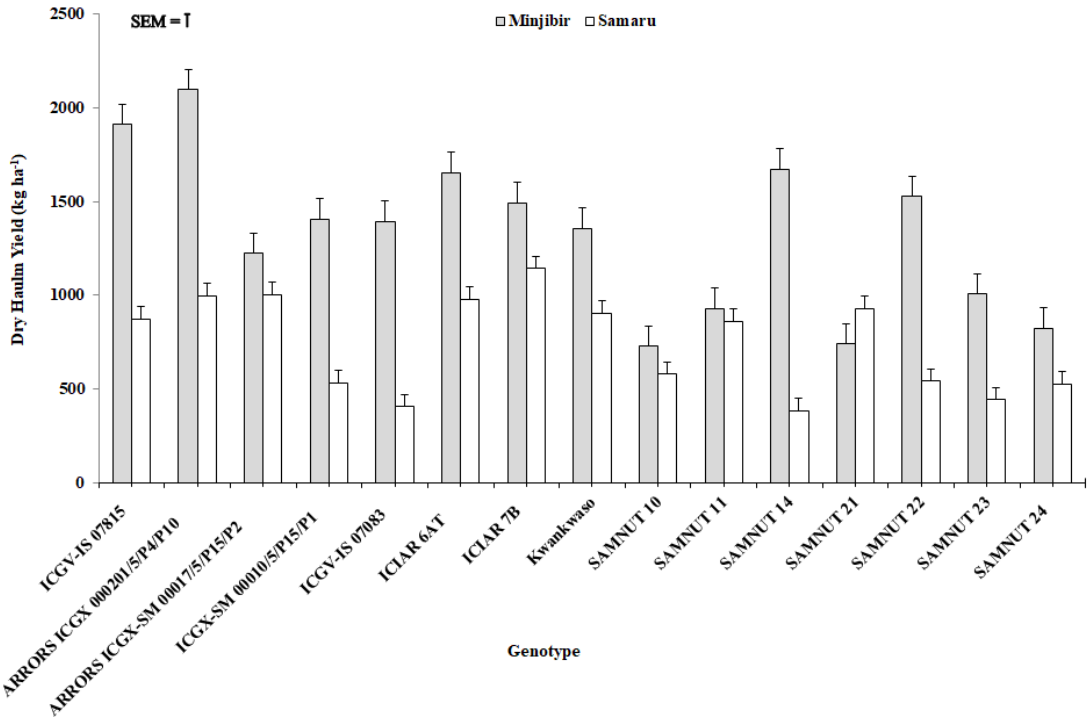



Figure 4.7: Genotype by location interaction on dry haulm yield in 2016 field trial

#### *4.6.3.5 Genotype and location interaction on dry haulm yield in the field trials mean across the seasons*

The genotype by location interaction on the dry haulm yield performance of groundnut genotypes in the mean across the seasons was significant ($P \leq 0.05$) (Figure 4.8). Although almost all the genotypes were statistically similar in terms of the parameter (dry haulm yield), the highest yield record was observed for ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1772 kg $ha^{-1}$), which was statistically at par with up to 73% of the genotypes in Minjibir, prominent of which was ICGV-IS 07815 (1039 kg $ha^{-1}$). The lowest DHY was, however, recorded for SAMNUT 14 (327 kg $ha^{-1}$) in Samaru, which was at par with many other genotypes, across both locations, especially ICGX-SM 00010/5/$P_{15}$/$P_1$ (427 kg $ha^{-1}$) and ICGV-IS 07083 (451 kg $ha^{-1}$) both also in Samaru

(Figure 4.8). There was a better DHY recorded in Minjibir than in Samaru. Hence, 80% of the genotypes in Minjibir in the mean across the seasons have significantly produced higher dry haulm yields. However, only 20% of the genotypes in Samaru proved relatively good in terms of the yield. Also, unlike in the 2016 trial season, the 2015/2016 trials mean had more than a genotype being versatile. Hence, up to 73% of the genotypes were observed to possibly be grown in both agro-ecologies with a potentially similar DHY guaranteed. There were, however, also genotypes observed as having location-specific DHY potentials in favour of Minjibir. A significantly higher yield was, therefore, recorded for SAMNUT 14 (1582 kg $ha^{-1}$), SAMNUT 22 (1503 kg $ha^{-1}$), SAMNUT 24 (1218 kg $ha^{-1}$) and SAMNUT 23 (1189 kg $ha^{-1}$) in Minjibir as depicted in Figure 4.8 below.

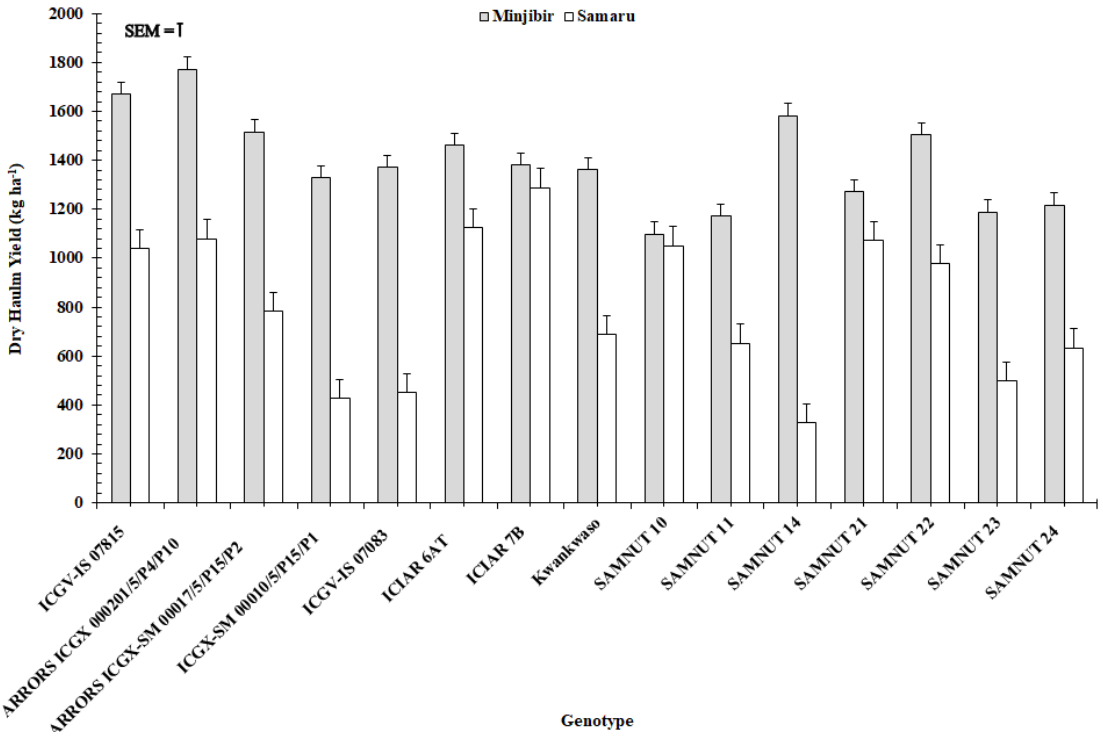



Figure 4.8: Genotype and location interaction on dry haulm yield in the field trials mean across the seasons

*4.6.3.6 Phosphorus by location interaction on dry haulm yield in the 2015 field trial*

There was also a significant ($P \leq 0.01$) P source by location interaction in the groundnuts' performance in terms of dry haulm yield in 2015 experiment (Figure 4.9). Therefore, the overall highest dry haulm yield was observed in Minjibir under SSP (1560 kg $ha^{-1}$) was followed by SRP (1495 kg $ha^{-1}$) and then control (1311 kg $ha^{-1}$) P sources. Greater yield was, therefore, observed even under the control, in Minjibir than

under SSP and SRP in Samaru. The lowest dry matter yield was observed in Samaru, under the control P source (790 kg $ha^{-1}$).

The previous explanations, on the possibility of the influence of AcPhase secretion under lower soil P condition (Giller and Wilson, 1991; Krasilnikoff *et al.*, 2003) and weather differences between the two agro-ecologies may still remain a logical reason for these and similar results observed. These results were also in conformity with the findings by Musa *et al*. (2015) on the significance of SSP on dry haulm yields.

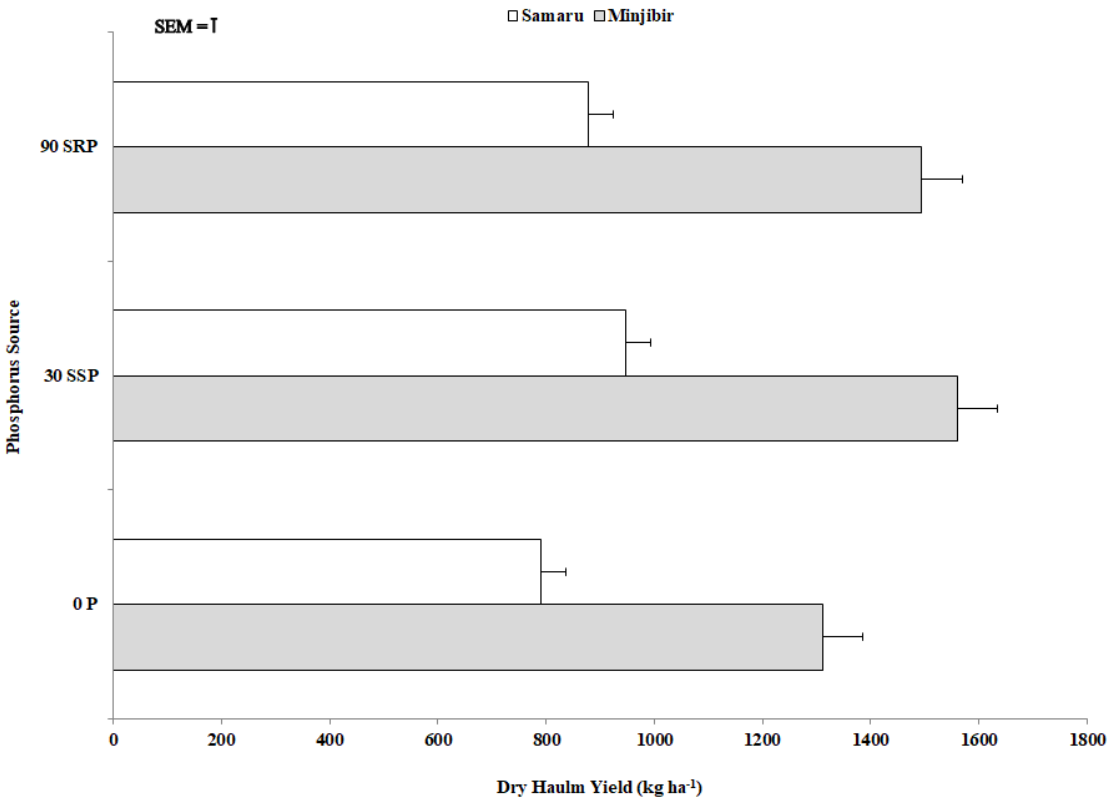



Figure 4.9: Phosphorus by location interaction on dry haulm yield in 2015 field trial

*4.6.3.7 Phosphorus by Location Interaction on Dry Haulm Yield in 2016 Field Trial*

Also in the 2016 trial season, a significant ($P \leq 0.01$) P source versus location interaction in the groundnuts' performance, in terms of dry haulm yield was observed (

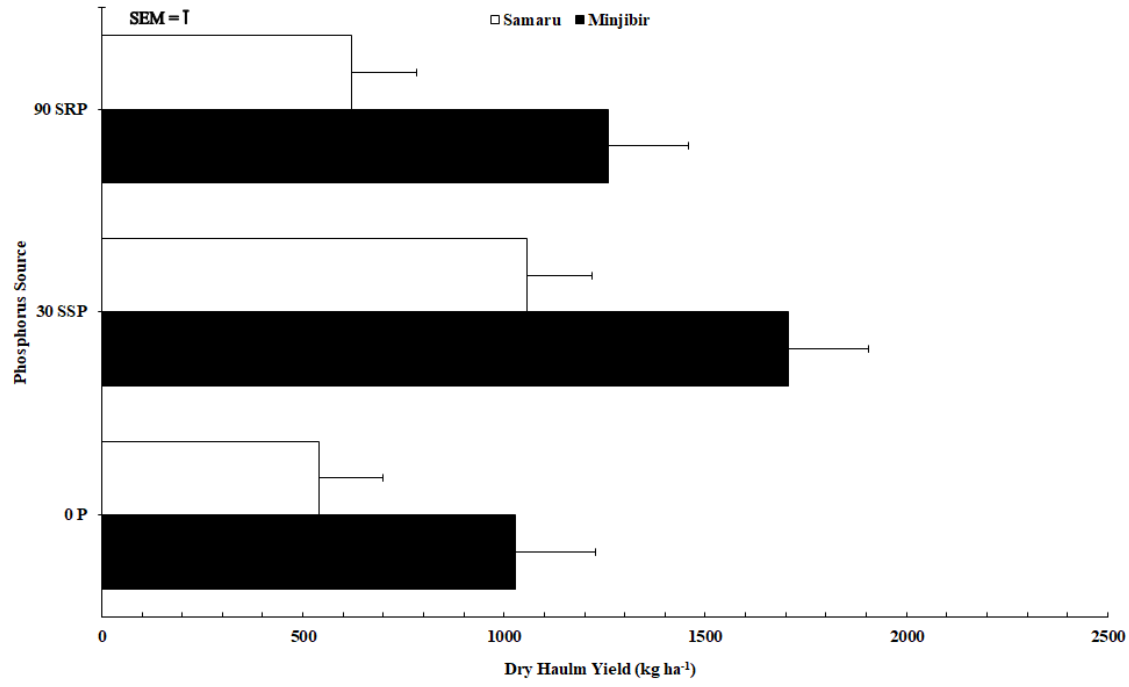


Figure 4.10). An overall high yield was recorded in Minjibir under SSP (1706 kg $ha^{-1}$), followed by SRP (1258 kg $ha^{-1}$). The single superphosphate sourced P in Samaru (1057 kg $ha^{-1}$), which was at par with the control P source in Minjibir (1028 kg $ha^{-1}$), followed these (SSP and SRP in Minjibir). The control P source in Samaru (539 kg $ha^{-1}$) had the significantly overall lowest record of the parameter. The same control in Minjibir was, however, statistically not different from SSP in Samaru (Figure 4.10). This further reiterates the more favourable nature of Minjibir location for a better dry haulm yield compared to Samaru's.

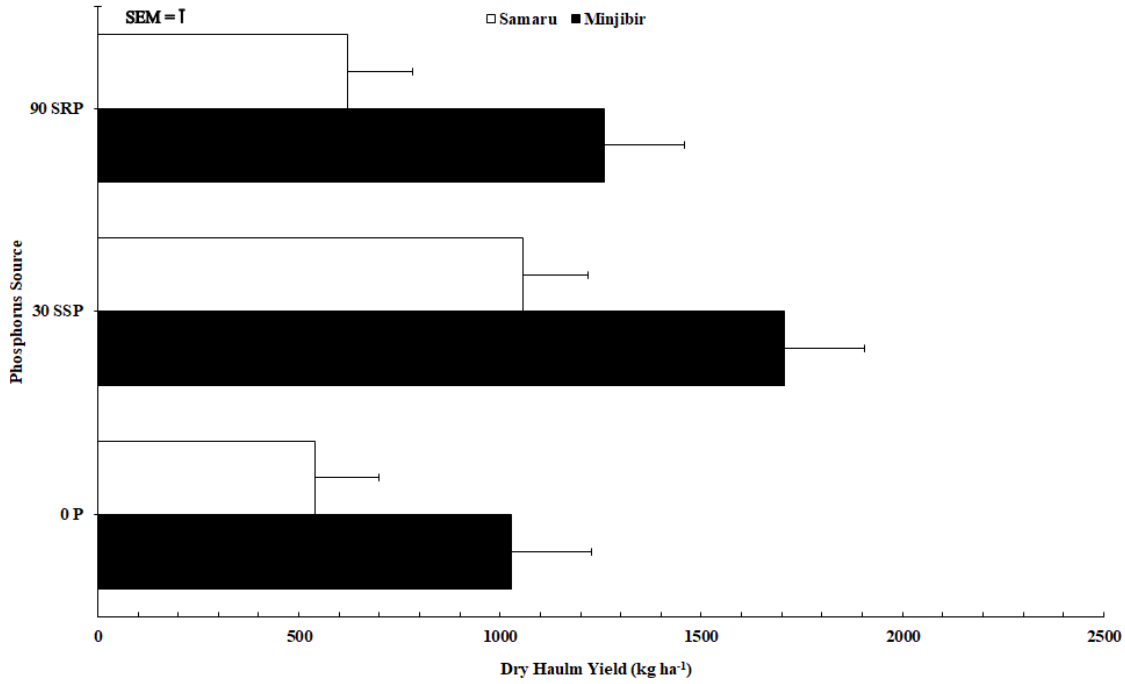



Figure 4.10: Phosphorus by location interaction on dry haulm yield in 2016 field trial

### *4.6.3.8 Phosphorus by location interaction on dry haulm yield in the field trials mean across the seasons*

The P source by location interaction was significant ($P \leq 0.01$) in terms of the dry haulm yield of the genotypes in the 2015 and 2016 mean across the seasons (Figure 4.11). In that, the Minjibir location generally out yielded the Samaru location in terms of dry haulm yield under all the P sources thereby further confirming the edge of Minjibir location over Samaru's. The importance of SSP, in terms of dry haulm yield is, therefore further stressed (Musa *et al*., 2015; Musa *et al*., 2017). In Minjibir, the SSP P source (1633 kg $ha^{-1}$) out-yielded SRP (1377 kg $ha^{-1}$) and the control (1170 kg $ha^{-1}$) P sources. The generally lowest DHY was recorded for each of the statistically similar

SRP (750 kg ha$^{-1}$) and control (665 kg ha$^{-1}$) both in Samaru. It is, however, worth noting that the SSP P source (1003 kg ha$^{-1}$) also had the highest DHY of all the P sources even in Samaru location.

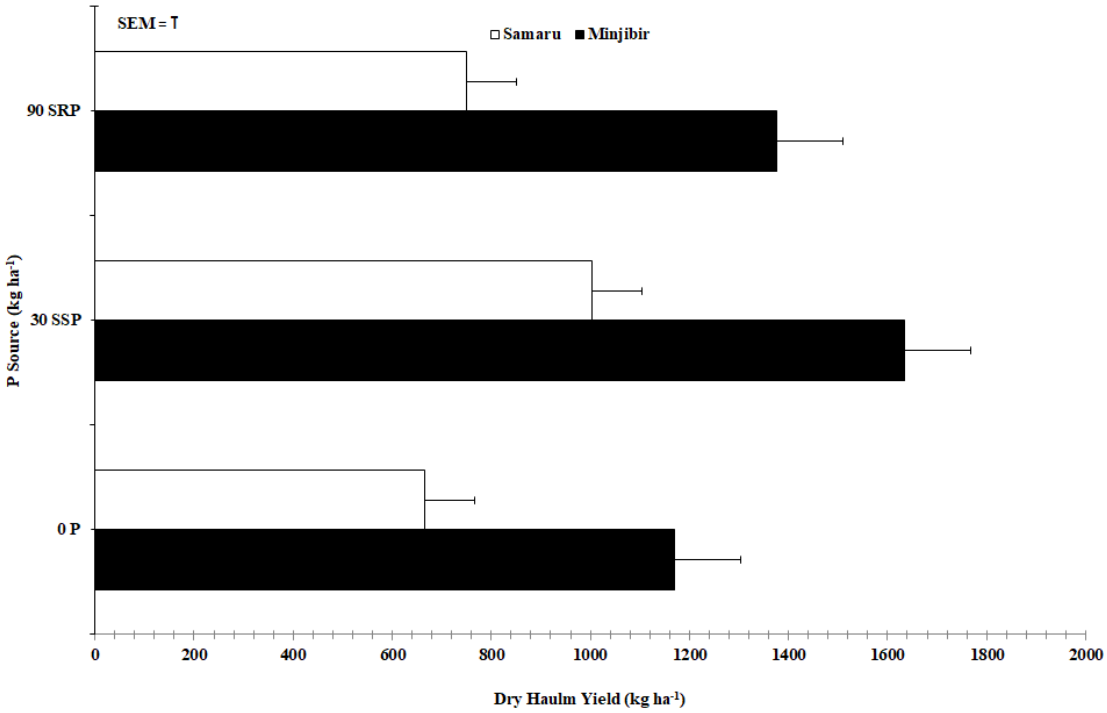



Figure 4.11: Phosphorus by location interaction on dry haulm yield in the field trials mean across the seasons

### *4.6.3.9 Genotype by phosphorus versus location interaction on dry haulm yield in the 2015 field trial*

The genotype by P source versus location interaction in the 2015 trial season was significant ($P \leq 0.01$) in terms of dry haulm yield performance of the groundnuts (Figure 4.12). The overall DHY was recorded for SAMNUT 14 and SAMNUT 21 (each 2000 kg ha$^{-1}$) observed under SSP and SRP, respectively, both in Minjibir. These genotypes were, however, statistically similar to SAMNUT 24 (1900 kg ha$^{-1}$), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1889 kg ha$^{-1}$) and Kwankwaso (1703 kg ha$^{-1}$) in the same location and under SSP P. They were also similar to ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1947.25 kg ha$^{-1}$), SAMNUT 24 (1817 kg ha$^{-1}$) and SAMNUT 22 (1703 kg ha$^{-1}$) under SRP and in the same Minjibir. They were followed by SAMNUT 21 (1689 kg ha$^{-1}$) and SAMNUT 10 (1647 kg ha$^{-1}$), respectively under SSP and SRP P sources, in Minjibir location. Significantly lower dry haulm yields were recorded for Samaru, with generally the lowest yield recorded in SAMNUT 14 (156 kg ha$^{-1}$ and 306

kg ha$^{-1}$) respectively under the control and SSP P sources, both in Samaru, which was comparable to ICGX-SM 00010/5/$P_{15}$/$P_1$ (214 kg ha$^{-1}$ and 239 kg ha$^{-1}$) at the same location but under the control and SRP P source respectively (Figure 4.12).

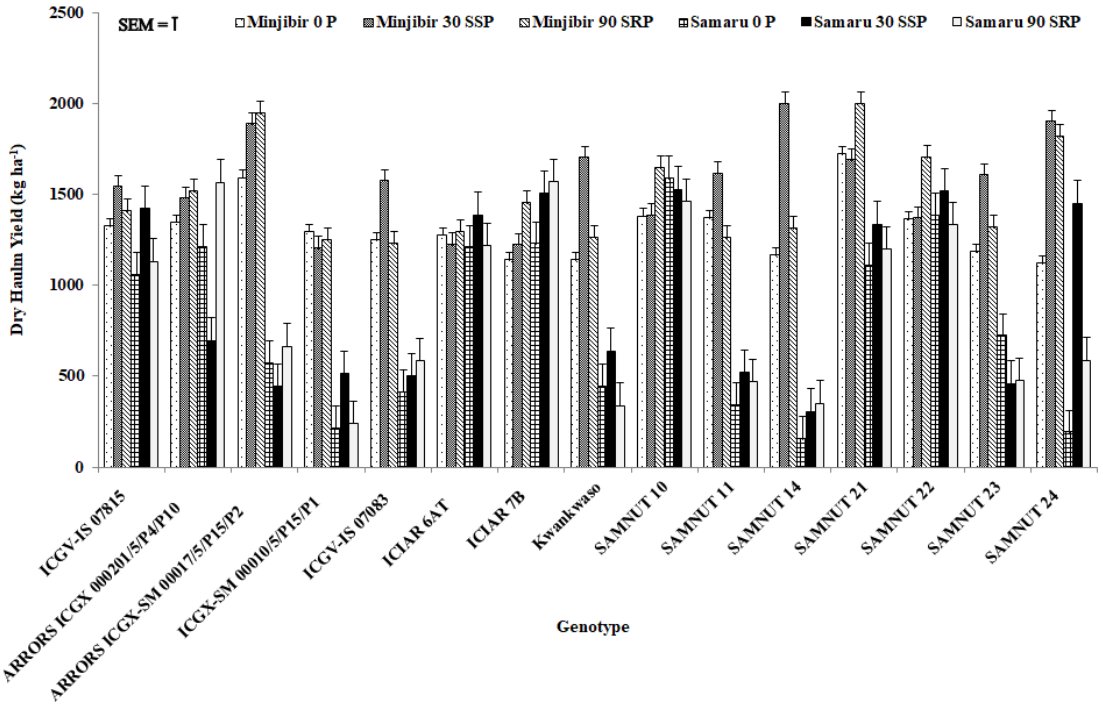



Figure 4.12: Genotype by phosphorus versus location interaction on dry haulm yield in 2015 field trial

Generally in Minjibir, SAMNUT 21 had the significantly highest DHY, under both SRP (2003 kg ha$^{-1}$) and the control (1726 kg ha$^{-1}$). The genotype was, interestingly, statistically not different from SAMNUT 10 under similar control in Samaru (1589 kg ha$^{-1}$). This ranked the genotypes (SAMNUT 21 and SAMNUT 10) the best in Minjibir and Samaru, respectively. This result also maintained the DHY difference of the two agro-ecologies. Hence, 13% and 7% of the genotypes were observed as having performed well, respectively in Minjibir and Samaru, each under the control. It was respectively 40% and 33% under SSP; and 33% and 13% under SRP (Figure 4.12).

#### *4.6.3.10 Genotype by phosphorus versus location interaction on dry haulm yield in the 2016 field trial*

The genotype versus P source by location interaction in the 2016 trial season was also significant ($P \leq 0.01$) in terms of dry haulm yield (DHY) performance of the genotypes (Figure 4.14). In that, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (3033 kg ha$^{-1}$), under SSP P source in Minjibir out-yielded all other genotypes under all the P sources, although statistically

similar to some few others. It was, for example, statistically at par with ICGV-IS 07815 (2694 kg $ha^{-1}$) under SRP in Minjibir and ICIAR 7B under SSP (2728 kg $ha^{-1}$) and SRP (2689 kg $ha^{-1}$) in Minjibir and Samaru locations respectively. These were immediately followed, in performance, by Kwankwaso (2615 kg $ha^{-1}$) under SSP P source in Minjibir, and which was at par with ICIAR 6AT (2567 kg $ha^{-1}$) and ICGV-IS 07815 (2533 kg $ha^{-1}$) both in the same Minjibir location and under same SSP P source. The lowest DHY of the season was recorded for ICIAR 6AT (176 kg $ha^{-1}$) under the control P source in Samaru, and was statistically similar to at least one genotype under each of the P sources in Minjibir. It was also comparable to up to 53% of the genotypes under each of SRP and control (Figure 4.13) in the season.

A relative higher versatility, in terms of better DHY performance, irrespective of location and/or P source, was detected with the ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$. Relative higher DHY record under control was observed in Minjibir for SAMNUT 14, SAMNUT 22 and SAMNUT 23. However, no similar trend was observed in Samaru but for a somewhat related scenario with the ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ under the control and SRP which also performed better than under SSP (Figure 4.13). More genotypes (40%) had higher DHY records under SSP in Minjibir than SRP (20%) and control (13%). A near similar observation was also obtainable in Samaru, in terms of superiority of SSP (13%). This reiterated Musa *et al*. (2015)'s report. Areas with a relatively easy access to Sokoto phosphate rock (SPR) could, therefore, employ the use of such high DHY performance genotypes, under SRP in Minjibir, as ICGV-IS 07815 (2694 kg $ha^{-1}$), ICGV-IS 07083 (1667 kg $ha^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (1359 kg $ha^{-1}$), SAMNUT 24 (1239 kg $ha^{-1}$) and SAMNUT 11 (1150 kg $ha^{-1}$). SAMNUT 21 (1100 kg $ha^{-1}$) and SAMNUT 14 (478 kg $ha^{-1}$) also numerically performed better under SRP than the other two sources in Samaru, as also indicated by Figure 4.13 below. This hinted for a better groundnut genotype candidate of choice for the resource-constrained farmer in each of the two locations vis-à-vis the farmer's resource acquisition strengths and weaknesses.

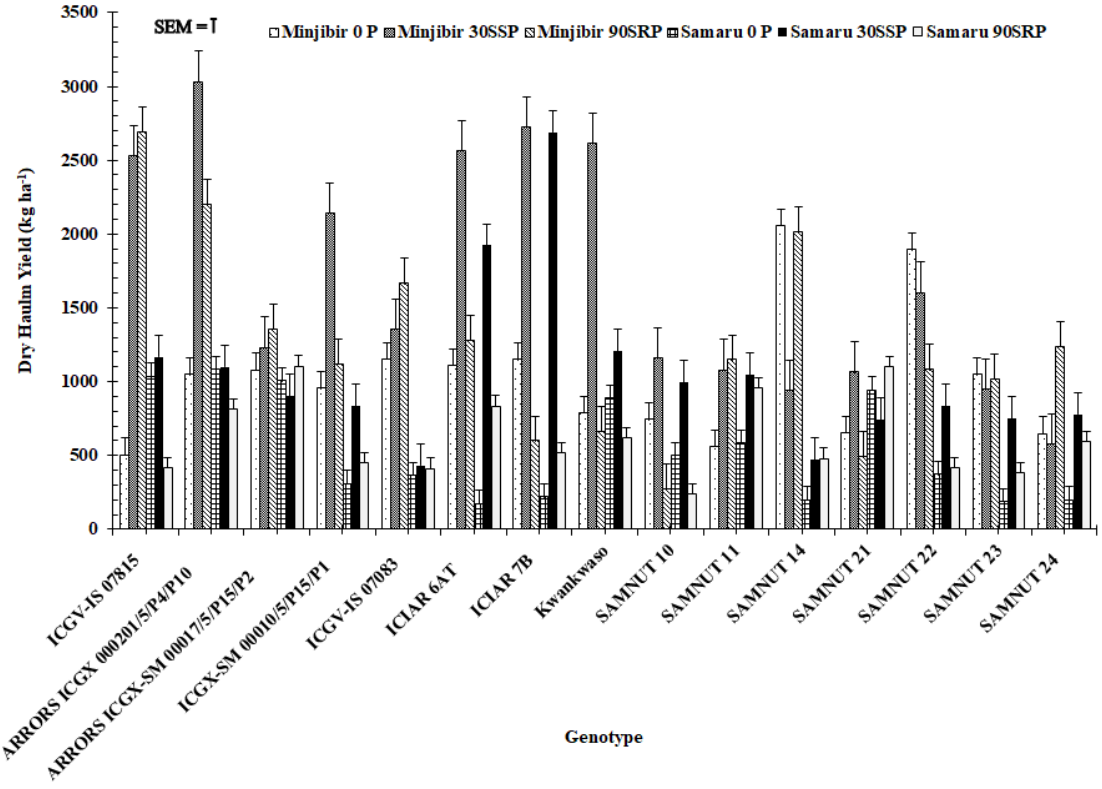



Figure 4.13: Genotype by phosphorus versus location interaction on dry haulm yield in the 2016 field trial

*4.6.3.11 Genotype by phosphorus versus location interaction on dry haulm yield in the field trials mean across the seasons*

The genotype by P source versus location interaction in the mean across the seasons was also significant ($P \leq 0.01$) in terms of dry haulm yield performance of the groundnuts (Figure 4.14). ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (2256 kg $ha^{-1}$) under SSP in Minjibir had the highest yield record of the mean across the seasons. The genotype was, statistically alike to Kwankwaso (2159 kg $ha^{-1}$) under the control, 60% of other genotypes under SSP and 40% of them under SRP, all in Minjibir. It was also similar to 13% of other genotypes under SSP in Samaru (Figure 4.14). At least 36% of the genotypes, across all the P sources, in Minjibir performed significantly. Most notable amongst them were ARRORS ICGX 000201/5/$P_4$/$P_{10}$, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, SAMNUT 14 and SAMNUT 22. Up to about 73% of the genotypes, in each of the locations, were observed to be more dry haulm productive under SSP. About 87% and 67% of the genotypes under SRP, respectively in Minjibir and Samaru, were also observed to have performed well in terms of this yield in the 2015 and 2016 seasons, as means. This suggests for a window of diverse scale of preference in the choice of

befitting genotype(s) vis-à-vis the availability of a given P source. It can, therefore, be deduced that more genotypes (87%) responded to SRP in Minjibir under the mean across the seasons. The SRP might be fortified by organic materials in the soil, as the process is reported to improve agronomic efficiency, thereby aiding nutrient solubility and retention as reported by Sanginga and Woomer (2009) amongst others.

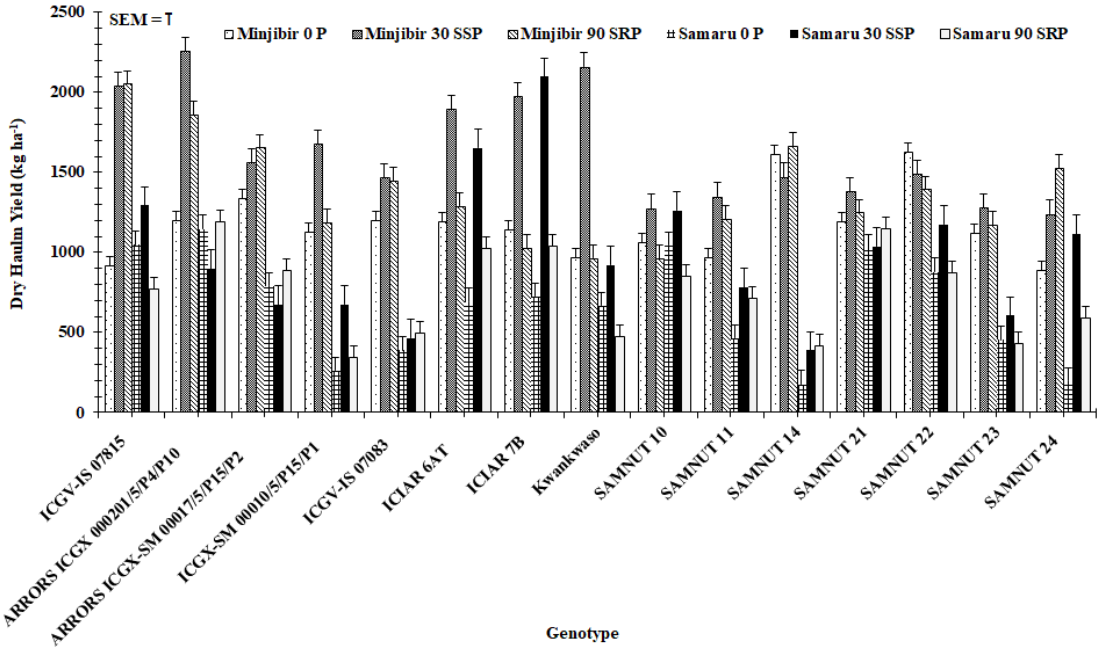



Figure 4.14: Genotype by phosphorus versus location interaction on dry haulm yield in the field trials mean across the seasons

### 4.6.4 Genotype by phosphorus versus location interaction on pod yield in the 2015, 2016 field trials and the mean across the seasons

*4.6.4.1 Genotype by phosphorus interaction on pod yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) genotype versus P source interaction on the genotypes in terms of the pod yield (kg $ha^{-1}$) recorded in the 2015 trial season (Figure 4.15). Significantly highest pod yield of 860 kg $ha^{-1}$ was observed for SAMNUT 24 under SSP in the 2015 trial season. This was at par with ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (758.38 kg $ha^{-1}$) and SAMNUT 24 (695.63 kg $ha^{-1}$), respectively under control and SRP. SAMNUT 24 (663.63 kg $ha^{-1}$), SAMNUT 22 (654.50, 653.63 and 581.25 kg $ha^{-1}$), respectively under SSP, SRP and control; and SAMNUT 14 (575 kg $ha^{-1}$), under the control, followed those. However, ICIAR 6AT (200.50 kg $ha^{-1}$), although

comparable to many genotypes under all the P sources, had the overall lowest yield record of this trial season (Figure 4.15).

In general terms, 33% of the genotypes under SRP had a good pod yield record, whereas 27% and 20% of them had good records, respectively under the control and SSP influence. SAMNUT 24 and SAMNUT 22, and to some extent SAMNUT 10 and SAMNUT 14, were observed to be versatile in terms of pod yield, as they performed relatively higher than other genotypes under all the P source treatments in the 2015 trial season (Figure 4.15). SAMNUT 24 (860.00 kg $ha^{-1}$) and, to an extent, SAMNUT 14 (357.50 kg $ha^{-1}$) responded very well to SSP source. The same SAMNUT 24 and SAMNUT 14 were also observed to be versatile in pod yield, as they performed well under all sources. Interestingly, ARRORS ICGX 000201/5/$P_4$/$P_{10,}$ without any P application, was observed to produce the highest pod yield (758.38 kg $ha^{-1}$) than 93% of the genotypes under the control. It was statistically similar to the overall highest genotype of the season (SAMNUT 24 under SSP) and also higher than up to 93% of the genotypes under each of SSP and SRP. This, therefore, suggests ARRORS ICGX 000201/5/$P_4$/$P_{10}$ to be a highly suitable candidate genotype for our resource-constrained farmers.

*4.6.4.2 Genotype by phosphorus interaction on pod yield in the 2016 field trial*

The genotypes, in the 2016 trial season, were significantly ($P \leq 0.01$) different in terms of their pod yield performances under the influence of genotype versus P source interaction (Figure 4.16). Significantly highest pod yield was recorded for ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (2200 kg $ha^{-1}$) under the control P source in the season, and it was at par with ICGV-IS 07083 (1945 kg $ha^{-1}$) under the same P source. It was followed by statistically similar Kwankwaso (1800 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1714 kg $ha^{-1}$), ICIAR 6AT (1691 kg $ha^{-1}$) and SAMNUT 23 (1672 kg $ha^{-1}$), all under SSP; and ICGV-IS 07083 (1688 kg $ha^{-1}$), under SRP P sources. The lowest yield was, however, recorded for SAMNUT 10 (422 kg $ha^{-1}$), which was at par with many other genotypes under all P sources in the season (Figure 4.16). ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-IS 07083 were observed to have consistently performed relatively well under the control source irrespective of trial season.

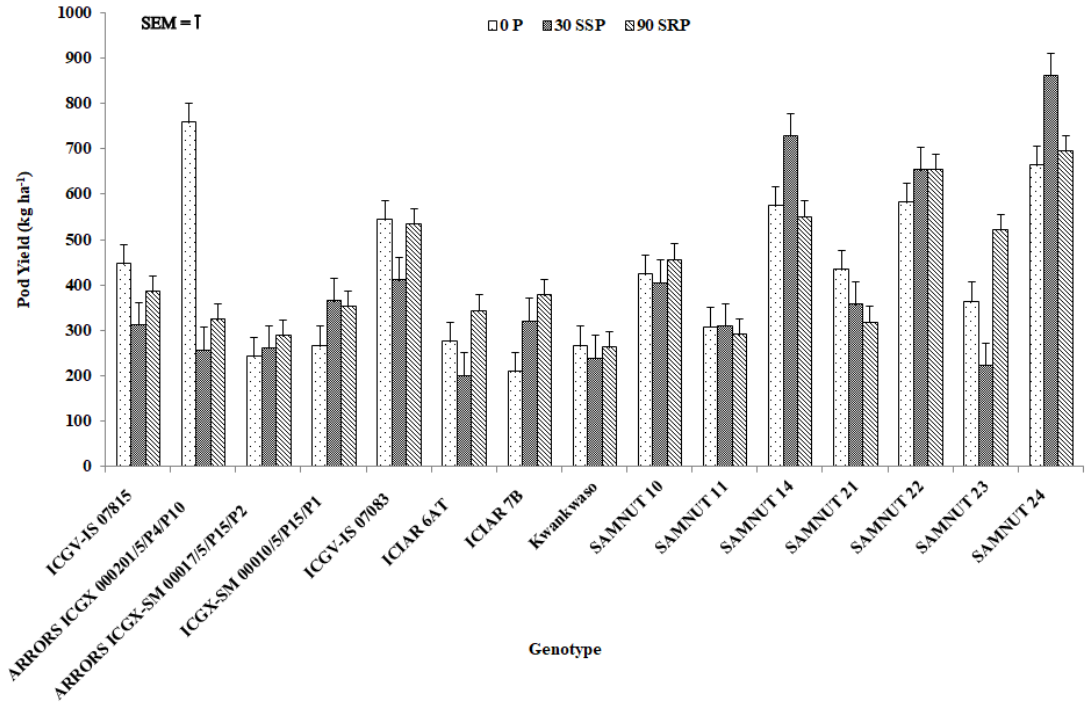



Figure 4.15: Genotype by phosphorus interaction on pod yield in the 2015 field trial

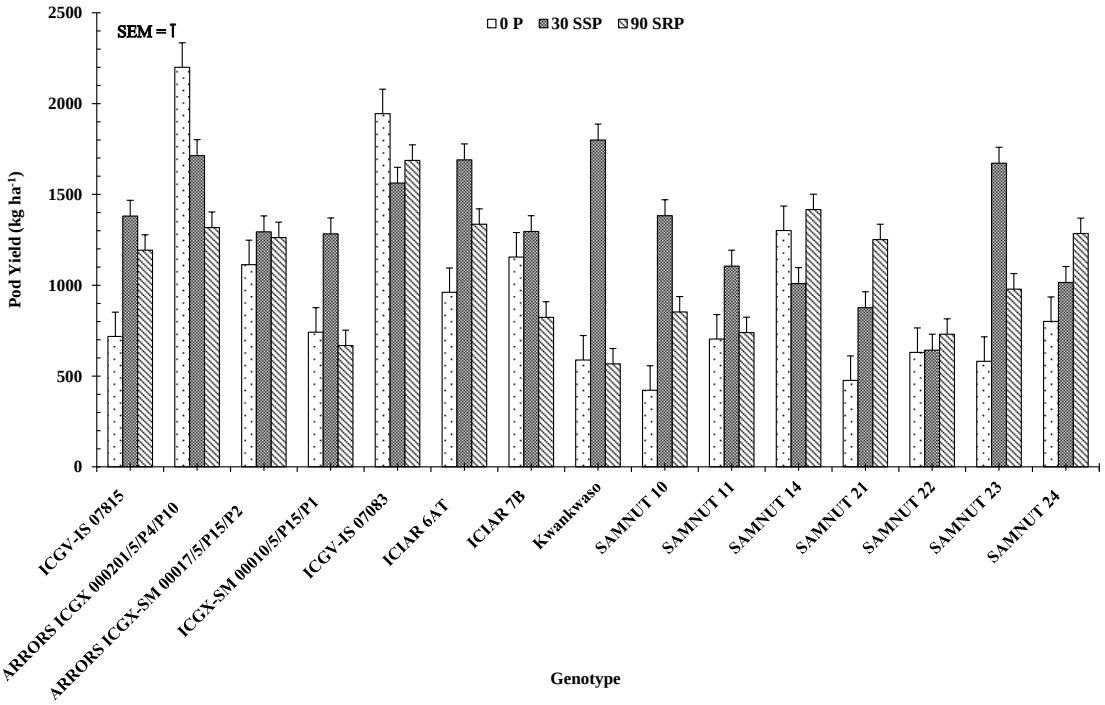



Figure 4.16: Genotype by phosphorus interaction on pod yield in the 2016 field trial

About 27%, 13% and only about 7% of the genotypes, respectively under SSP, control and SRP had a record of better pod yield in the 2016 trial season. Some soil and

environmental factors may possibly have influenced the assimilation of the SSP especially considering its readily-soluble nature when compared to SRP. Exudation of enzymes and/or organic acids into the rhizosphere by roots of plants grown in a P-deficient condition may also explain the rationale for the pod yield difference between SRP sourced P and the control, as earlier suggested.

#### *4.6.4.3 Genotype by phosphorus interaction on pod yield in the field trials mean across the seasons*

In the mean 2015 and 2016 trial seasons also, significant genotype versus P source interaction had significantly ($P \leq 0.01$) influenced the genotypes' performances on their pod yield (Figure 4.17). Hence, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1479 kg $ha^{-1}$), under control, had the highest pod yield record. It was statistically akin to many other genotypes under all the P sources, and was followed by 40%, 20% and about 27% of the genotypes under control, SSP and SRP P sources respectively. Kwankwaso (415 kg $ha^{-1}$) under SRP; and SAMNUT 11, under both control (513 kg $ha^{-1}$) and SRP (515 kg $ha^{-1}$) have the lowest pod yield record of this season (Figure 4.17).

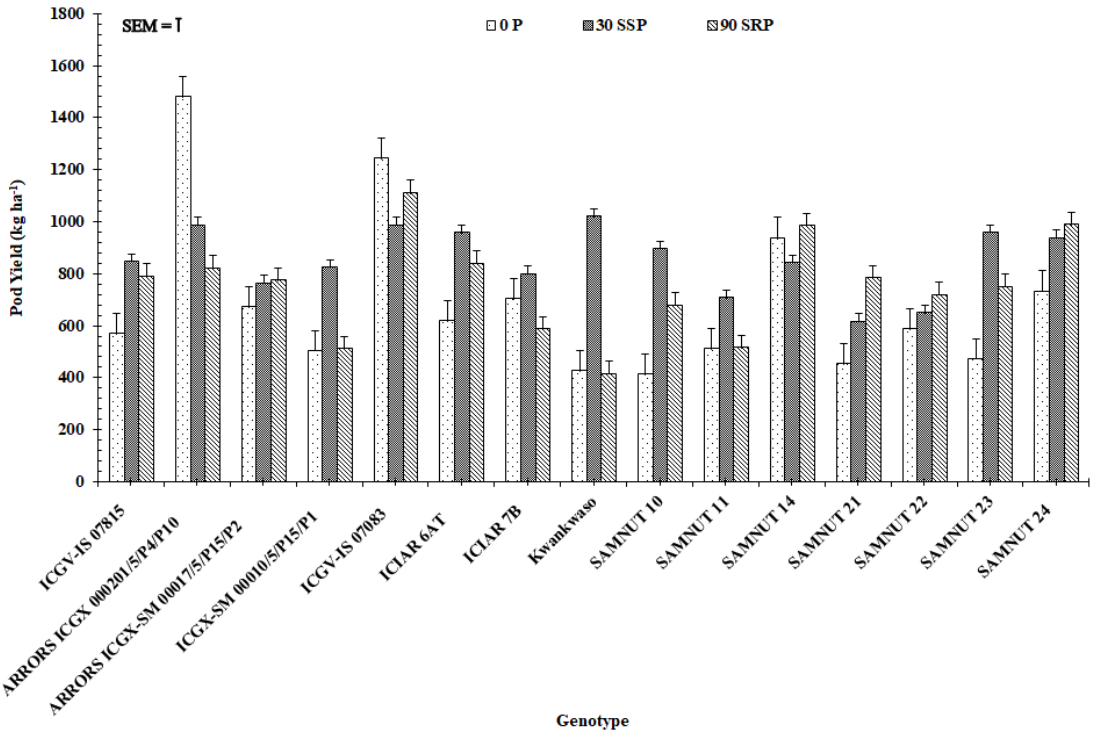



Figure 4.17: Genotype by phosphorus interaction on pod yield in the field trials mean across the seasons

These were still similar to many other genotypes across the P sources during the trial season. It is interestingly noteworthy that ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-

IS 07083 were relatively better under the control P source condition whereas the SAMNUT 24 usually required either or both of the two (SSP and/or SRP) fertiliser P sources. Up to 73%, about 67% and a little above 53% of the genotypes, respectively under SRP, SSP and control were recorded as having performed well, in terms of this yield in the mean across the seasons. All the genotypes (100%) under the mean across the seasons were also interestingly observed to be versatile, as they performed well irrespective of P source.

#### *4.6.4.4 Genotype by location interaction on pod yield in the 2015 field trial*

The genotype versus location interaction on pod yield of the genotypes, in the 2015 trial season, was significant ($P \leq 0.01$) (Figure 4.18). SAMNUT 24 (832 kg $ha^{-1}$) in Minjibir location, generally, out-yielded all other genotypes grown in both locations. It was followed by, statistically similar, SAMNUT 22 (675 kg $ha^{-1}$), ICGV-IS 07083 (667 kg $ha^{-1}$) and SAMNUT 14 (643 kg $ha^{-1}$), all in Minjibir; and SAMNUT 24 (647 kg $ha^{-1}$), which was at par with SAMNUT 14 (592 kg $ha^{-1}$) and SAMNUT 22 (584 kg $ha^{-1}$), all in Samaru. The significantly lowest pod yielding genotypes were ICIAR 6AT (211 kg $ha^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (235 kg $ha^{-1}$) and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (237 kg $ha^{-1}$), all in Samaru, although other genotypes were at par with them in both locations (Figure 4.18). Also noteworthy were ICSV-IS 07815 and SAMNUT 21, as were observed to have been instrumental to the observed significance of interaction. Both genotypes were significant in Samaru, in terms of the parameter during the season, and not any other as also depicted in the Figure 4.18 below. Although only about 7% of the genotypes had a statistically highest pod yield record in Minjibir, no less than 73% of the genotypes were versatile in the 2015 trial season. These were statistically similar in terms of pod yield in both locations (Figure 4.18).

#### *4.6.4.5 Genotype by location interaction on pod yield in the 2016 field trial*

Also, the genotype by location interaction on pod yield of the genotypes, in 2016 trial season, was significant ($P \leq 0.01$) (Figure 4.19). ICGV-IS 07083 (2906 kg $ha^{-1}$), in Minjibir, out-yielded all others irrespective of location. It was immediately followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1821 kg $ha^{-1}$) at the same location, and was statistically similar to ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1667 kg $ha^{-1}$) and ICIAR 6AT (1616 kg $ha^{-1}$), respectively in Samaru and Minjibir.

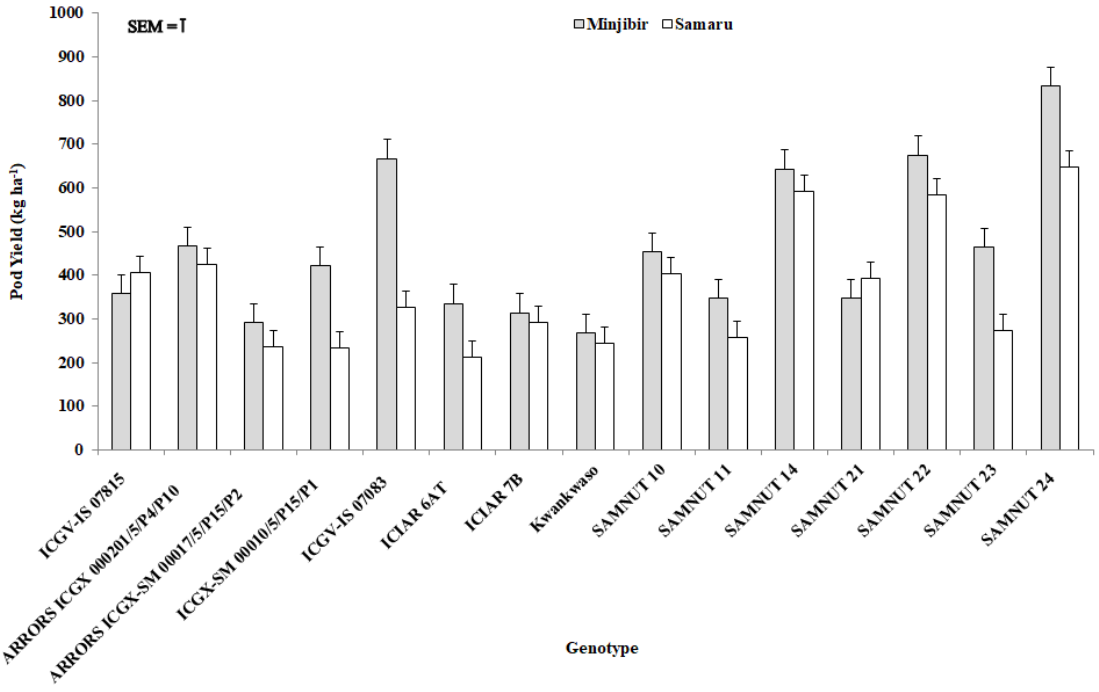



Figure 4.18: Genotype by location interaction on pod yield in the 2015 field trial

Lowest pod yield was recorded, in Samaru, for ICGV-IS 07083 (557 kg $ha^{-1}$), which was at par with some other genotypes, including those in Minjibir like SAMNUT 22 (595 kg $ha^{-1}$), SAMNUT 21 (630 kg $ha^{-1}$) and SAMNUT 11 with 656 kg pod yield $ha^{-1}$ (Figure 4.19). Generally, 20% of the groundnuts were observed to have performed well in both agro-ecologies, although more have performed better in Minjibir than Samaru as shown in Figure 4.19 below.

#### *4.6.4.6 Genotype by location interaction on pod yield in the field trials mean across the seasons*

Significantly ($P \leq 0.01$) different pod yield was recorded for the genotypes, in the mean of 2015 and 2016 seasons, due to genotype versus location interactions on the genotypes (Figure 4.20). In that, ICGV-IS 07083 (1786 kg $ha^{-1}$), in Minjibir, out-yielded all other genotypes regardless of location. The genotype was followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1144 kg $ha^{-1}$), which was statistically similar to many other in both locations although SAMNUT 24 (1096 kg $ha^{-1}$) and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1046 kg $ha^{-1}$) in Minjibir and Samaru respectively, were relatively more exceptional than all of their counterparts. The overall lowest pod yield record was recorded for each of SAMNUT 21 (489 kg $ha^{-1}$) and Kwankwaso (459 kg $ha^{-1}$), respectively in Minjibir and Samaru (Figure 4.20).

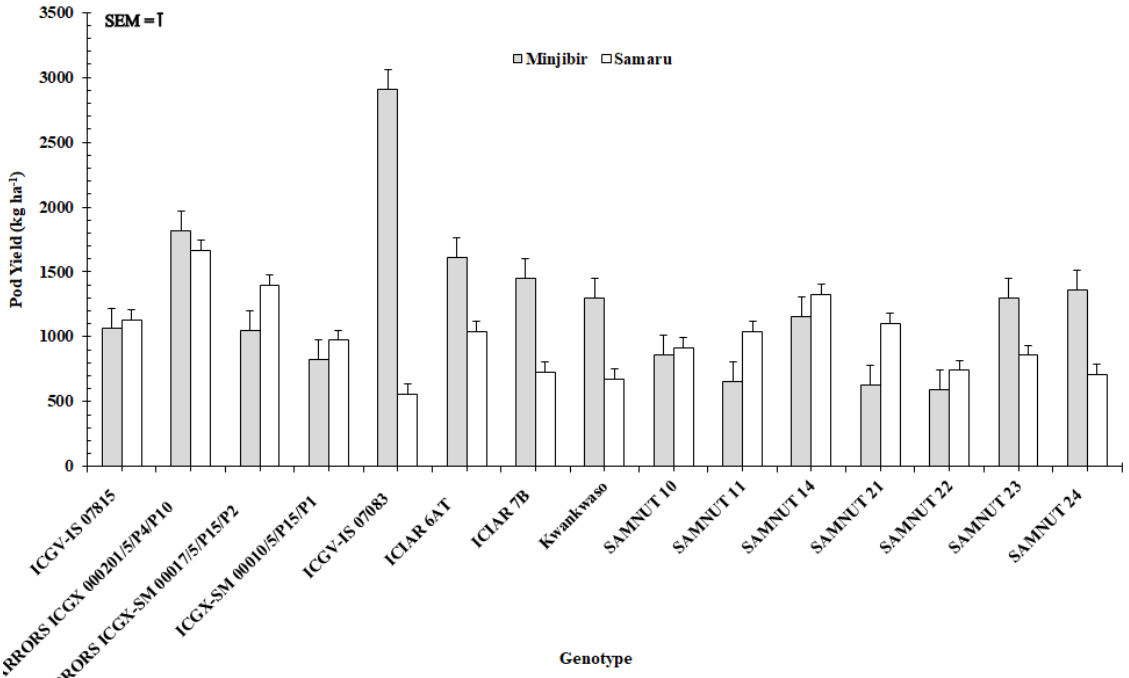



Figure 4.19: Genotype by location interaction on pod yield in the 2016 field trial

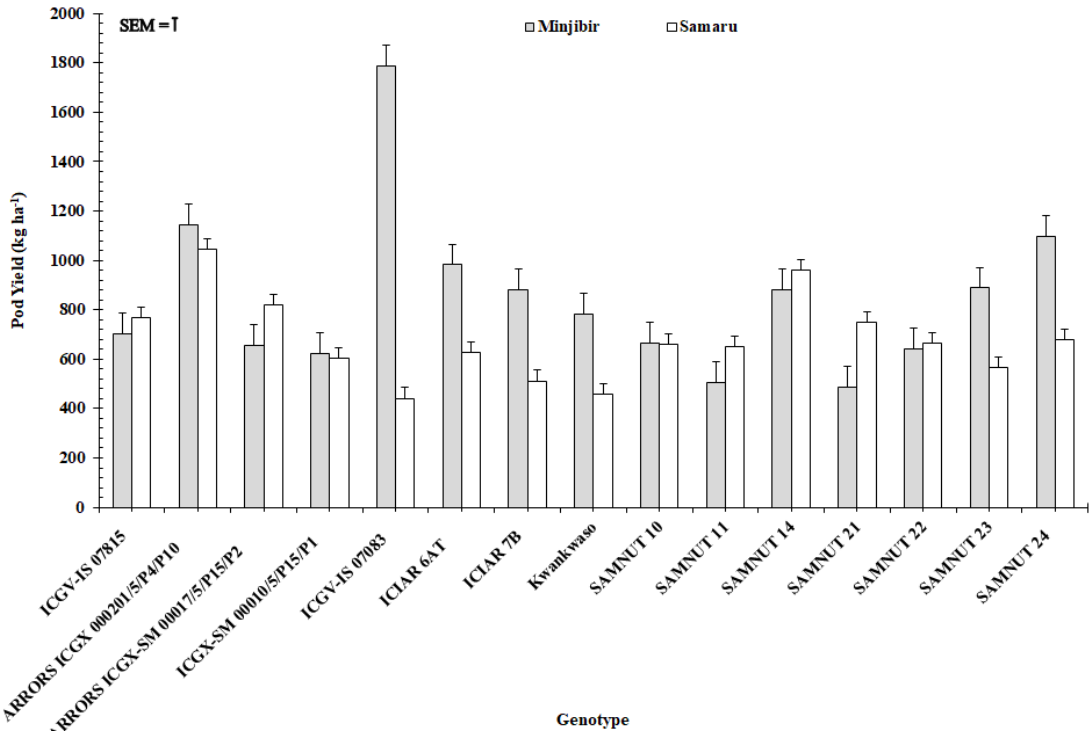



Figure 4.20: Genotype by location interaction on pod yield in the field trials mean across the seasons

Up to 93% of the genotypes were observed to have performed fairly well in both locations in the mean across the seasons. However, only about 47% and 27% of the genotypes were observed to be of high pod yield in Minjibir and Samaru, respectively.

*4.6.4.7 Phosphorus by location interaction on pod yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) P source by location interaction on the differences between genotypes in terms of their pod yield in 2015 season's field trial (Figure 4.21)

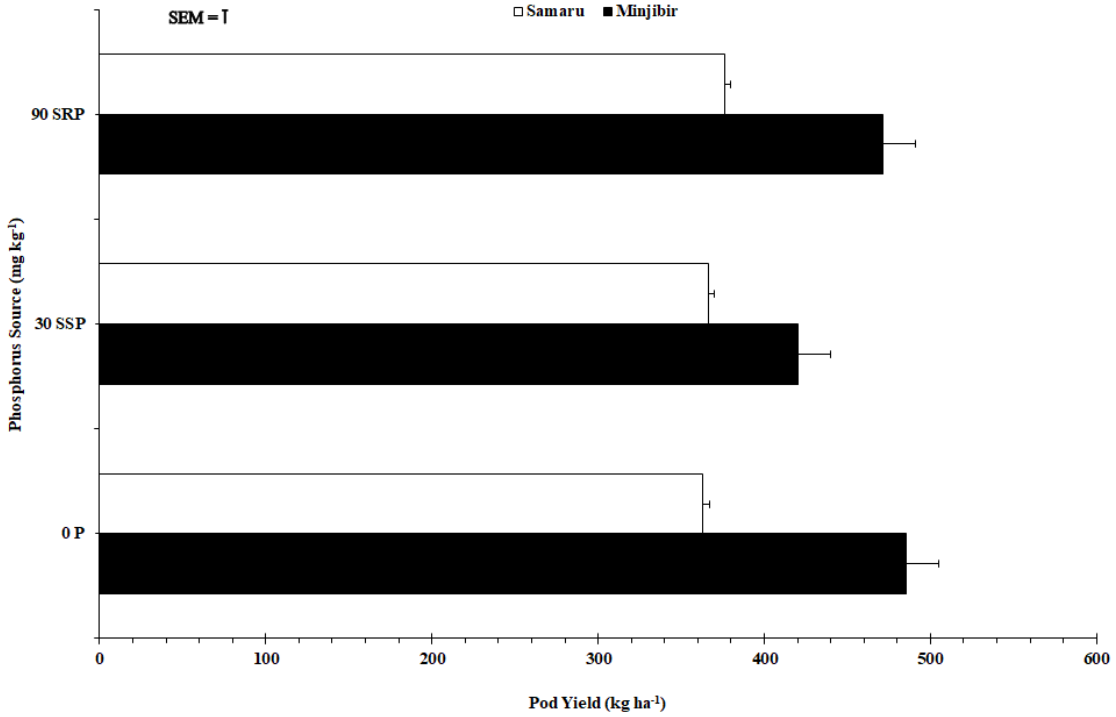



Figure 4.21: Phosphorus by location interaction on pod yield in the 2015 field trial

Although statistically at par with SRP P source in Minjibir (472 kg $ha^{-1}$), the control at the same Minjibir (485 kg $ha^{-1}$) outperformed SSP Minjibir (420 kg $ha^{-1}$) record, which statistically followed those in the 2015 trial season. There was no significant difference between all the P sources, in terms of pod yield in Samaru. The SRP P source (376 kg $ha^{-1}$) in Samaru was, nevertheless, statistically at par with the SSP in Minjibir in terms of the pod yield in the season. The reason for this being secretion of enzymes and/or organic acids into the rhizosphere by plants (Yadav and Tarafdar, 2001; Inal *et al*., 2007), via their roots, living in a P-deficient soil environments still holds. The AcPhase activity observed in this study (Table 4.11 and Figure 4.78) partly also reaffirmed this.

*4.6.4.8 Phosphorus by location interaction on pod yield in the 2016 field trial*

There was also a significant ($P \leq 0.01$) P source by location interaction on the differences between genotypes in terms of their pod yield in the 2016 season's field trial (Figure 4.22). Single superphosphate (SSP) P source in Minjibir (1489 kg $ha^{-1}$) significantly ($P \leq 0.01$) out-yielded the other two P sources in both locations. The

control P source, in the same Minjibir location (1171 kg $ha^{-1}$), followed the SSP P source, and was statistically at par with the SSP (1141 kg $ha^{-1}$) and SRP (1091 kg $ha^{-1}$) in Samaru. These were, in turn, also at par with SRP P source in Minjibir (1057 kg $ha^{-1}$). The control P source in Samaru had the significantly lowest pod yield of 742 kg $ha^{-1}$ amongst the P sources during the 2016 trial season's study (Figure 4.22).

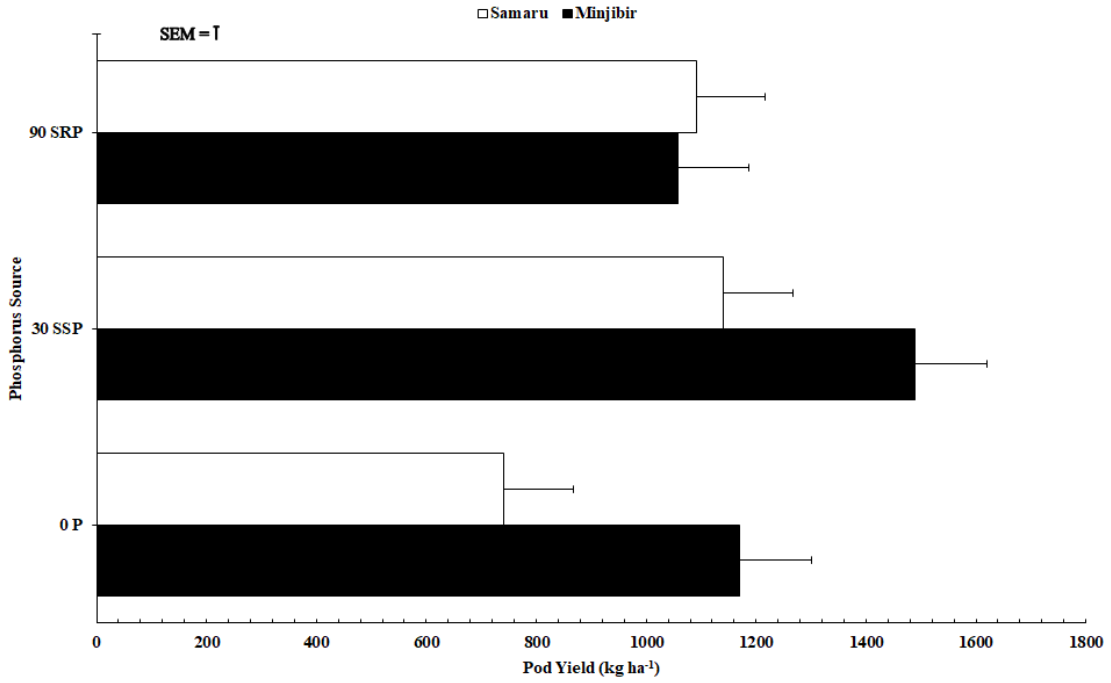



Figure 4.22: Phosphorus by location interaction on pod yield in the 2016 field trial

The advantage of solubility characteristic of SSP, as established (Lewis *et al*., 1997; Rech *et al*., 2019), may possibly be part of the reasons behind the pod yield recorded under the P source in Minjibir in the 2016 field trial. Earlier, Aduayi *et al*. (2002) clearly explained the necessity of supplying sulphur to any P source added other than SSP if the source is to be available to crop plants.

### *4.6.4.9 Phosphorus by location interaction on pod yield in the field trials mean across the seasons*

There was also a significant ($P \leq 0.05$) P source by location interaction on the differences between genotypes in terms of their pod yield in the mean 2015 and 2016 seasons' field trial (Figure 4.22). All the P sources were statistically at par with one another in each of the two agro-ecological locations, although SSP P source in Minjibir (951 kg $ha^{-1}$) outperformed the same SSP P (754 kg $ha^{-1}$) in Samaru; and control P (552 kg $ha^{-1}$) sources, also in Samaru. The pod yield value recorded for the control fertiliser P

source in Minjibir (825 kg ha$^{-1}$) was statistically at par with the SRP (734 kg ha$^{-1}$) and SSP (754 kg ha$^{-1}$) P sources observed in Samaru.

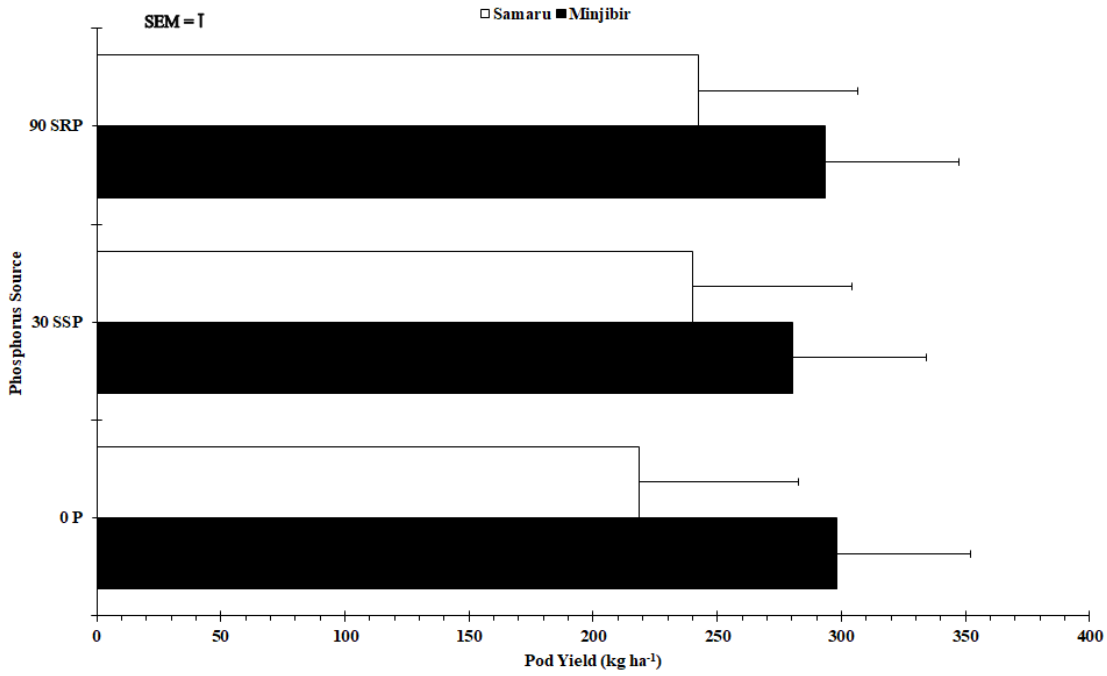



Figure 4.23: Phosphorus by location interaction on pod yield in the field trials mean across the seasons

The same control in Minjibir (825 kg ha$^{-1}$), however, also out-yielded its Samaru control P source (219 kg ha$^{-1}$) counterpart in the seasons as mean (Figure 4.22). Significance of, a relative, low soil *p*H on the solubility of SRP, and hence the relative more release of nutrient P into the soil (Meyer *et al*., 2011), and the OM content (Table 4.1) may, in part, be the reason behind SRP having an edge above SSP and the control in terms of this yield. This was especially in the case of Minjibir, considering OM (Table 4.1), and Samaru, when *p*H is considered (Table 4.1).

#### *4.6.4.10 Genotype by phosphorus versus location interaction on pod yield in the 2015 field trial*

There was also a significant ($P \leq 0.01$) genotype by P source versus location interaction differences between the groundnuts in terms of pod yield in 2015 trial season (Figure 4.24). SAMNUT 23, under SRP in Samaru (975 kg ha$^{-1}$), which was statistically not different from SAMNUT 24 under SSP in Samaru; and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (856 kg ha$^{-1}$) and SAMNUT 10 (842 kg ha$^{-1}$), both under the control, in

Minjibir, outperformed all the others in terms of this yield in the 2015 trial season (Figure 4.25). On the other hand, SAMNUT 11 under SRP in Samaru (833 kg $ha^{-1}$) followed these highest performed genotypes, and was similar to SAMNUT 11 under SSP in Minjibir (722 kg $ha^{-1}$). The lowest yield of the season was, however, recorded for SAMNUT 21 (136 kg $ha^{-1}$) under the control in Minjibir. This genotype was also variously similar to some others under all the P sources and across both locations (Figure 4.24).

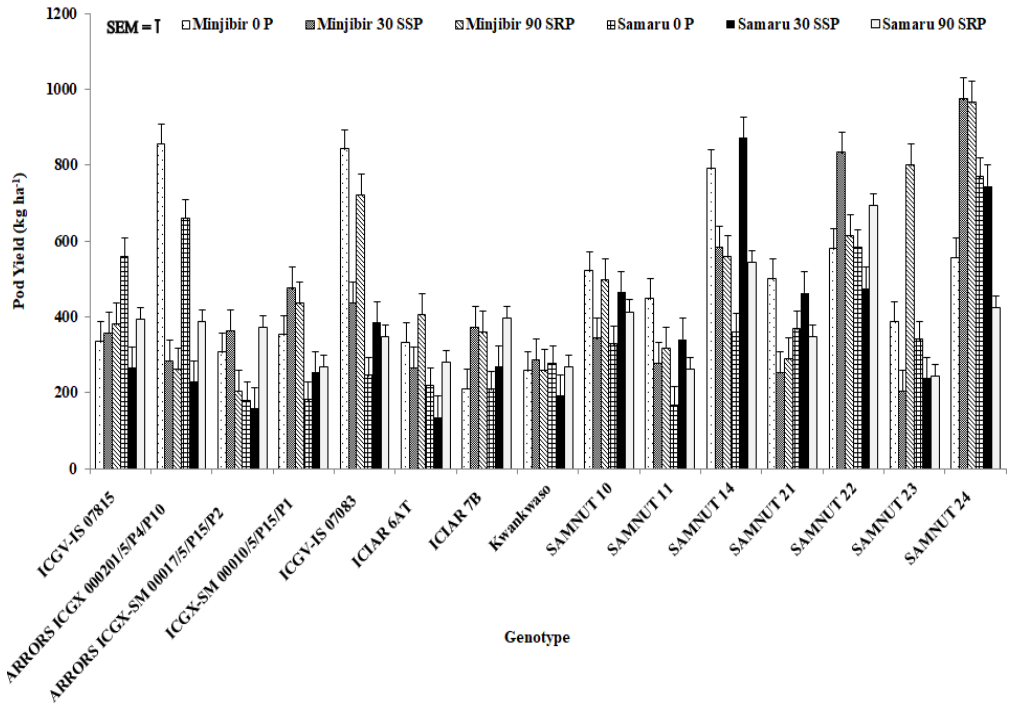



Figure 4.24: Genotype by phosphorus versus location interaction on pod yield in the 2015 field trial

During the 2015 trial season, 13% of the genotypes under each of control and SSP in Minjibir had a good pod yield record. In Samaru, however, 20% of the genotypes under each of the control and SRP sources had a good record of the parameter. About 27% of the genotypes performed well under the SSP in the same Samaru during the trial season.

#### *4.6.4.11 Genotype by phosphorus versus location interaction on pod yield in the 2016 field trial*

There was also a significant ($P \leq 0.01$) genotype versus P source versus location interaction differences between the genotypes in terms of pod yield in 2016 trial season (Figure 4.24). ICGV-IS 07083 under the control in Minjibir (3222 kg $ha^{-1}$) significantly

had higher pod yield over most other genotypes under all the P sources and across both locations. Kwankwaso (2956 kg $ha^{-1}$) and ICGV-IS 07083 (2742 kg $ha^{-1}$), both under SSP in Minjibir; and the same ICGV-IS 07083 under SRP also in Minjibir (2753 kg $ha^{-1}$) were similar to the highest genotype under the control in Minjibir (ICGV-IS 07083) as shown in Figure 4.6.4.11. The same Kwankwaso under SRP in Minjibir (314 kg $ha^{-1}$) had the significantly lowest pod yield record during the trial season. Genotypes that were statistically similar to the lowest pod-yielding Kwankwaso were spread across the P sources at both locations (Figure 4.24).

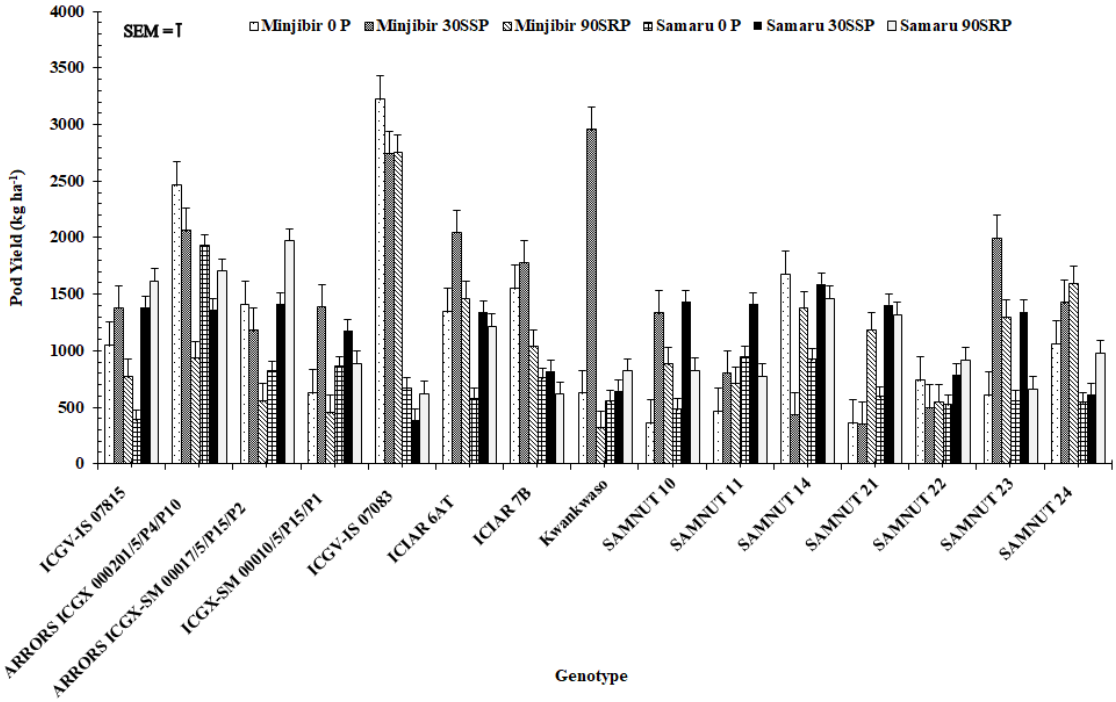



Figure 4.25: Genotype by phosphorus versus location interaction on pod yield in the 2016 field trial

Only about 7% and 13% of the genotypes under each of control/SRP and SSP in Minjibir location performed well in terms of pod yield in the 2016 trial season. None of the genotypes, under any of the sources or control, in Samaru was statistically at par with any of the highest performed genotypes in Minjibir. However, some of the genotypes were observed to be statistically at par under some P source(s) in both agro-ecological locations, as indicated earlier on.

*4.6.4.12 Genotype by phosphorus versus location interaction on pod yield in the field trials mean across the seasons*

There was also a significant ($P \leq 0.01$) genotype versus P source by location interaction differences between the genotypes in terms of pod yield in the mean across the 2015 and 2016 trial seasons (Figure 4.25). In Minjibir, ICGV-IS 07083 under the control (2032 kg $ha^{-1}$), had the highest pod yield record, but was at similar to many other genotypes under the various P sources across the locations. An example was the same ICGV-IS 07083 under SRP in the same Minjibir (1737 kg $ha^{-1}$). Kwankwaso under SSP in Minjibir (1620 kg $ha^{-1}$), although statistically similar to many other genotypes under each of the P sources across the locations, had the lowest pod yield record in the mean across the seasons (Figure 4.25).

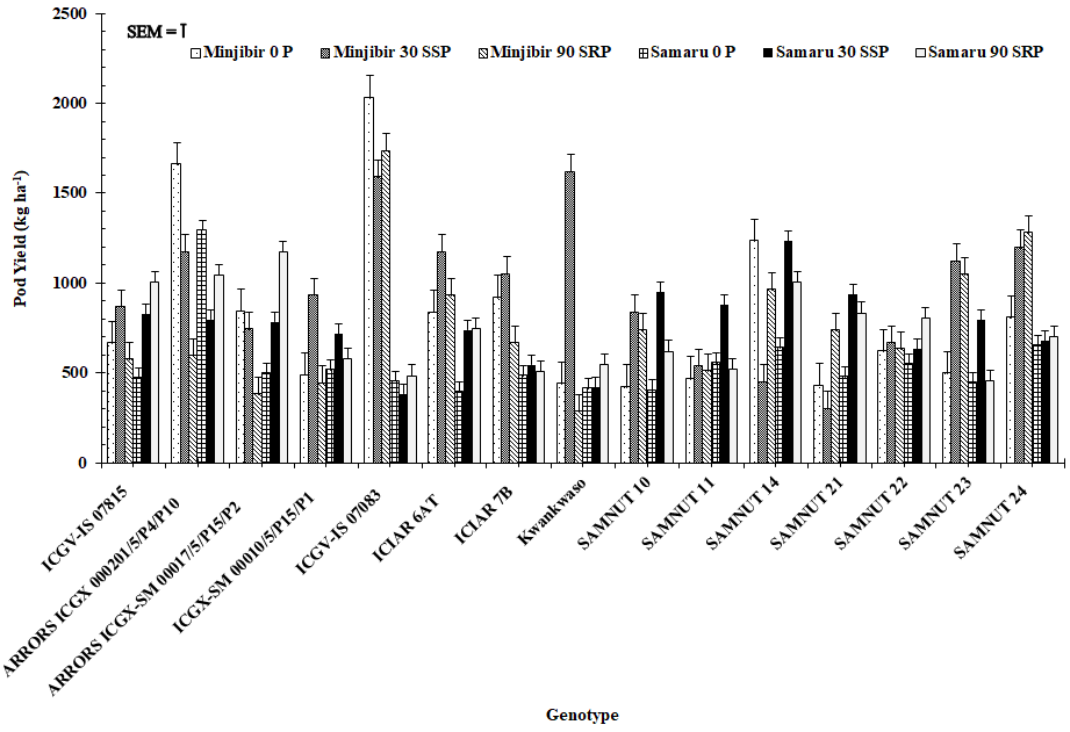



Figure 4.26: Genotype by phosphorus versus location interaction on pod yield in the field trials mean across the seasons

In the (2015/2016 trial seasons) mean, the Minjibir and Samaru respectively, had 93% and 60% genotypes that performed well in terms of pod yield under the control. There were, however, 93% and 80% under SSP and about 87% and 93% under SRP respectively in Minjibir and Samaru locations. This further reaffirmed the higher pod yield potential of Minjibir location over that of the Samaru location in the mean across

the seasons. Genotypes grown at the latter location, however, proved to be more productive under SRP P source than the former by about 7%.

## 4.7 Effects of Genotype, Phosphorus Source and Location on Dry Matter Yield and Harvest Index of the Groundnuts in 2015, 2016 Trial Seasons and Mean across the seasons

### 4.7.1 Effects of genotype, P source and location on dry matter yield of the groundnuts

There was a significant ($P \leq 0.01$) influence of each of location, genotype and P source, vis-à-vis their interactions ($P \leq 0.01$) on dry matter yield (DMY) observed for the groundnut genotypes in 2015, 2016 and mean across the seasons (Table 4.5). In this vein, SAMNUT 21 and SAMNUT 10, in 2015 and ARRORS ICGX 000201/5/$P_4$/$P_{10}$, in 2016 and mean across the seasons, respectively, outperformed all other genotypes in terms of DMY. SAMNUT 21 and SAMNUT 10 were statistically not different from SAMNUT 22 in the 2015 trial season. The highest performed groundnut in the 2016 and mean across the seasons (ARRORS ICGX 000201/5/$P_4$/$P_{10}$) was followed by ICIAR 6AT in 2016, which was in turn also similar to ICGV-IS 07083 and ICGV-IS 07815.

In the mean across the seasons, the genotype ARRORS ICGX 000201/5/$P_4$/$P_{10}$ was also still the best, followed by ICIAR 6AT and ICGV-IS 07815, both of which were statistically similar to ICIAR 7B. The lowest DMY was recorded for ICGX-SM 00010/5/$P_{15}$/$P_1$ in the 2015 trial season and was statistically comparable to SAMNUT 14. In the 2016 trial, and mean across the seasons, SAMNUT 10 had the lowest DMY record and did not differ, statistically, from SAMNUT 11, SAMNUT 21, SAMNUT 22 and SAMNUT 24 (Table 4.5). The genotypes under SSP out-yielded those under the other two sources in terms of the DMY assessed. Those under SRP generally followed whereas those under the control were lowest in terms of the parameter. Each of these observations was, as such, a characteristic of both trial seasons and mean across the seasons (Table 4.5). Significantly highest DMY was observed in Minjibir than Samaru. There was a significant influence of genotype and P on DMY of the groundnut genotypes reported by Mouri *et al.* (2018). In a groundnut population study conducted by Mukhtar *et al.* (2013), SAMNUT 21 was observed to be statistically similar to SAMNUT 23, in terms of total dry matter yield.

Table 4.5: Effects of genotype, P source and location on dry matter yield and harvest index of the groundnuts in 2015, 2016 and mean across the seasons

| Treatment | Dry Matter Yield (kg ha$^{-1}$) | | | Harvest Index (%) | | |
|---|---|---|---|---|---|---|
| | 2015 | 2016 | Mean across the seasons | 2015 | 2016 | Mean across the seasons |
| **Genotype (G)** | | | | | | |
| ICGV-IS 07815 | 1321$^{c}$ | 2496$^{b-d}$ | 1945$^{b}$ | 21$^{ef}$ | 48$^{ef}$ | 35$^{f}$ |
| ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 1311$^{c}$ | 3299$^{a}$ | 2425$^{a}$ | 26$^{cd}$ | 55$^{bc}$ | 39$^{de}$ |
| ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 1194$^{d}$ | 2346$^{de}$ | 1732$^{de}$ | 14$^{h}$ | 51$^{c-e}$ | 36$^{ef}$ |
| ICGX-SM 00010/5/$P_{15}$/$P_1$ | 793$^{f}$ | 1875$^{f}$ | 1424$^{f}$ | 23d$^{e}$ | 51$^{c-e}$ | 42$^{cd}$ |
| ICGV-IS 07083 | 932$^{e}$ | 2637$^{bc}$ | 1769$^{cd}$ | 33$^{ab}$ | 62$^{a}$ | 48$^{b}$ |
| ICIAR 6AT | 1275$^{cd}$ | 2652$^{b}$ | 1985$^{b}$ | 16$^{gh}$ | 55$^{bc}$ | 36$^{ef}$ |
| ICIAR 7B | 1361$^{bc}$ | 2418$^{cd}$ | 1869$^{bc}$ | 17$^{f-h}$ | 52$^{cd}$ | 35$^{f}$ |
| Kwankwaso | 929$^{e}$ | 2123$^{e}$ | 1628$^{e}$ | 16$^{f-h}$ | 43$^{f}$ | 34$^{f}$ |
| SAMNUT 10 | 1506$^{a}$ | 1546$^{g}$ | 1100$^{i}$ | 23$^{de}$ | 58$^{ab}$ | 39$^{de}$ |
| SAMNUT 11 | 937$^{e}$ | 1752$^{fg}$ | 1326$^{fg}$ | 20$^{e-g}$ | 48$^{de}$ | 38$^{d-f}$ |
| SAMNUT 14 | 890$^{ef}$ | 2279$^{de}$ | 1655$^{de}$ | 28$^{c}$ | 58$^{ab}$ | 53$^{a}$ |
| SAMNUT 21 | 1517$^{a}$ | 1709$^{fg}$ | 1272$^{gh}$ | 14$^{h}$ | 49$^{de}$ | 34$^{f}$ |
| SAMNUT 22 | 1453$^{ab}$ | 1711$^{fg}$ | 1374$^{fg}$ | 28$^{bc}$ | 43$^{f}$ | 36$^{ef}$ |
| SAMNUT 23 | 969$^{e}$ | 1809$^{f}$ | 1268$^{gh}$ | 26$^{cd}$ | 60$^{a}$ | 44$^{c}$ |
| SAMNUT 24 | 1186$^{d}$ | 1714$^{fg}$ | 1195$^{hi}$ | 35$^{a}$ | 61$^{a}$ | 52$^{ab}$ |
| SE± | 20.9 | 46.0 | 26.81 | 0.9 | 0.9 | 0.8 |
| **Phosphorus (P, kg $P_2O_5$ ha$^{-1}$)** | | | | | | |
| 0 P | 1059$^{c}$ | 1747$^{c}$ | 1266$^{c}$ | 25$^{a}$ | 55$^{a}$ | 43$^{a}$ |
| 30 SSP | 1262$^{a}$ | 2705$^{a}$ | 2044$^{a}$ | 20$^{c}$ | 49$^{b}$ | 37$^{c}$ |
| 90 SRP | 1194$^{b}$ | 2022$^{b}$ | 1482$^{b}$ | 23$^{b}$ | 55$^{a}$ | 41$^{b}$ |
| SE± | 9.35 | 20.7 | 12.0 | 0.4 | 0.4 | 0.4 |
| **Location (L)** | | | | | | |
| Minjibir | 1460$^{a}$ | 2574$^{a}$ | 1954$^{a}$ | 26$^{a}$ | 47$^{b}$ | 35$^{b}$ |
| Samaru | 883$^{b}$ | 1741$^{b}$ | 1242$^{b}$ | 19$^{b}$ | 59$^{a}$ | 45$^{a}$ |
| SE± | 7.6 | 16.9 | 9.8 | 0.4 | 0.3 | 0.3 |
| **Interactions** | | | | | | |
| G x P | ** | ** | ** | ** | ** | ** |
| G x L | ** | ** | ** | ** | ** | ** |
| P x L | ** | ** | ** | ** | * | ** |
| G x P x L | ** | ** | ** | ** | ** | ** |

SSP= Single superphosphate SRP= Sokoto rock phosphate, **=Significant at 1% level of probability, NS=Not significant at 5% level of probability; Means followed by same letter(s) within a treatment in a column do not differ significantly according to Tukey's honest significant difference (HSD).

### 4.7.2 Effects of genotype, P source and location on harvest index of the groundnuts

There were also significant ($P \leq 0.01$) main and interactive influences of location, genotype and P source on the harvest index (HI) observed for the groundnut genotypes over each of the 2015 and 2016 trial seasons and mean across the seasons (Table 4.5).

SAMNUT 24 out-yielded all the other genotypes in the 2015 trial season but was statistically akin to ICGV-IS 07083. These were followed by SAMNUT 22. SAMNUT 21 and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ were statistically similar and both were also similar to Kwankwaso and ICIAR 7B which made the significantly lowest HI of the 2015 trial season.

In the 2016 trial season, ICGV-IS 07083, SAMNUT 24 and SAMNUT 23 have the significantly highest HI record. These were also statistically at par with SAMNUT 14 and SAMNUT 10. The significantly lowest HI of the season was recorded in Kwankwaso and SAMNUT 22. In the mean across the seasons, SAMNUT 14, which was statistically similar to SAMNUT 24, outperformed all other genotypes in terms of the HI recorded. It was followed by ICGV-IS 07083, and then by SAMNUT 23. The significantly lowest HI was recorded, in the mean across the seasons, for Kwankwaso, SAMNUT 21, ICIAR 7B and ICGV-IS 07815. These were also statistically similar with ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, ICIAR 6AT, SAMNUT 11 and SAMNUT 22 (Table 4.5).

The main effects of P source and location on HI performance of the groundnut genotypes were also significant ($P \leq 0.05$). Hence, significantly ($P \leq 0.01$) greater HI values were recorded for the genotypes under the control P source in 2015 and 2016 trial seasons and was followed by the other two P sources (SSP and SRP) in both seasons. The HI value recorded the control P source was, however, highest (43%) in the mean across followed by SRP (41%) and SSP P source the least. Significantly ($P \leq 0.05$) highest HI (45%) was recorded in Samaru during the mean of the trial seasons as depicted by Table 4.5 above.

### 4.7.3 Genotype by phosphorus versus location interaction on dry matter yield and harvest index in the 2015 and 2016 field trials and mean across the seasons

*4.7.3.1 Genotype by phosphorus interaction on dry matter yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY) on the basis of genotype versus P source interaction in the 2015 trial season (Figure 4.26). SAMNUT 24 under SSP (1686 kg $ha^{-1}$) outperformed other genotypes in terms of DMY in the season, although was statistically similar to ICGV-IS

07815 (1488 kg $ha^{-1}$) and SAMNUT 21 (1521 kg $ha^{-1}$) under SSP; and SAMNUT 21 (1606 kg $ha^{-1}$), SAMNUT 10 (1562 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (1549 kg $ha^{-1}$), SAMNUT 22 (1524 kg $ha^{-1}$) and ICIAR 7B (1520 kg $ha^{-1}$) under SRP. All of those were followed by statistically similar SAMNUT 10 (1464 kg $ha^{-1}$) and SAMNUT 22 (1449 kg $ha^{-1}$), both under SSP; and SAMNUT 21 (1423 kg $ha^{-1}$) under the control. The significantly lowest DMY recorded for SAMNUT 24 (664 kg $ha^{-1}$) under the control, and was at par with SAMNUT 14 (670 kg $ha^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (762 kg $ha^{-1}$), Kwankwaso (800 kg $ha^{-1}$) and ICGV-IS 07083 (839 kg $ha^{-1}$), all under the control; while ICGX-SM 00010/5/$P_{15}$/$P_1$ (750 kg $ha^{-1}$), Kwankwaso (810 kg $ha^{-1}$) and SAMNUT 14 (838 kg $ha^{-1}$) under SRP P sources (Figure 4.26).

The result on DMY in the 2015 trial season indicated that the highest number of genotypes (33%) was observed to have the significantly highest recorded parameter under the SRP P source. The SSP P source and the control, respectively, followed SRP with 20% and, only about, 7% of the genotypes with a commendable DMY record in the season. There was no difference, neither between the two genotypes (SAMNUT 10 and SAMNUT 14) nor the two P sources (SSP and SRP) or the control, in terms of dry haulm yield, in the study of Musa *et al.* (2015). There was in that of Mukhtar *et al.* (2013), in terms of total dry matter yield (TDMY). In their 2003/2004 trial, Mukhtar *et al.* (2013) observed SAMNUT 23 and SAMNUT 11 as significantly having higher TDMY than the genotype SAMNUT 21. There were, therefore, significant differences among the genotypes in their TDMY in the three years in which their trials were conducted. Hence, SAMNUT 23 and SAMNUT 11 produced significantly highest TDMY than SAMNUT 21 in both seasons and mean across them, although SAMNUT 23 was statistically similar with SAMNUT 21 in 2004/2005. This was, in a way, the reverse situation of the finding of this work, in which SAMNUT 21 had a significantly more DMY record than the genotypes SAMNUT 23 and SAMNUT 11. This may possibly be due to the differences in the trial locations and composition of treatments used in the two different trials. Still in this work, however, a point of corroboration is the genotypes SAMNUT 23 and SAMNUT 11 being also statistically at par in terms of the parameter, under SRP and the control in Minjibir, and to some extent in Samaru (Figure 4.26). SAMNUT 10 used in this study, and not in Mukhtar *et al*. (2013)'s, is known to be similar with the genotype SAMNUT 11, which they also used in their

study. The two genotypes are reported to be similar in, virtually, all characteristics/traits (IAR, 1989).

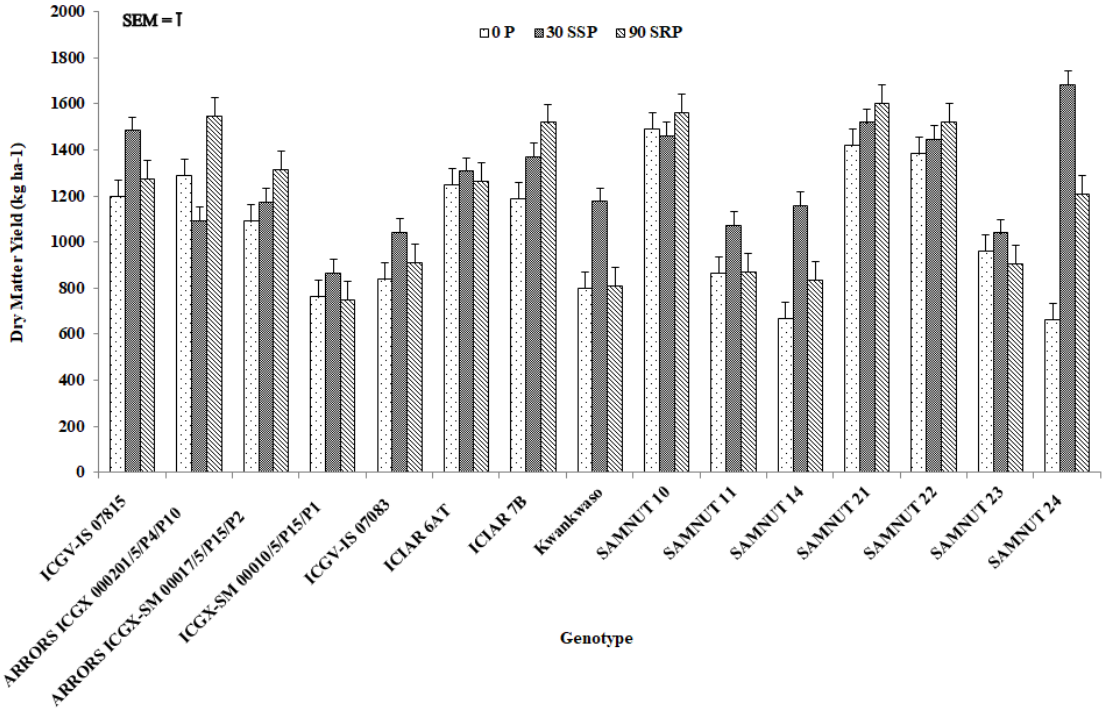



Figure 4.27: Genotype by phosphorus interaction on dry matter yield in 2015 field trial

*4.7.3.2 Genotype by phosphorus interaction on dry matter yield in the 2016 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY), based on genotype versus P source interaction in the 2016 trial season (Figure 4.27). Significantly ($P \leq 0.01$) highest DMY was recorded, in the trial season, for ICIAR 7B (4015 kg $ha^{-1}$), ICIAR 6AT (3943 kg $ha^{-1}$) and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (3789 kg $ha^{-1}$), all under SSP. These were statistically at par with Kwankwaso (3717 kg $ha^{-1}$), also under the same SSP fertiliser. These were, in turn, followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (3274 kg $ha^{-1}$) under the control. The lowest yield of the 2016 trial season was recorded for SAMNUT 10 under the control (1051 kg $ha^{-1}$) and SRP (1117 kg $ha^{-1}$) sources (Figure 4.27). The lowest yield groundnut was, however, statistically similar to 53% and 33% of those respectively under the control and SRP during the season's trial (Figure 4.27). About 27% of the genotypes performed significantly well, in terms of DMY, under SSP in the 2016 trial season. Only 13% and about 7% of the other genotypes performed well respectively, under control and SRP P sources in terms of the DMY. At least about 67% of the

genotypes were observed to be productive, in terms of the parameter DMY, under at least two of the P sources during the 2016 trial season (Figure 4.27).

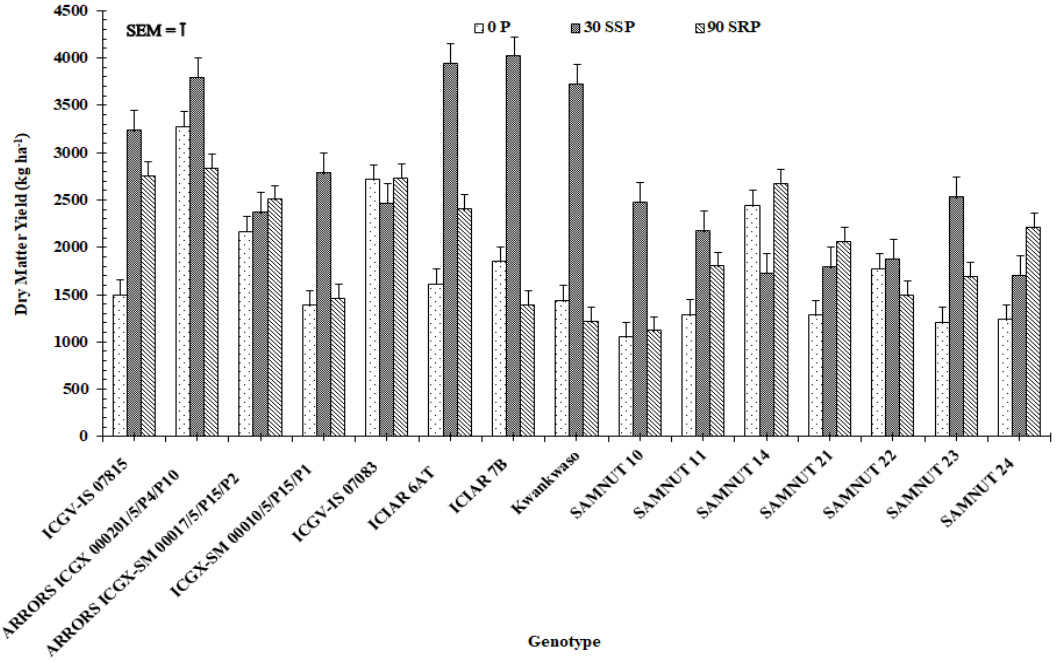



Figure 4.28: Genotype by phosphorus interaction on dry matter yield in the 2016 field trial

### *4.7.3.3 Genotype by phosphorus interaction on dry matter yield in the field trials mean across the seasons*

There was also a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY), based on genotype versus P source interaction in the mean across the seasons (Figure 4.28). The highest DMY was, therefore, recorded for ICIAR 7B (3363 kg $ha^{-1}$) under SSP P source. This genotype (under the said P source) was statistically at par with up to about 67% of the other genotypes under the same SSP P source. It was also at par with about 27% and about 47% of the other genotypes grown, respectively under control and SRP P sources. Although also at par with many other genotypes across all the P sources (*i.e.*, 80%, 33% and 53%, respectively under the control, SSP and SRP), SAMNUT 10 under the control (838 kg $ha^{-1}$), and SRP (687 kg $ha^{-1}$), had the lowest DMY record of the mean across the seasons (Figure 4.28).

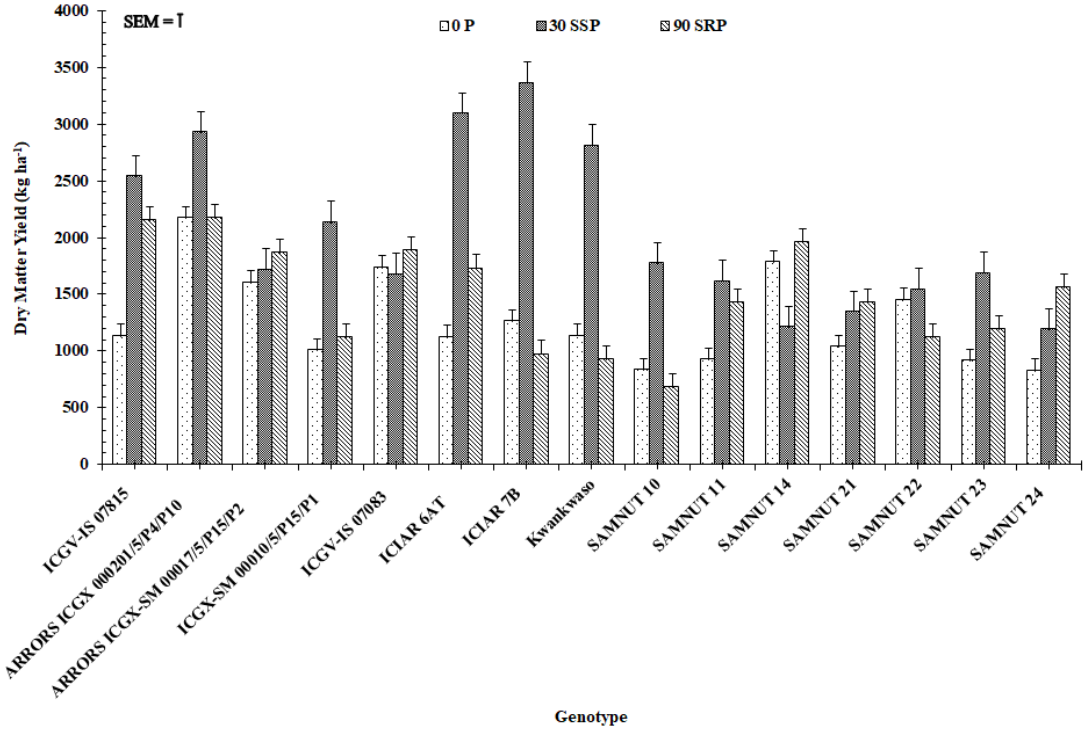



Figure 4.29: Genotype by phosphorus interaction on dry matter yield in the field trials mean across the seasons

Up to 60% of the genotypes were observed to have performed excellently well, in terms of DMY, under at least two of the P sources in the mean across the field trial seasons. Only about 27% of the genotypes were, however, observed not to be versatile. This percentage of genotypes was, therefore, observed to be not high yielding, in terms of the DMY, particularly under the control treatment.

*4.7.3.4 Genotype by location interaction on dry matter yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY) on the basis of genotype versus location interaction in 2015 trial season (Figure 4.30). Significantly ($P \leq 0.01$) highest DMY was recorded by each of ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1813 kg ha$^{-1}$) and SAMNUT 21 (1807 kg ha$^{-1}$), both in Minjibir. These were followed by SAMNUT 24 (1617 kg ha$^{-1}$) at the same Minjibir. This genotype was statistically at par with SAMNUT 10 (1536 kg ha$^{-1}$) in Samaru and SAMNUT 14 (1497 kg ha$^{-1}$), SAMNUT 22 (1483 kg ha$^{-1}$) and SAMNUT 10 (1476 kg ha$^{-1}$), all in Minjibir. The overall significantly ($P \leq 0.01$) lowest yield in the 2015 trial season was recorded in Samaru for SAMNUT 14 (282 kg ha$^{-1}$), which was, in turn, statistically at par with ICGX-SM 00010/5/$P_{15}$/$P_1$ (333 kg ha$^{-1}$) at the same Samaru (Figure 4.30). Although only 13% of the genotypes significantly outperformed others in

terms of DMY, and these were all observed in Minjibir, 20% of all the genotypes were also observed to have performed fairly well at both agro-ecological locations in terms of DMY of the 2015 trial season.

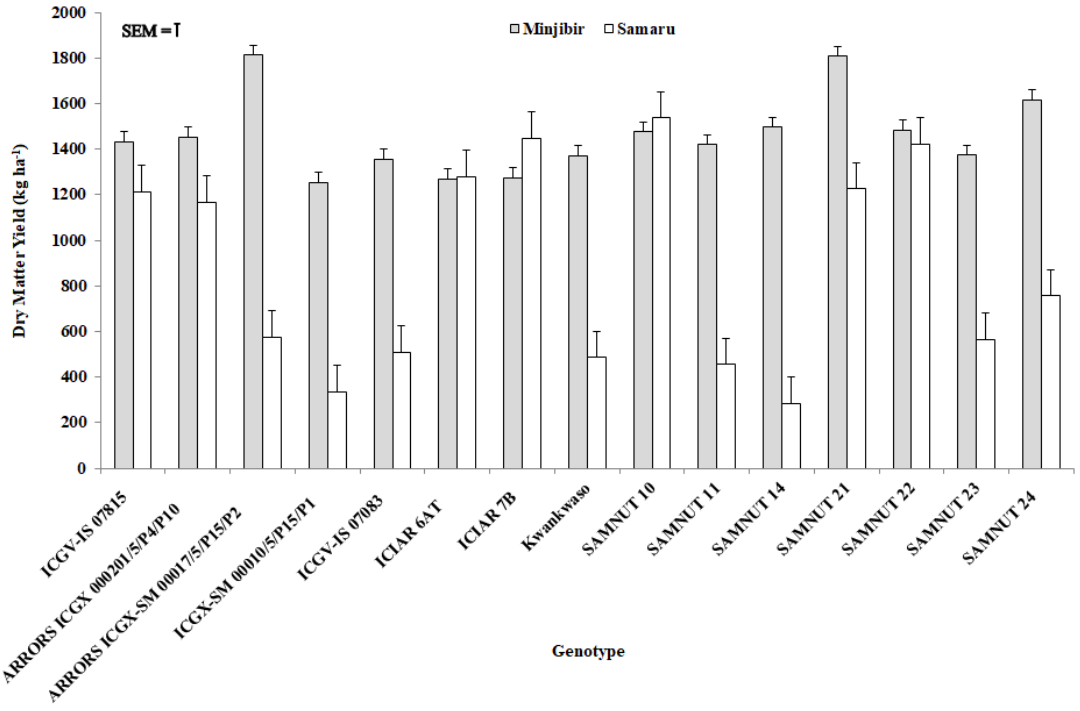



Figure 4.30: Genotype by location interaction on dry matter yield in 2015 field trial

*4.7.3.5 Genotype by location interaction on dry matter yield in the 2016 field trial*

A significant ($P \leq 0.01$) difference between the genotypes existed in terms of dry matter yield (DMY) on the basis of genotype versus location interaction in 2016 trial season (Figure 4.31). ICGV-IS 07083 (4303 kg $ha^{-1}$) in Minjibir, significantly ($P \leq 0.01$) out-yielded all the other genotypes across the two locations in terms of DMY of the groundnuts. It was followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (3923 kg $ha^{-1}$) also in Minjibir, which was also followed by ICIAR 6AT (3273 kg $ha^{-1}$). The significantly lowest DMY was observed for ICGV-IS 07083 (972 kg $ha^{-1}$) in Samaru. This genotype (ICGV-IS 07083) was statistically at par with SAMNUT 24 (1243 kg $ha^{-1}$), SAMNUT 22 (1295 kg $ha^{-1}$) and SAMNUT 23 (1308 kg $ha^{-1}$), constituting 20% of all the genotypes grown in Samaru (Figure 4.31). A good DMY yield record, across both locations, was observed for not less than 40% of the groundnut genotypes, thereby indicating the versatility of some of the genotypes in terms of the parameter across the

locations. This was with reference to, especially, ARRORS ICGX 000201/5/$P_4$/$P_{10}$, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ and SAMNUT 14.

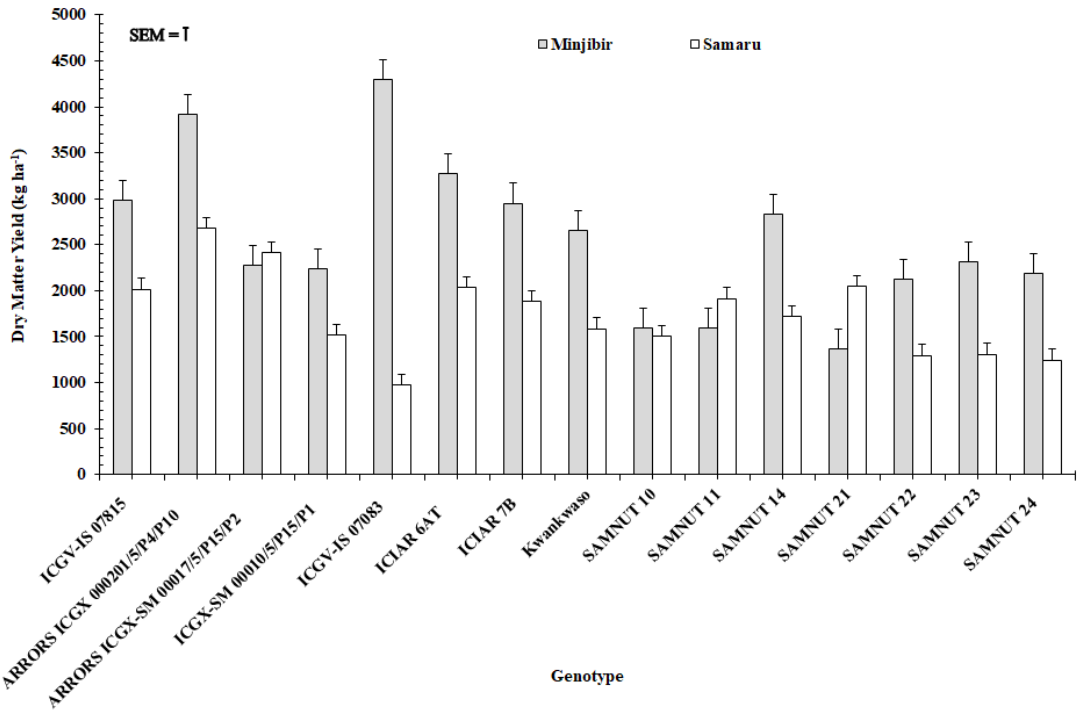



Figure 4.31: Genotype by location interaction on dry matter yield in 2016 field trial

### *4.7.3.6 Genotype by location interaction on dry matter yield in the field trials mean across the seasons*

Also, a significant ($P \leq 0.01$) difference between the genotypes existed in terms of dry matter yield (DMY) on the basis of genotype versus location interaction in 2015 and 2016 means (Figure 4.7.3.6). In the mean across the seasons trials, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (3011 kg $ha^{-1}$) in Minjibir had the highest DMY record. This was statistically at par with SAMNUT 14 (2256 kg $ha^{-1}$), ICGV-IS 07815 (2446 kg $ha^{-1}$), ICIAR 6AT (2465 kg $ha^{-1}$) and, especially, ICGV-IS 07083 (2849 kg $ha^{-1}$). All these were followed by ICIAR 7B with a DMY recorded at 2224 kg $ha^{-1}$ (Figure 4.32). In Samaru, ICGV-IS 07083 (689 kg $ha^{-1}$) had the lowest DMY record, although it was at par with some other genotypes (20% and 60% in Minjibir and Samaru respectively). Forty percent (40%) of the genotypes were observed to be versatile by relatively having performed well, in terms of DMY in the mean across the seasons, in both (Minjibir and Samaru) as depicted in Figure 4.32 below.

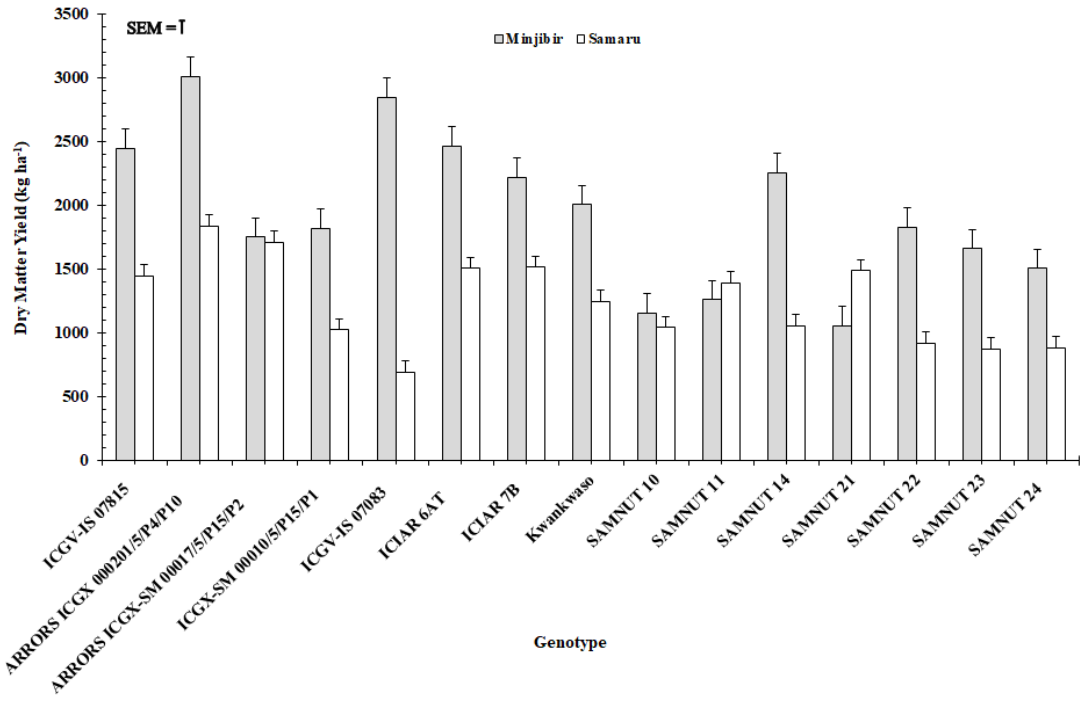



Figure 4.32: Genotype by location interaction on dry matter yield in the field trials mean across the seasons

*4.7.3.7 Phosphorus by location interaction on dry matter yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes, in terms of their dry matter yield (DMY), based on P source by location interaction in the 2015 trial season as indicated in Figure 4.33 below. The SSP P source in Minjibir significantly ($P \leq 0.01$) had the highest DMY of 1565 kg $ha^{-1}$ and was followed by SRP P source (1495 kg $ha^{-1}$) in the same Minjibir location.

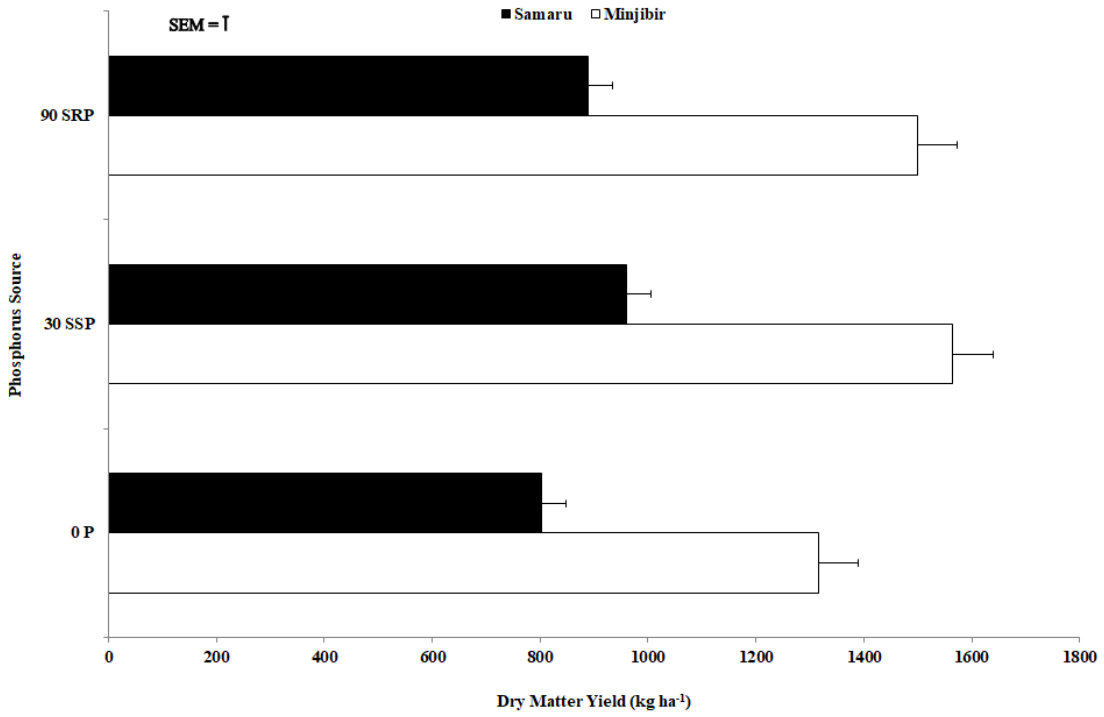



Figure 4.33: Phosphorus by location interaction on dry matter yield in 2015 field trial

Although the control in Minjibir had the lowest DMY record in that location, it was still even significantly ($P \leq 0.01$) higher than SSP P source in Samaru (959 kg $ha^{-1}$), which was the highest in the (Samaru) agro-ecological location. The control in Samaru (802 kg $ha^{-1}$) was, however, the overall lowest in terms of the DMY in the 2015 trial season (Figure 4.33). This reaffirmed the significance of SSP source of P in groundnut genotypes nutrition, especially due to its solubility advantage over the SRP (Lewis *et al*., 1997; Aduayi *et al*., 2002; Rech *et al*., 2019), which seems to also be displayed in the DMY of the genotypes in question.

*4.7.3.8 Phosphorus by location interaction on dry matter yield in the 2016 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes, in terms of dry matter yield (DMY), based on P source versus location interaction in the 2016 trial season (Figure 4.34). The SSP P source in Minjibir (3200 kg $ha^{-1}$) significantly ($P \leq 0.01$) out-yielded the other P sources across both agro-ecological locations. it was immediately followed by the statistically similar control (2203 kg $ha^{-1}$) and SRP (2320 kg $ha^{-1}$) both also in Minjibir; and SRP P sources in Samaru (2209 kg $ha^{-1}$). The significantly lowest DMY of 1724 kg $ha^{-1}$ was observed under SRP P source in Samaru during the 2016 trial season (Figure 4.34). This suggested for, and corroborated, the highest AcPhase activity observed in Minjibir (Table 4.11 and Figure 4.75).

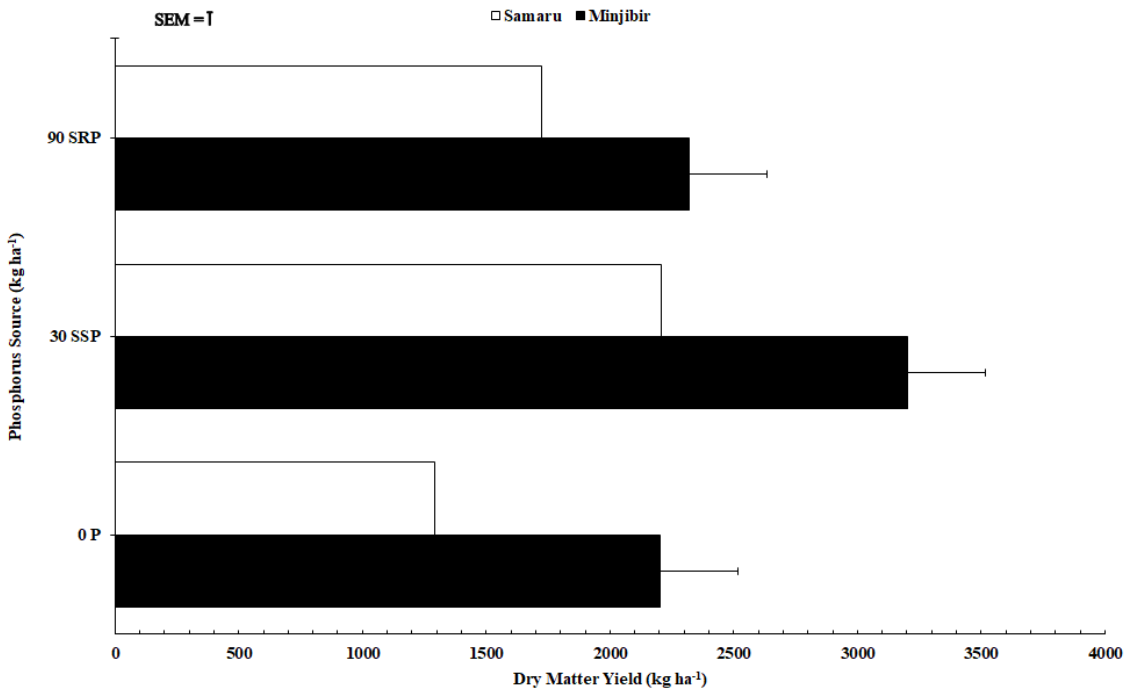



Figure 4.34: Phosphorus by location interaction on dry matter yield in 2016 field trial

#### *4.7.3.9 Phosphorus by location interaction on dry matter yield in the field trials mean across the seasons*

There was also a significant ($P \leq 0.05$) difference between genotypes, in terms of dry matter yield (DMY), based on P source versus location interaction in the mean across 2015 and 2016 trial seasons (Figure 4.35). The SSP P source (2454 kg $ha^{-1}$) in Minjibir location outperformed the other two P sources across both locations. This was followed by SRP (1790 kg $ha^{-1}$) and control (1616 kg $ha^{-1}$) P sources, both in Minjibir; and SRP (1635 kg $ha^{-1}$) in Samaru. The lowest DMY of the mean across the seasons was, however, recorded in the statistically similar SRP (1174 kg $ha^{-1}$) and control (916 kg $ha^{-1}$) P sources, both in Samaru location (Figure 4.35). The AcPhase activity, vis-à-vis the SSP solubility advantage to a certain extent, may partly explain the difference observed between the agro-ecological locations in terms of the DMY been observed.

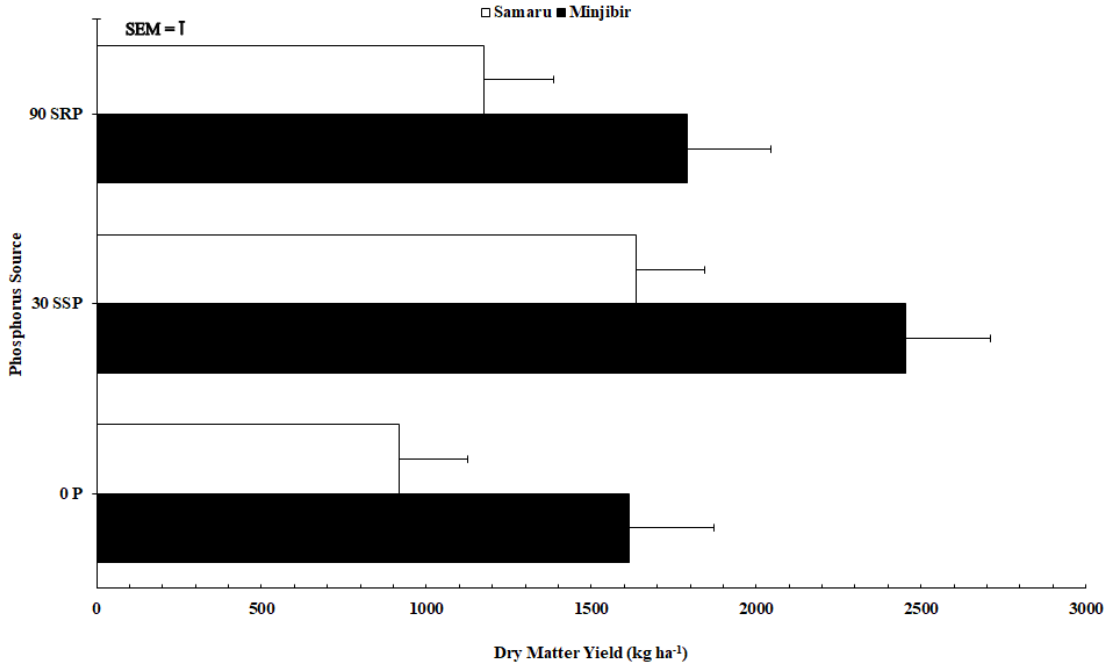



Figure 4.35: Phosphorus by location interaction on dry matter yield in the field trials mean across the seasons

*4.7.3.10 Genotype by phosphorus versus location interaction on dry matter yield in the 2015 field trial*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY) on the basis of genotype by phosphorus versus location interaction in the 2015 trial season (Figure 4.36). Significantly ($P \leq 0.01$) highest DMY was recorded, in Minjibir, for SAMNUT 14 (2005 kg $ha^{-1}$) and SAMNUT 21 (2003 kg $ha^{-1}$), respectively under SSP and SRP. These were statistically comparable to SAMNUT 21 (1726 kg $ha^{-1}$) under the control in Minjibir. Other genotypes were SAMNUT 24 (1903 kg $ha^{-1}$), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1893 kg $ha^{-1}$) and Kwankwaso (1706 kg $ha^{-1}$) under SSP. Addition to those were ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (1952 kg $ha^{-1}$), SAMNUT 24 (1822 kg $ha^{-1}$) and SAMNUT 22 (1706 kg $ha^{-1}$), under SRP also in Minjibir. The significantly lowest DMY was recorded for SAMNUT 14 (170 kg $ha^{-1}$) under the control in Samaru. This was, however, at par with many genotypes under the three P sources, in Samaru location only and none in Minjibir (Figure 4.36).

Location wise, Minjibir had about 27% and 20% of the genotypes with a high DMY yield record, respectively under of SSP and SRP. Only about 7% of the genotypes were observed to have performed well in terms of DMY in the 2015 trial season under the P

sources at both locations (Figure 4.36). ICIAR 7B was observed to have performed well in both locations and under all P sources. SAMNUT 21, ARRORSICGX-SM00017/5/$P_{15}$/$P_2$, ICGX-SM00010/5/$P_{15}$/$P_1$, ICGV-IS 07083, ICIAR 6AT, SAMNUT 10, SAMNUT 21, SAMNUT 23 and SAMNUT 24 were observed to perform better in Minjibir. SAMNUT 23, SAMNUT 22, SAMNUT 21, SAMNUT 14, ICIAR 6AT, ICGV-IS 07083 and ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ were particularly good (Figure 4.30).

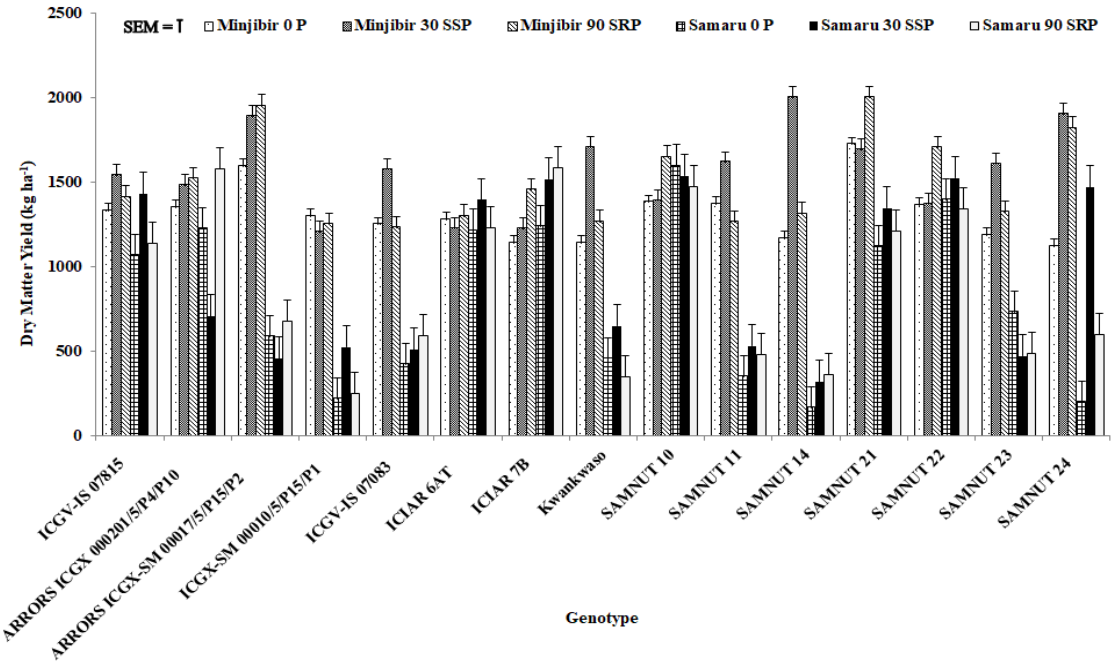



Figure 4.36: Genotype by phosphorus versus location interaction on dry matter yield in the 2015 field trial

### *4.7.3.11 Genotype by phosphorus versus location interaction on dry matter yield in the 2016 field trial*

There was also a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY), based on genotype versus P source by location interaction in the mean across the seasons (Figure 4.38). The highest DMY was recorded for Kwankwaso (5573 kg $ha^{-1}$), under SSP in Minjibir. The genotype was, however, statistically at par with ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (5104 kg $ha^{-1}$), which was also at par with ICIAR 6AT (4611 kg $ha^{-1}$) and ICIAR 7B (4512 kg $ha^{-1}$), also under SSP and ICGV-IS 07083 (4424 kg $ha^{-1}$) under SRP all in the same Minjibir. The genotypes SAMNUT 24 (751 kg $ha^{-1}$) and SAMNUT 23 (757 kg $ha^{-1}$), were comparable to many other genotypes under the P sources across both locations and had the lowest DMY record

(Figure 4.37). They were statistically similar with about 27% and 13% the groundnuts respectively under control; and each of SSP and SRP in Minjibir. About 67%, 13% and 40% of them, respectively under the control, SSP and SRP, were also statistically similar to those with the lowest DMY record in Samaru (Figure 4.37).

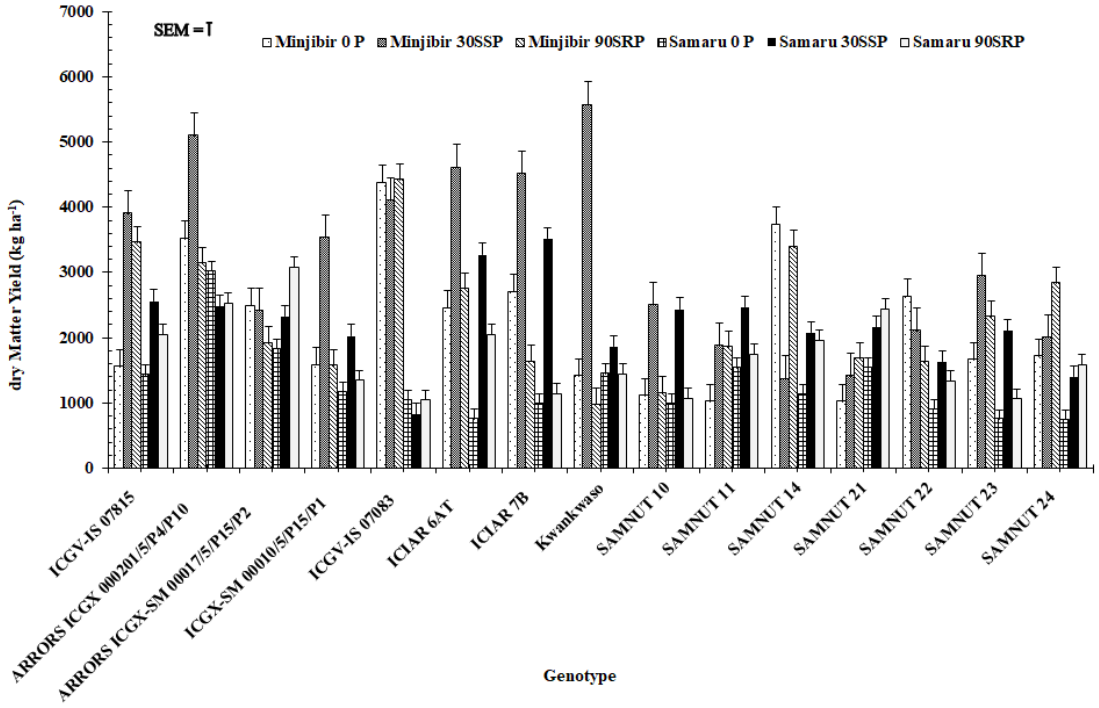



Figure 4.37: Genotype by phosphorus versus location interaction on dry matter yield in the 2016 field trial

*4.7.3.12 Genotype by phosphorus versus location interaction on dry matter yield in the field trials mean across the seasons*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of dry matter yield (DMY), based on genotype versus P source by location interaction in the mean of 2015 and 2016 trial seasons (Figure 4.38). Significantly highest DMY was recorded, in the trial season, for Kwankwaso (4095 kg $ha^{-1}$) under SSP in Minjibir, which was statistically comparable to ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (4070 kg $ha^{-1}$) under the same P source and in the same location (Figure 4.38). Other genotypes that were also statistically akin to the highest performed were ICIAR 7B (3621 kg $ha^{-1}$), ICIAR 6AT (3590 kg $ha^{-1}$), ICGV-IS 07815 (3224 kg $ha^{-1}$), ICGX-SM 00010/5/$P_{15}$/$P_1$ (2842 kg $ha^{-1}$) and ICGV-IS 07083 (2730 kg $ha^{-1}$), under SSP; and ICGV-IS 07815 (3082 kg $ha^{-1}$), ICGV-IS 07083 (3047 kg $ha^{-1}$) and SAMNUT 14 (2710 kg $ha^{-1}$), under SRP. All the aforementioned genotypes were also in Minjibir. The lowest DMY was,

however, recorded for each of ICIAR 6AT (471 kg $ha^{-1}$), SAMNUT 24 (477 kg $ha^{-1}$) and SAMNUT 23 (474 kg $ha^{-1}$) all under the control, and in Samaru. These genotypes were, however, statistically at par with up to 73%, 53% and 60% of the genotypes in Minjibir respectively under the control, SSP and SRP. They were also at par with all the genotypes grown in Samaru under all the P sources, except for ARRORS ICGX 000201/5/$P_4$/$P_{10}$ under the control; and ICIAR 6AT and ICIAR 7B both under SSP (Figure 4.38).

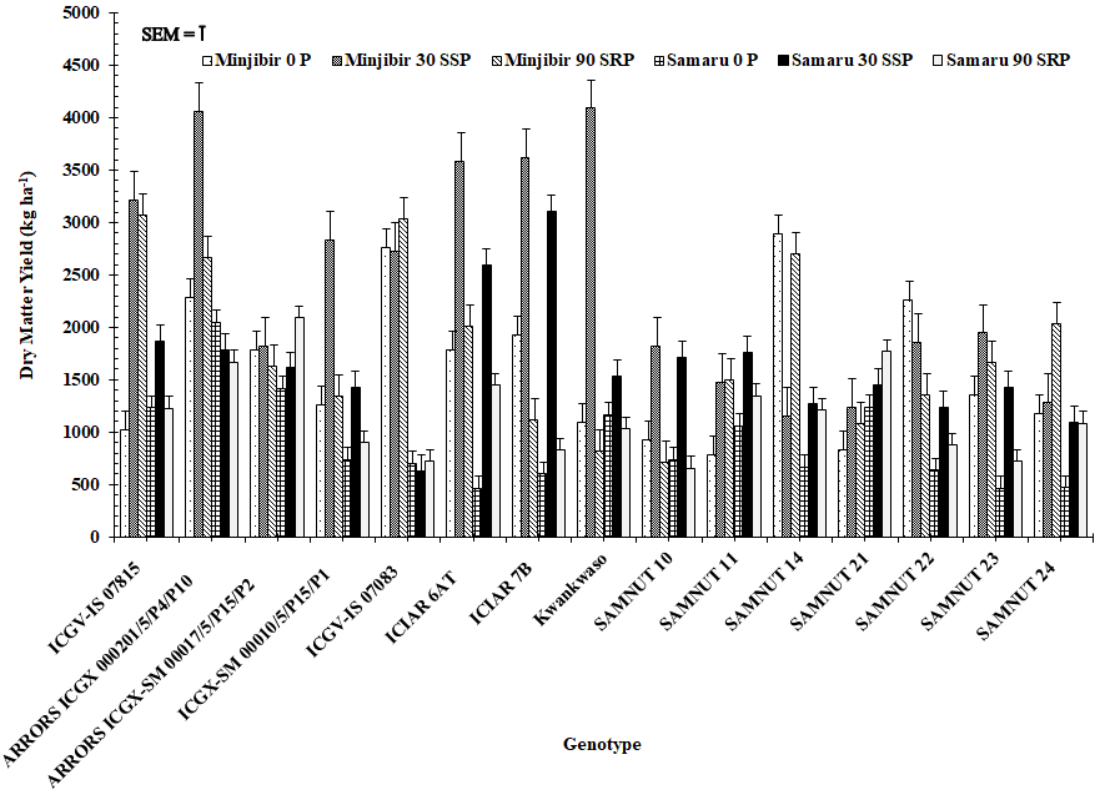



Figure 4.38: Genotype by phosphorus versus location interaction on dry matter yield in the field trials mean across the seasons

Like in Mukhtar *et al*. (2013), the genotypes SAMNUT 23 and SAMNUT 11 were statistically similar in both locations and under all the P sources during the mean across the seasons. Also in corroboration, SAMNUT 11 (1757 kg $ha^{-1}$ and 1482 kg $ha^{-1}$) performed better than SAMUT 21 (396.60 kg $ha^{-1}$ and 1449 kg $ha^{-1}$) under SSP, respectively in Samaru and Minjibir (Figure 4.38). In general terms, up to 80% of the genotypes were observed to have produced good DMY in Minjibir under SSP and SRP (Figure 4.38).

### 4.7.4 Genotype by phosphorus versus location interaction on harvest index (%) in the 2015, 2016 field trials and mean across the seasons

*4.7.4.1 Genotype by phosphorus interaction on harvest index in the 2015 field trial*

A significant ($P \leq 0.01$) difference between the genotypes in terms of genotype versus P source interaction on their harvest index (HI) performances in the 2015 trial season (Figure 4.39) was observed. A significantly ($P \leq 0.01$) highest HI was observed in ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (47%) under the control. It was statistically similar to ICGV-IS 07083 (44, 36 and 45%) under the control, SSP and SRP, respectively. It was also comparable to SAMNUT 24 under both SSP (45%) and the control (43%) and some other genotypes across the P sources. These were followed by ICGX-SM 00010/5/$P_{15}$/$P_1$ (35%) and SAMNUT 22 (35%) both under SRP, SAMNUT 23 (34%) and SAMNUT 11 (34%) both under the control; and SAMNUT 14 (34%) under SSP. The significantly lowest HI was recorded in ICIAR 6AT under SSP (14%), which was statistically not different under the other P sources. It was also comparable to 20, about 47 and 33% of the other genotypes under the control, SSP and SRP, respectively (Figure 4.39). Forty percent (40%), 20% and 13% of the genotypes respectively under the control, SSP and SRP were observed to have significantly ($P \leq 0.05$) performed better than others in terms of HI in the 2015 trial season. About 47% were, however, observed to be versatile as they performed fairly well under all the P sources, as clearly observed in Figure 4.39 below.

*4.7.4.2 Genotype by phosphorus interaction on harvest index in the 2016 field trial*

There was a significant ($P \leq 0.01$) genotype by the P source interaction difference between the genotypes in terms of harvest index (HI) performance of the genotypes in the 2016 trial season (Figure 4.40). Thence, SAMNUT 10 (76%) under SRP had the highest HI record in the 2016 season. The genotype was, however, statistically similar to ICGV-IS 07083 (68%) under the control. ICGV-IS 07083 was also similar to 33% of the genotypes under the control, SAMNUT 23 under SSP and 13% of the other genotypes under SRP during the 2016 trial season. The season's lowest HI was, on the other hand, recorded in ICIAR 7B (31%) under SSP (Figure 4.40). This was also statistically at par with SAMNUT 21 (39%) under the control and SAMNUT 22 (37%) under SSP.

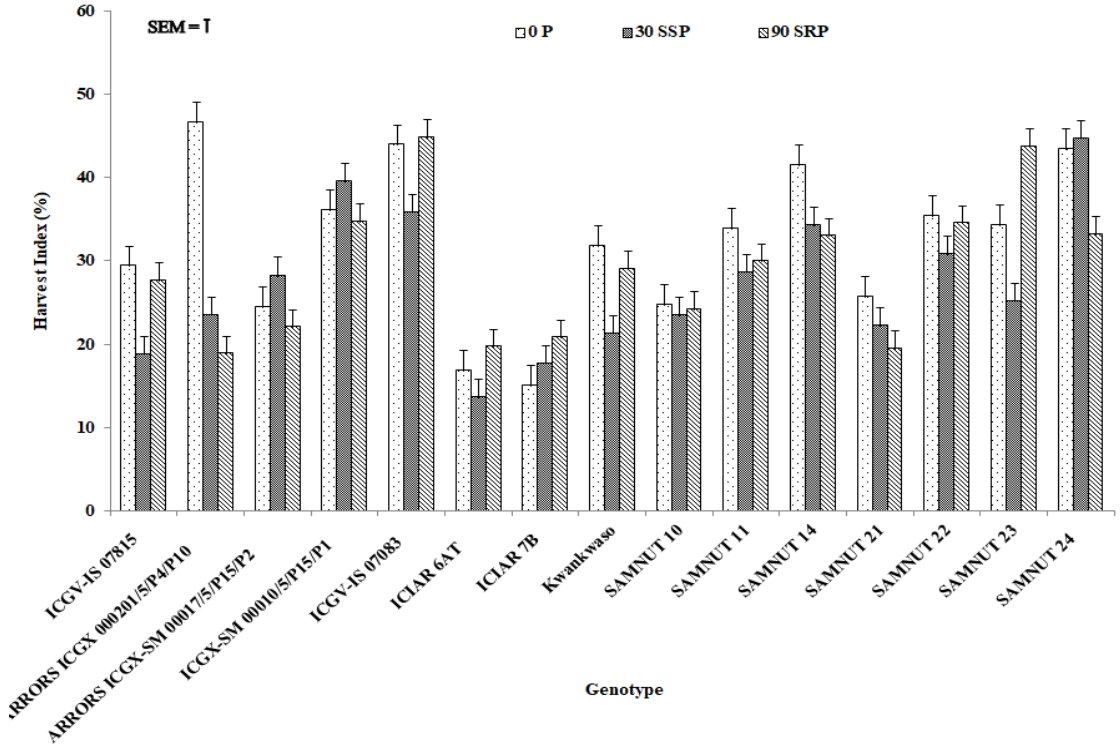



Figure 4.39: Genotype by phosphorus interaction on harvest index in the 2015 field trial

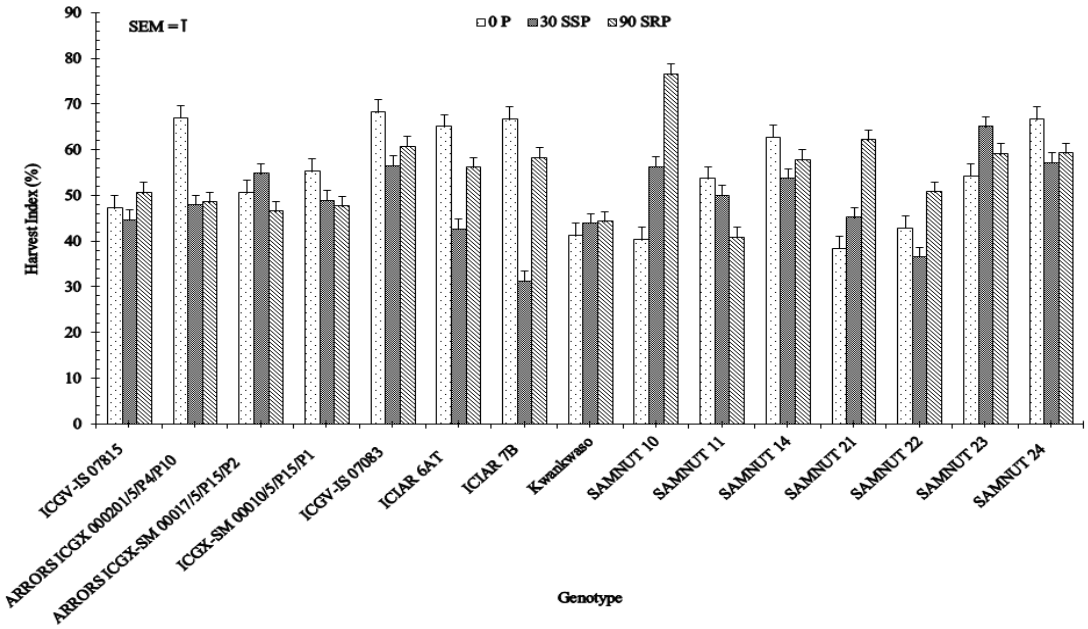



Figure 4.40: Genotype by phosphorus interaction on harvest index in the 2016 field trial

*4.7.4.3 Genotype by phosphorus interaction on harvest index in the field trials mean across the seasons*

The genotype by P source interaction was observed to be significant ($P \leq 0.05$) between the groundnuts in terms of harvest index (HI) performance in the mean across 2015 and 2016 trial seasons (Figure 4.41). SAMNUT 24 under the control (62%) had the highest HI record of the mean across the seasons. It was followed by ICGV-IS 071815 (37 and 36%, under the control and SRP, respectively) SAMNUT 10 (38%) and Kwankwaso (39%), both under SRP. The lowest HI was observed in ICIAR 7B (25%) under SSP (Figure 4.41).

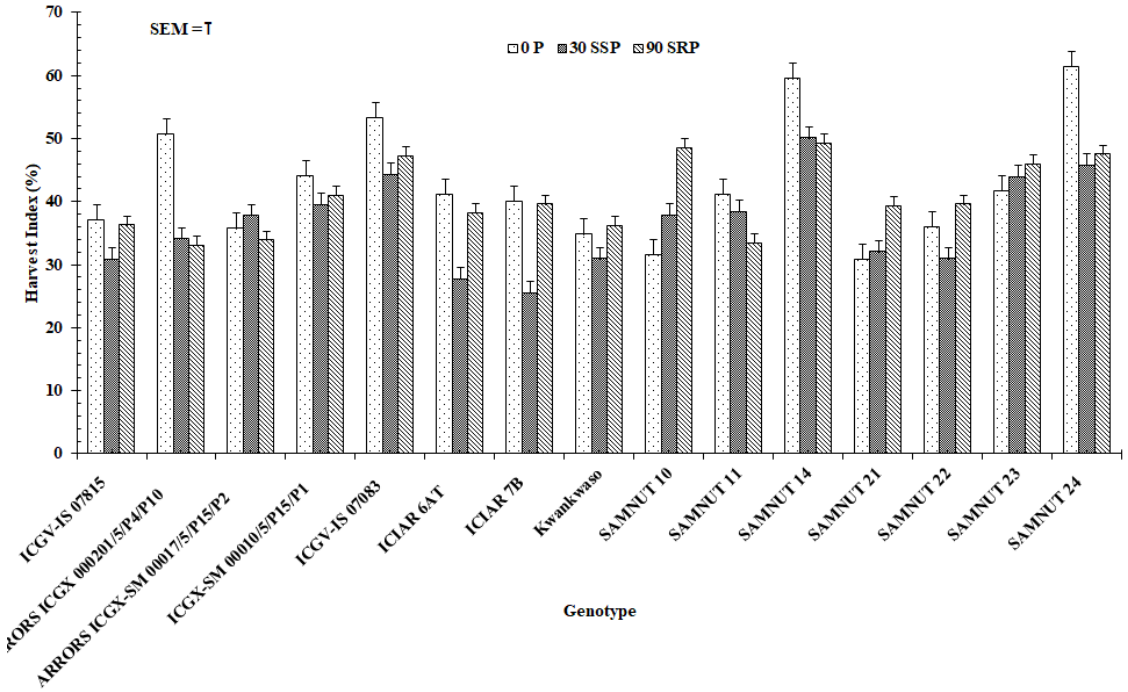



Figure 4.41: Genotype by phosphorus interaction on harvest index in the field trials mean across the seasons

*4.7.4.4 Genotype by location interaction on harvest index in the 2015 field trial*

The genotypes were significantly ($P \leq 0.01$) different in terms of their harvest index (HI) performance on the basis of genotype versus location interaction in the 2015 trial season (Figure 4.42). A significantly ($P \leq 0.01$) highest HI of 45% was recorded for SAMNUT 24 in Minjibir location and was statistically similar to ICGV-IS 07083, in Samaru (44%) and Minjibir (39%), SAMNUT 14 (37%) in Minjibir; and ICGX-SM 00010/5/$P_{15}$/$P_1$ (43%), SAMNUT 23 (39%), SAMNUT 11 (39%), Kwankwaso (37%), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (37%) and SAMNUT 24 (36%), all also in Minjibir. The significantly ($P \leq 0.01$) lowest HI observed in the 2015 trial season was,

on the other hand, recorded for ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (13%) in Minjibir, which was, akin to some other genotypes across both agro-ecological locations within the season (Figure 4.42). Only 20% of the genotypes were, however, observed to have significantly outperformed others in terms of HI in the season in Minjibir whereas about 47% were at the Samaru location. Up to 60% 0f the genotypes were on the other hand observed to perform fairly well at both locations. The remaining (40%) genotypes were observed to perform well only in either of the two locations (Figure 4.42).

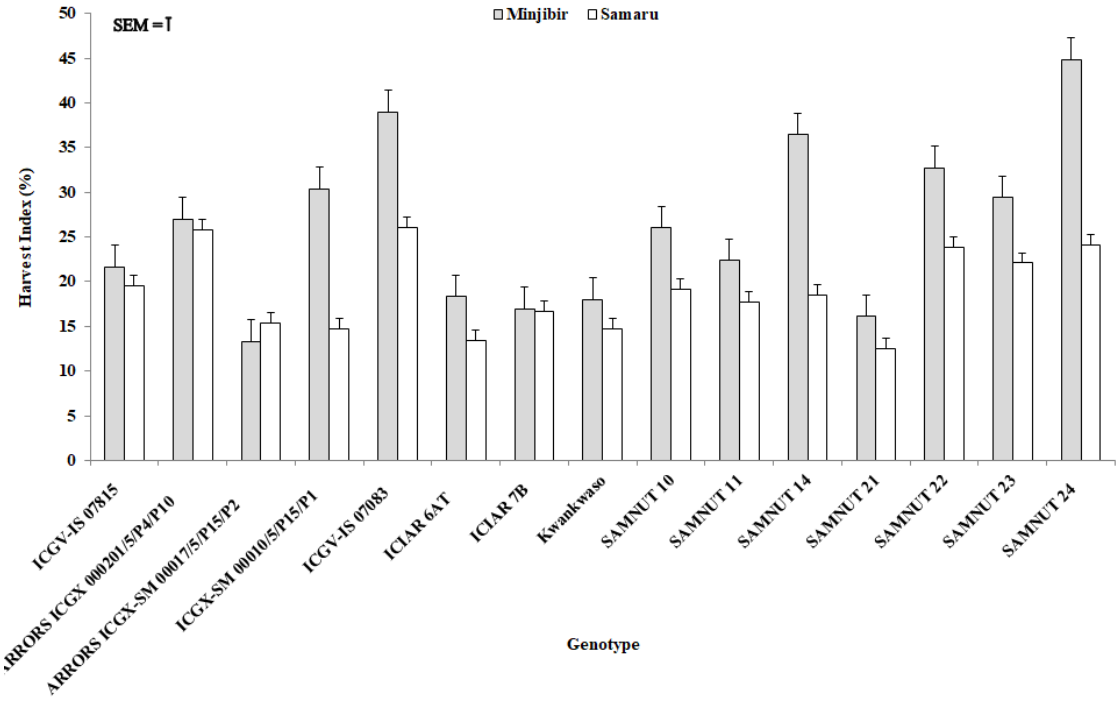



Figure 4.42: Genotype by location interaction on harvest index in the 2015 field trial

*4.7.4.5 Genotype by location interaction on harvest index in the 2016 field trial*

The groundnuts were significantly ($P \leq 0.01$) different in terms of their HI performance. This was according to genotype by location interaction during the trial season (Figure 4.43). Significantly ($P \leq 0.01$) highest HI was observed for SAMNUT 14 (77%) in Samaru. It was followed by ICGV-IS 07083 (67%) in Minjibir, which was statistically alike to ICGX-SM 00010/5/$P_{15}$/$P_1$ and SAMNUT 23 (66% each) in Samaru. These genotypes were, in turn, statistically at par with SAMNUT 24 (63%) in Minjibir; and ARRORS ICGX000201/5/$P_4$/$P_{10}$ (62%) and SAMNUT 10 (61%) both in Samaru. The SAMNUT 22 (28%) in Minjibir had the lowest HI record of the trial season, although statistically similar to ICGX-SM 00010/5/$P_{15}$/$P_1$ (35%), also in Minjibir (Figure 4.43). Up to about 67% of the genotypes were observed to have performed

outstandingly well in Samaru, whereas only 13% of them in Minjibir showed a good HI performance in relation to other genotypes during the 2016 trial season, as indicated in Figure 4.43 below.

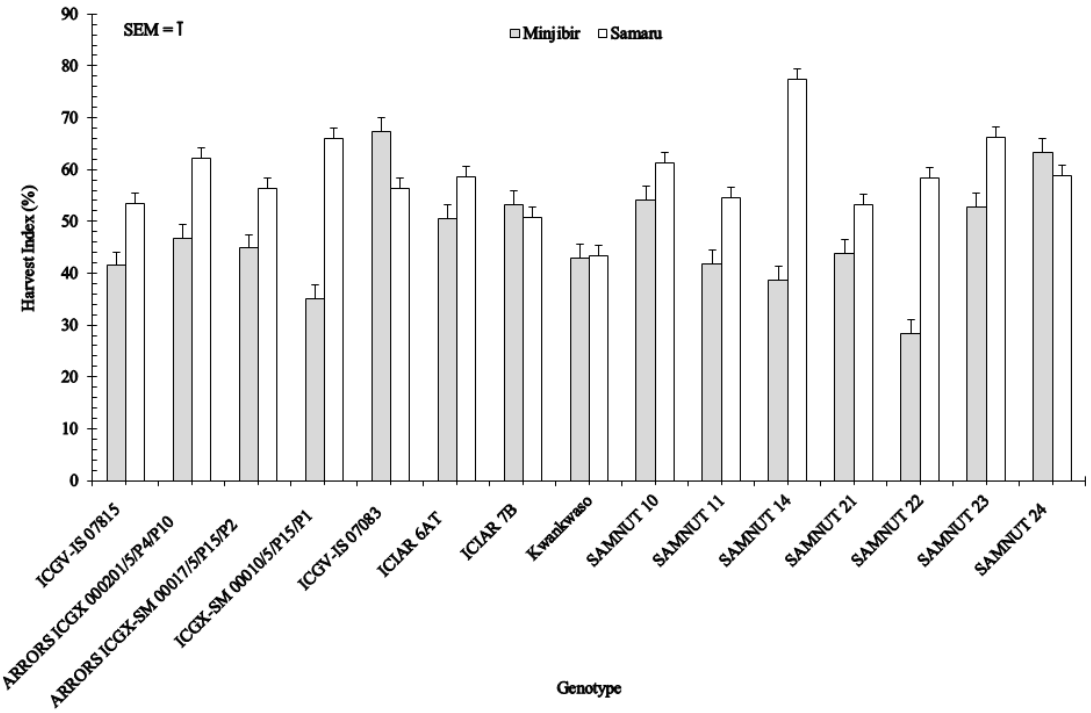



Figure 4.43: Genotype by location interaction on harvest index in 2016 field trial

Differences in weather conditions of the two locations must have favoured Samaru to have recorded this outstanding HI relative to its Minjibir counterpart. Harvest index was observed to be unstable in groundnut, relative to cowpea, varieties due to water stress in a study by Halilou *et al.* (2015). They also observed other variations in groundnut yield/yield components that were not explained by harvest index (but clearly explained by transpiration efficiency). Predominant additive gene effect have been repoted to influence HI in three groundnut genotypes in a study by Suriharn *et al.* (2005). Low HI of a crop could variously be attributable to various crop, seed, management and/or sowing factors. Ahmad *et al.* (2007), for example, reported late sowing/sowing method problems, poor crop population and protection as examples of important low HI causes. Earlier studies by Bindi *et al.* (1999), however, indicated changes in HI due a number of conditions of growth, including soil fertility issues. Bell *et al.* (1994) obtained great variations in harvest index over a period of time.

#### *4.7.4.6 Genotype by location interaction on harvest index in the field trials mean across the seasons*

The genotypes were also different, significantly ($P \leq 0.01$), in terms of their harvest index (HI) recorded on the basis of genotype versus location interaction in the (2015 and 2016 seasons) means (Figure 4.44). A significantly ($P \leq 0.01$) highest HI was recorded for the SAMNUT 14 (72%) in Samaru. It was statistically akin to SAMNUT 24 (54%), also in Samaru. Thirty-three percent (33%) of the genotypes in Minjibir, and up to 80% in Samaru, were also statistically not different with SAMNUT 24, in terms of the parameter in the mean across the seasons. The lowest HI record was observed in Minjibir for SAMNUT 22 (27%), which was at par with most other genotypes across the two agro-ecological locations in the mean across the seasons (Figure 4.44).

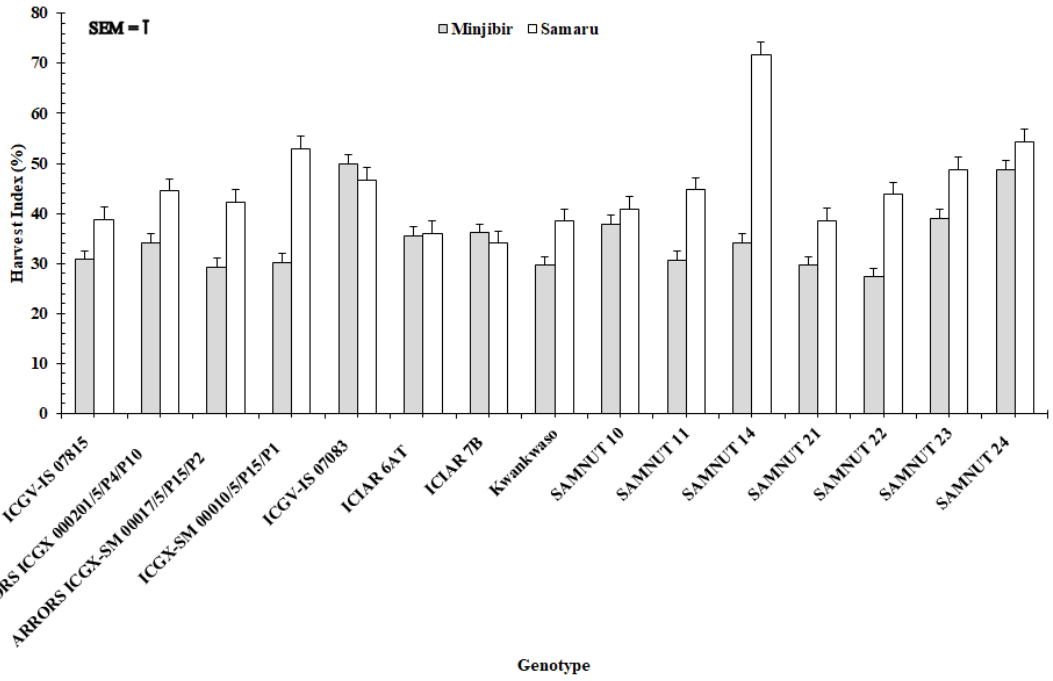



Figure 4.44: Genotype by location interaction on harvest index in the field trials mean across the seasons

#### *4.7.4.7 Phosphorus by location interaction on harvest index in the 2015 field trial*

The genotypes were also significantly ($P \leq 0.01$) different in terms of their harvest index (HI) performances on the basis of P source versus location interaction in the 2015 trial season (Figure 4.45). A significantly ($P \leq 0.01$) highest HI was recorded in the control (35%) in Samaru, which was statistically at par with the HI recorded in Samaru SSP P source (32%). These were followed by Samaru SRP (31%), which was at par with

Minjibir control (29%) and even the Samaru SSP. The significantly ($P \leq 0.01$) lowest HI of 22% in the season was, however, recorded for Minjibir SSP (Figure 4.45). The solubility advantage in favour of SSP and against SRP is further made clear from this result.

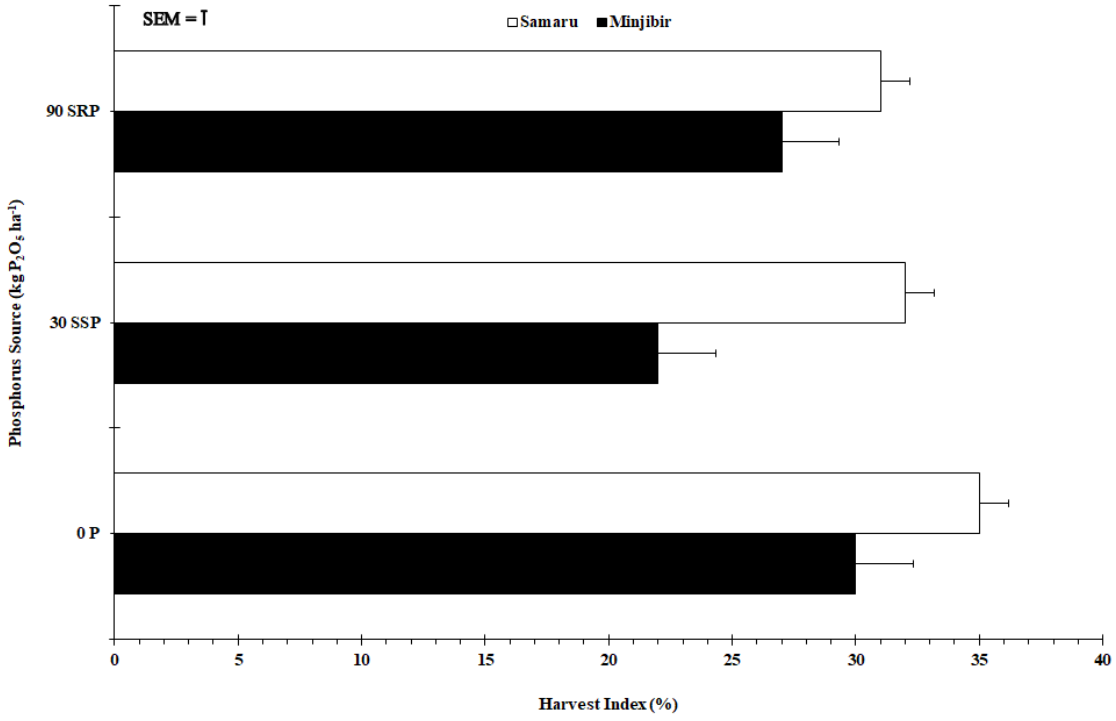



Figure 4.45: Phosphorus by location interaction on harvest index in the 2015 field trial

*4.7.4.8 Phosphorus by location interaction on harvest index in the 2016 field trial*

The genotypes were also significantly ($P \leq 0.05$) different in terms of their harvest index (HI) performance on the basis of P source versus location interaction in the 2016 trial season (Figure 4.46). The significantly ($P \leq 0.01$) highest HI was recorded for SRP (63%) in Samaru, which was immediately followed by the control P source (60%) in same Samaru location. Following these was SSP (53%) in the same Samaru. The SRP (46%) and SSP (45%) P sources in Minjibir were statistically similar and had the significantly lowest HI of the 2016 trial season (Figure 4.46), indicating that the control P fertiliser source was even better up than the two other P sources (SSP and SRP) in Minjibir during the trial season.

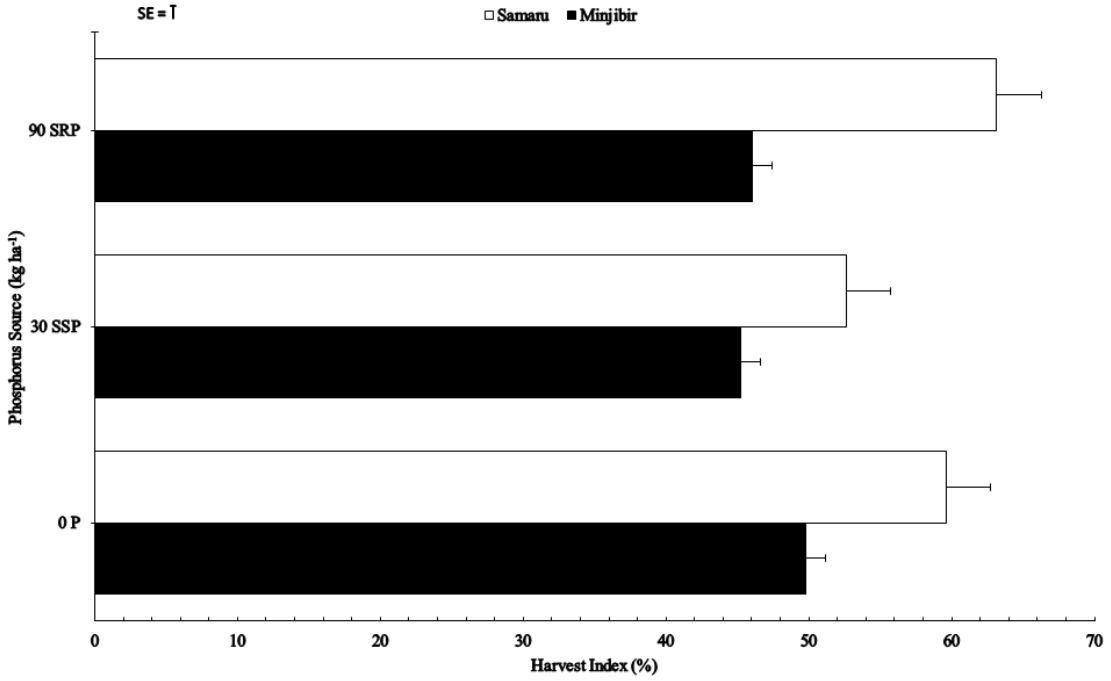



Figure 4.46: Phosphorus by location interaction on harvest index in the 2016 field trial

#### *4.7.4.9 Phosphorus and location interaction on harvest index in the field trials mean across the seasons*

The genotypes were also significantly ($P \leq 0.01$) different in terms of their harvest index (HI) performances on the basis of P source versus location interaction in the mean across 2015 and 2016 trial seasons (Figure 4.47). A significantly ($P \leq 0.01$) highest HI was recorded in Samaru under the control P source (48%), which was statistically similar to SRP (47%) in the same Samaru. They were followed by SSP (41%), also in Samaru. The SSP (32%) and SRP (35%) P sources were statistically similar, in terms of HI in the mean across the seasons, and each had the lowest HI record of the mean across the seasons in Minjibir (Figure 4.47).

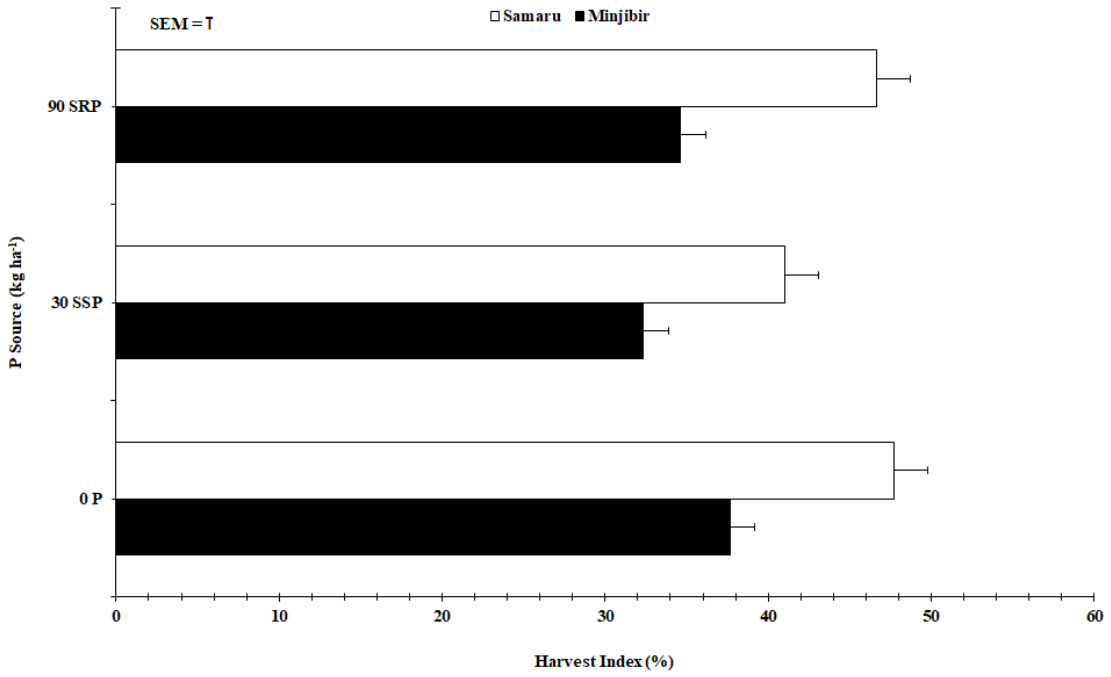



Figure 4.47: Phosphorus by location interaction on harvest index in the field trials mean across the seasons

*4.7.4.10 Genotype by phosphorus versus location interaction on harvest index in the 2015 field trial*

A significant ($P \leq 0.01$) genotype by P source versus location interaction differences between the genotypes was observed, in terms of their harvest index (HI), during the 2015 trial season (Figure 4.48). The highest HI was observed for SAMNUT 14 (48%) and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (487%) in Minjibir under the control and SAMNUT 23 (47%) and ICGV-IS 07083 under SRP. These were statistically comparable to some other genotypes across the P sources and locations. The overall lowest HI record of the 2015 trial season was observed in ICIAR 6AT (9%) under SSP in Samaru, which was also similar to many other genotypes across the P sources and locations (Figure 4.48).

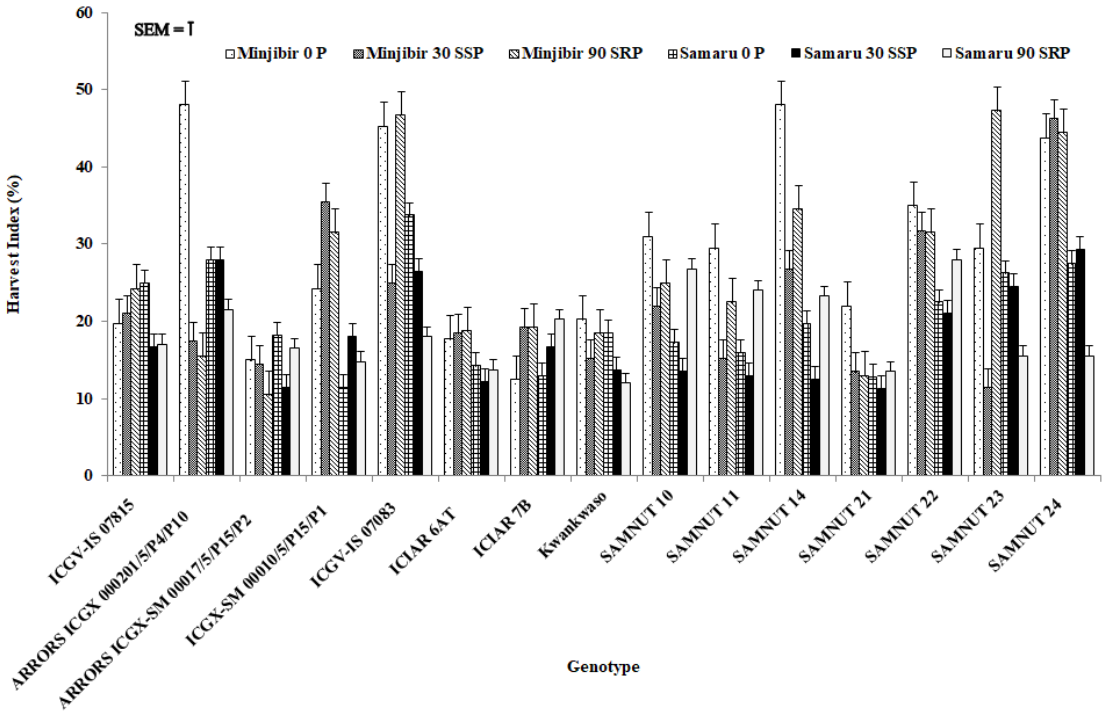



Figure 4.48: Genotype by phosphorus versus location interaction on harvest index in the 2015 field trial

Forty percent (40%) of the genotypes in Minjibir were under the control and SRP and only 20% were under SSP performed well in terms of HI in the 2015 trial season. In Samaru location, however, 73%, 53% and 60% of the genotypes observed, respectively, under the control, SSP and SRP have good HI records during the 2015 trial. Interestingly, ICGX-SM 00010/5/$P_{15}$/$P_1$, SAMNUT 14 and SAMNUT 22 performed significantly well under all the P sources and in both agro-ecological locations. Also, ICGV-IS 07083 and SAMNUT 24 performed significantly well at both agro-ecological locations and under all, but one P source. The same ICGV-IS 07083 and SAMNUT 24 were, particularly, not observed to have commensurate HI records under SSP and SRP in Minjibir and Samaru, respectively.

*4.7.4.11 Genotype by phosphorus versus location interaction on harvest index in the 2016 field trial*

A significant ($P \leq 0.01$) genotype by P source versus location interaction differences between the genotypes was also observed, in terms of their harvest index (HI), during the 2016 trial season (Figure 4.49). The highest HI was observed for SAMNUT 14 (81%) under the control in Samaru. This was statistically similar to ICGV-IS 07815 (79%), SAMNUT 10 (76%) and SAMNUT 14 (75%) all under SRP P in Samaru. In

Minjibir, ICGV-IS 07083 (74%) and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (70%) both under the control, SAMNUT 24 (71%) under SSP; and SAMNUT 10 (76%) and SAMNUT 21 (70%) both under SRP were also statistically comparable. All these were followed by ICGV-IS 07815 (67%), ICGV-IS 07083 (67%), and ICIAR 7B (63%) respectively under the control, SSP and SRP, also in Minjibir. Also similar to these in Samaru, respectively under the control, SSP and SRP P were the statistically similar ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (64%) and ICGV-IS 07083 (63%), SAMNUT 21 (66%); and statistically similar ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGX-SM 00010/5/$P_{15}$/$P_1$ having a HI of 67% (Figure 4.49).

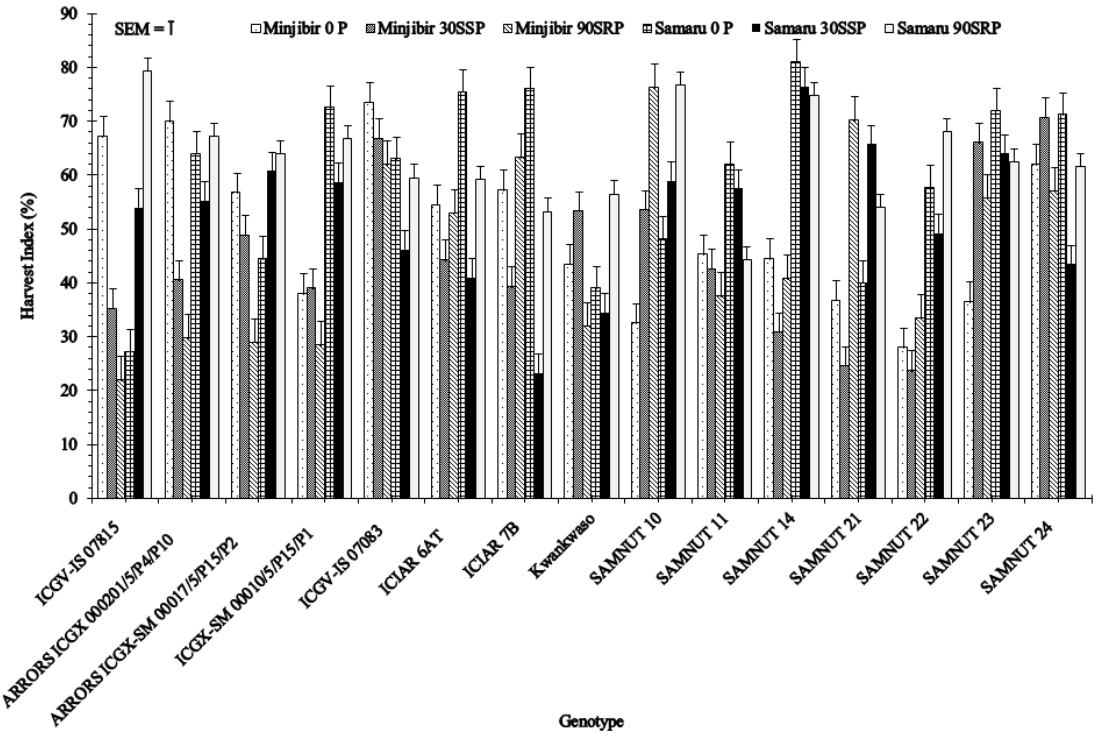



Figure 4.49: Genotype by phosphorus versus location interaction on harvest index in the 2016 field trial

The lowest HI record of the 2016 trial season was observed in SAMNUT 21 and SAMNUT 22 (24% each) under the control P in Minjibir. These were, however, statistically at par with at least two genotypes under each P source in Minjibir and at least one in Samaru but for SRP in Samaru (Figure 4.49).

*4.7.4.12 Genotype by phosphorus versus location interaction on harvest index in the field trials mean across the seasons*

A significant ($P \leq 0.01$) genotype by P source versus location interaction differences between the genotypes was also observed in the 2015 and 2016 seasons means, in terms of their harvest index (HI) as shown in Figure 4.50 below. The highest HI was observed for SAMNUT 14 (78%) under the control in Samaru. The genotype was similar to about 27% of other genotypes under control and SRP each and 13% under SSP, all in Minjibir. Sixty percent (60%) of those in Samaru were also at par with the highest performed genotype. The lowest HI record of the mean across the seasons was observed in SAMNUT 21 (19%) under SSP in Minjibir. This was also at par with most of other genotypes under each of the P sources, and across both agro-ecological locations (Figure 4.50).

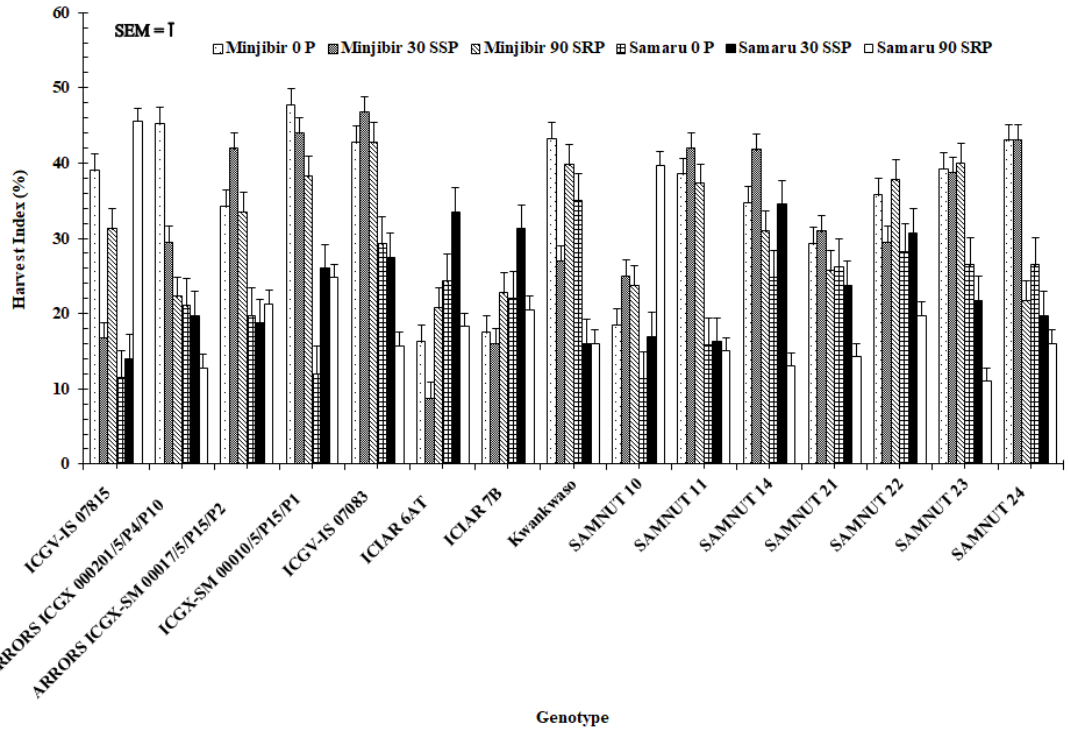



Figure 4.50: Genotype by phosphorus versus location interaction on harvest index in the field trials mean across the seasons

Generally, harvest index that ranged from 33% to 56%, depending on cultivar, was reported by Bell *et al*., 1991. Recently, HI of groundnut varieties in a database, that covered main groundnut producing agro-ecological regions of China between 1993 and 2018, was reported to range from 31% to up to 82% (Xie *et al*., 2020).

## 4.8 Effects of Genotype, Phosphorus and Location on SPAD Chlorophyll Content (SCMR) of the Groundnuts in 2015, 2016 Trial seasons and Mean across the seasons

### 4.8.1 SPAD chlorophyll content of the groundnut genotypes

There were significant effects of location and genotype ($P \leq 0.01$) in both seasons and the mean across the seasons, in terms of SPAD chlorophyll content (CC) but for location in 2015 ($P > 0.05$). All the P sources, in terms of CC, but in the mean across the seasons ($P \leq 0.05$) were not significant ($P > 0.05$). Besides the location of P source interaction, in both seasons and mean across the seasons ($P > 0.05$), and location by genotype by P source, in the mean across the seasons ($P > 0.05$), all the interactions of location, genotype and P source, in terms of CC in both seasons and the mean across them, were significant ($P \leq 0.01$) as shown in Table 4.6. In the 2015 trial season, the groundnut genotypes statistically had similar CC except for ICIAR 7B, which contained relatively lower CC. In the 2016 trial season, the genotypes differed slightly in their CC content. For example, ICGV-IS 07083 out-yielded ICGV-IS 07815, ICIAR 7B, Kwankwaso, SAMNUT 14 and SAMNUT 24. It was statistically not different from all other genotypes. SAMNUT 11, in the mean across the seasons, was statistically at par with all other genotypes in terms of the CC observed, but for ICIAR 6AT, SAMNUT 14 and SAMNUT 24. It was noteworthy, here, that SAMNUT 24 had the lowest CC record of all but 2015 trial season (Table 4.6).

The P sources also slightly differed in their recorded CC values. In 2015, the control P source produced the crops with highest CC, but it was statistically comparable with SSP. The crops treated with SRP contained the lowest amount of CC. Significantly ($P \leq 0.05$) highest CC was, also, observed in Minjibir than Samaru, in 2016 and mean across the seasons. There was, however, no significant ($P > 0.05$) difference between the locations, in terms of CC, in the 2015 trial season, whereas Minjibir proved higher in terms of the parameter in the 2016 and mean of the seasons (Table 4.6). The highest CC observed for ICGV-IS 07815 (37.22 SCMR) and in 2015, ICGV-IS 07083 in the same 2015 (36.83 SCMR) and 2016 (37.07 SCMR) and SAMNUT 11 (36.45) in the mean across the seasons suggested for their potential candidature for $N_2$ fixation. The reverse became the case for the statistically lower CC recorded genotypes, especially SAMNUT 14 and SAMNUT 24 that were commonly the lowest in two of the seasons (Table 4.6).

Table 4.6: Effects of genotype, P source and location on the chlorophyll content of the groundnuts in 2015, 2016 and mean across the seasons

| Treatment | Chlorophyll Content (SCMR) | | |
|---|---|---|---|
| | 2015 | 2016 | Mean across the seasons |
| **Genotype (G)** | | | |
| ICGV-IS 07815 | 37.22$^{a}$ | 34.07$^{b-d}$ | 34.87$^{a-d}$ |
| ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 35.67$^{ab}$ | 34.75$^{a-d}$ | 35.35$^{a-d}$ |
| ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 35.94$^{ab}$ | 36.36$^{ab}$ | 36.28$^{ab}$ |
| ICGX-SM 00010/5/$P_{15}$/$P_1$ | 36.20$^{ab}$ | 35.15$^{a-c}$ | 35.99$^{a-c}$ |
| ICGV-IS 07083 | 36.83$^{a}$ | 37.07$^{a}$ | 36.02$^{a-c}$ |
| ICIAR 6AT | 34.96$^{ab}$ | 35.26$^{a-c}$ | 34.54$^{b-d}$ |
| ICIAR 7B | 33.83$^{b}$ | 33.89$^{b-d}$ | 34.56$^{a-d}$ |
| Kwankwaso | 35.23$^{ab}$ | 34.45$^{b-d}$ | 35.30$^{a-d}$ |
| SAMNUT 10 | 36.14$^{ab}$ | 35.38$^{a-c}$ | 35.61$^{a-c}$ |
| SAMNUT 11 | 35.83$^{ab}$ | 35.68$^{a-c}$ | 36.45$^{a}$ |
| SAMNUT 14 | 35.08$^{ab}$ | 33.38$^{cd}$ | 34.23$^{cd}$ |
| SAMNUT 21 | 36.53$^{ab}$ | 35.97$^{ab}$ | 36.25$^{ab}$ |
| SAMNUT 22 | 35.95$^{ab}$ | 34.54$^{a-d}$ | 35.25$^{a-d}$ |
| SAMNUT 23 | 36.24$^{ab}$ | 36.29$^{ab}$ | 36.26$^{ab}$ |
| SAMNUT 24 | 34.68$^{ab}$ | 32.49$^{d}$ | 33.58$^{d}$ |
| SE± | 0.578 | 0.531 | 0.392 |
| **Phosphorus Rate (P, kg $P_2O_5$ $ha^{-1}$)** | | | |
| 0 P | 36.20$^{a}$ | 35.12 | 35.66$^{a}$ |
| 30 SSP | 35.74$^{ab}$ | 35.04 | 35.39$^{ab}$ |
| 90 SRP | 35.32$^{b}$ | 34.79 | 35.06$^{b}$ |
| SE± | 0.259 | 0.238 | 0.176 |
| **Location (L)** | | | |
| Minjibir | 35.91 | 35.36$^{a}$ | 35.64$^{a}$ |
| Samaru | 35.60 | 34.60$^{b}$ | 35.10$^{b}$ |
| SE± | 0.211 | 0.194 | 0.143 |
| **Interactions** | | | |
| G x P | ** | ** | ** |
| G x L | ** | ** | ** |
| P x L | NS | NS | NS |
| G x P x L | ** | ** | NS |

SCMR=SPAD Chlorophyll Meter Reading, SSP= Single Superphosphate SRP= Sokoto Rock Phosphate, **=Significant at 1% level of probability, NS=Not Significant at 5% level of probability; Means followed by same letter(s) within a treatment in a column do not differ significantly according to Tukey's honest significant difference (HSD).

Richardson *et al.* (2001a) reported that there is an intimate relationship between the CC of a plant and its N concentration, to the extent that its (CC) measurement could compliment $N_2$ fixation quantification (Richardson *et al.*, 2001a; Vollmann *et al.*, 2010). Total CC, in a study by Doley and Jite (2012), revealed a significant rise in the CC at both low and high fertiliser P levels of application.

There was also no significant difference between the SSP P source and the control in terms of the SPAD CC recorded in the 2015 season and mean across the seasons (Table 4.6). Other factors, biotic and/or abiotic may, however, also be at play to hasten or mar the chlorophyll content levels (Giller and Wilson, 1991). Root-mediated processes, in the rhizosphere, such as phosphatases and/or organic acid excretion, *p*H changes and increased non-available soil P transformation into its plant-available form, are reported to highly favour crops in P-deficient conditions (Krasilnikoff *et al.*, 2003).

### 4.8.2 Genotype by phosphorus versus location interaction on SPAD chlorophyll content of groundnuts in the 2015, 2016 field trials and mean across the seasons

#### *4.8.2.1 Genotype by phosphorus interaction on SPAD chlorophyll content of groundnuts in the 2015 field trial*

There was a significant ($P \leq 0.01$) genotype by P source interaction difference between the genotype in terms of chlorophyll content (CC) of the genotypes in the 2015 trial season (Figure 4.51). Significantly ($P \leq 0.01$) highest CC was recorded for ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (39.33 SCMR), under the control, which was statistically at par with many other genotypes under the other P sources. These were, however, immediately followed by statistically similar ICIAR 6AT (33.72 SCMR) and SAMNUT 24 (33.67 SCMR), both under SSP; and ICGV-IS 07815 (33.73 SCMR), ICIAR 7B (33.61 SCMR) and ICGV-IS 07083 (32.58 SCMR), all under SRP. The lowest CC was recorded for ICIAR 6AT (32.13 SCMR), under the control (Figure 4.51).

Up to 93%, about 87% and 80% of the genotypes were observed to perform significantly well in terms of their CC under the control, SSP and SRP respectively. This reaffirmed the significance of AcPhase activity in groundnut P, and consequently N, nutrition. Close relationship between the CC of plants and their N concentration has been reported (Richardson *et al.*, 2001a). The CC measurement of a plant has, as such, been reported to possibly been used in complimenting $N_2$ fixation quantification (Vollmann *et al.*, 2010). SSP's contribution to the CC may be due to its being more readily soluble than SRP (Musa *et al*., 2012).

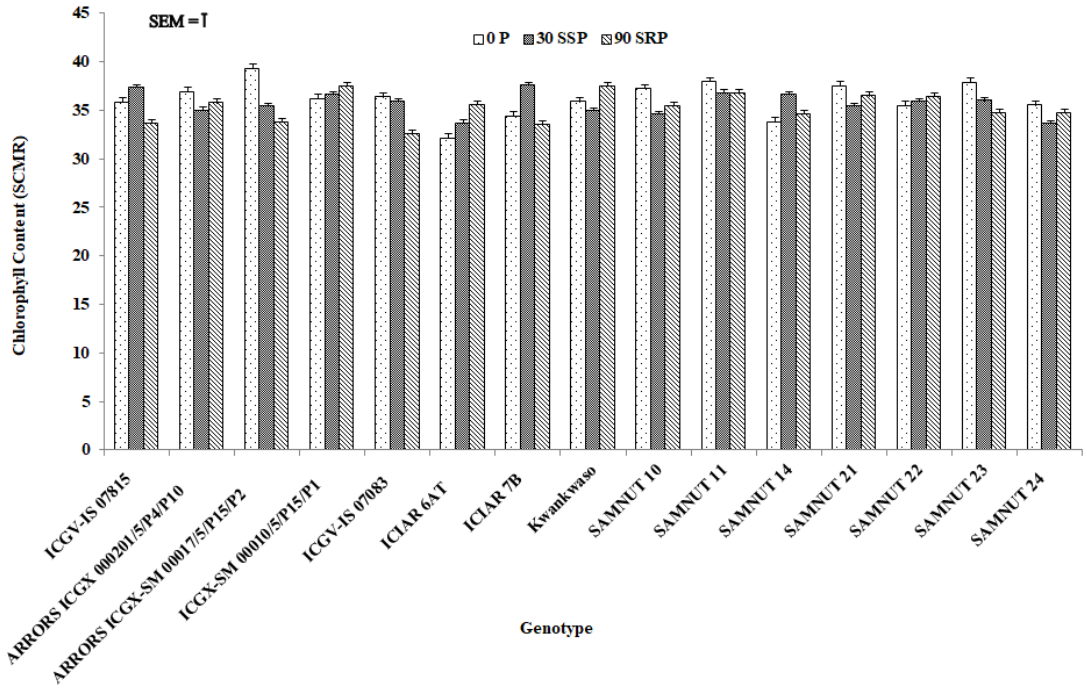



Figure 4.51: Genotype by phosphorus interaction on chlorophyll content of groundnuts in the 2015 field trial

Although soils of the study locations were relatively acidic in reaction (Table 4.1), the relative small Ca sink of soils (Table 4.1) might have contributed to the poor dissolution of SRP (Dodor *et al*., 1999), and hence it's being lower in the CC performance compared to SSP.

### *4.8.2.2 Genotype by phosphorus interaction on chlorophyll content of groundnuts in the 2016 field trial*

Significant ($P \leq 0.01$) difference was observed between the genotypes in terms of genotype versus P source interaction on the chlorophyll content (CC) of the groundnuts in the 2016 trial season (Figure 4.52). ICGV-IS 07083, under SSP (39.54 SCMR) had the highest CC record, bt was statistically similar to many other genotypes under all the P sources across the two locations. The lowest CC of 30.62 SCMR was recorded in SAMNUT 24 under SSP, which was still also similar to many other genotypes under all sources and across both locations (Figure 4.52).

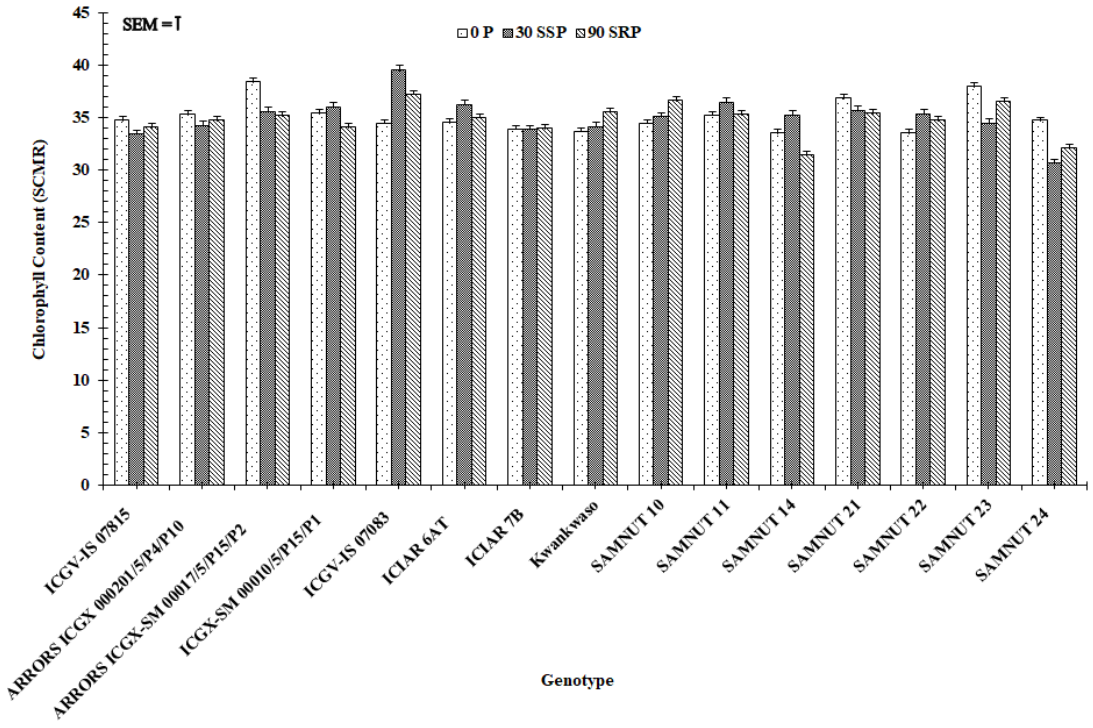



Figure 4.52: Genotype by phosphorus interaction on chlorophyll content of groundnuts in the 2016 field trial

### *4.8.2.3 Genotype by phosphorus interaction on chlorophyll content of groundnuts in the field trials means across the seasons*

The genotype by P source interaction on chlorophyll content (CC) of the genotypes, in the mean across the 2015 and 2016 trial seasons was significantly ($P \leq 0.01$) different (Figure 4.53). Hence, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ under the control (38.87 SCMR) had the highest CC record. It was, however, statistically at par with many other genotypes under the other P sources. The lowest CC of 32.14 SCMR was recorded for SAMNUT 24 under SSP, but was at par with many other genotypes under the other P sources in the mean across the seasons (Figure 4.53). The CC recorded for the groundnuts in the mean across the seasons was also very high. In that, 93%, 73% and about 67% of them were observed as having recorded high CC measures under SSP, the control and SRP, respectively.

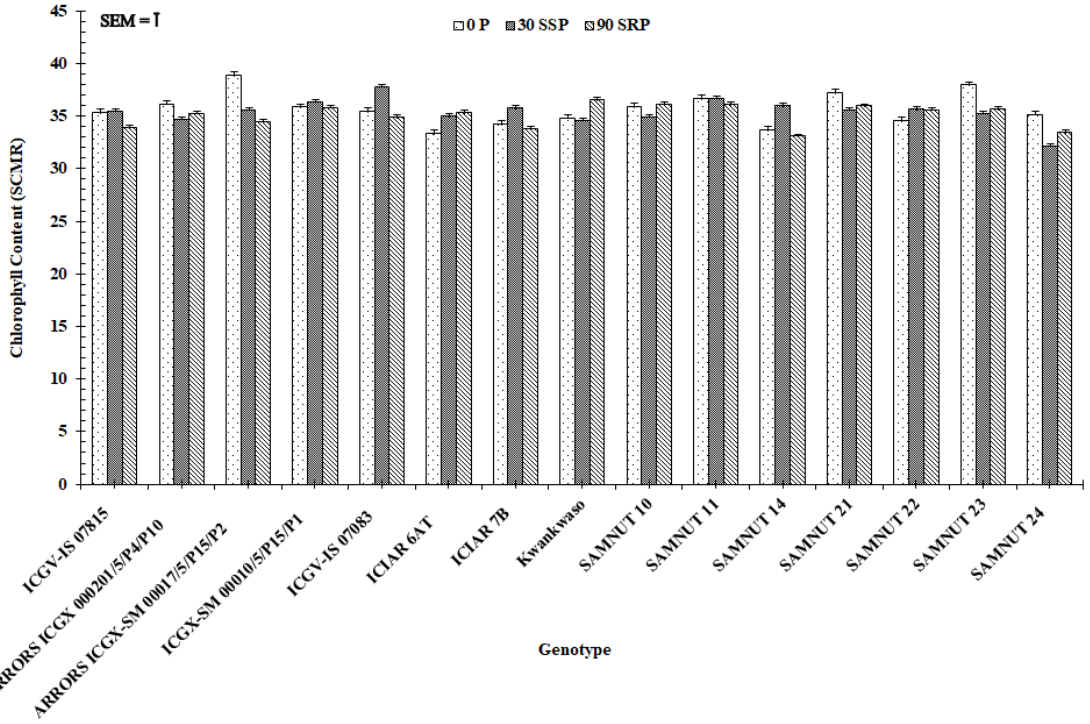



Figure 4.53: Genotype by phosphorus interaction on chlorophyll content of groundnuts in the mean field trials across the seasons

### *4.8.2.4 Genotype by location interaction on chlorophyll content (SCMR) of groundnuts in the 2015 field trial*

A significant ($P \leq 0.01$) difference was observed, between the genotypes, in terms of genotype and location interaction on the chlorophyll content (CC) in the 2015 trial season (Figure 4.54). In that, SAMNUT 10 (38.24 SCMR) and SAMNUT 11 (38.21 SCMR), in Samaru; and ICGX-SM 00010/5/$P_{15}$/$P_1$ (38.18 SCMR) in Minjibir, had the highest CC record and were statistically similar with most other genotypes across the locations. ICIAR 6AT (33.57 SCMR) and SAMNUT 14 (33.54 SCMR) in Samaru; and SAMNUT 10 (33.47 SCMR), in Minjibir, immediately followed those. The lowest CC in the season was, however, recorded for SAMNUT 24 (32.85 SCMR) in Samaru, although it was similar to the intermediately performed genotypes in terms of the parameter (Figure 4.54). Ninety-three percent (93%) of the genotypes in Minjibir and 80% in Samaru were observed to have performed well in terms of the CC measured in the 2015 trial season. About 73% of the genotypes were observed perform extraordinarily well in both locations. This indicated the common nature of the locations in terms of the factors that affect CC of the groundnut genotypes.

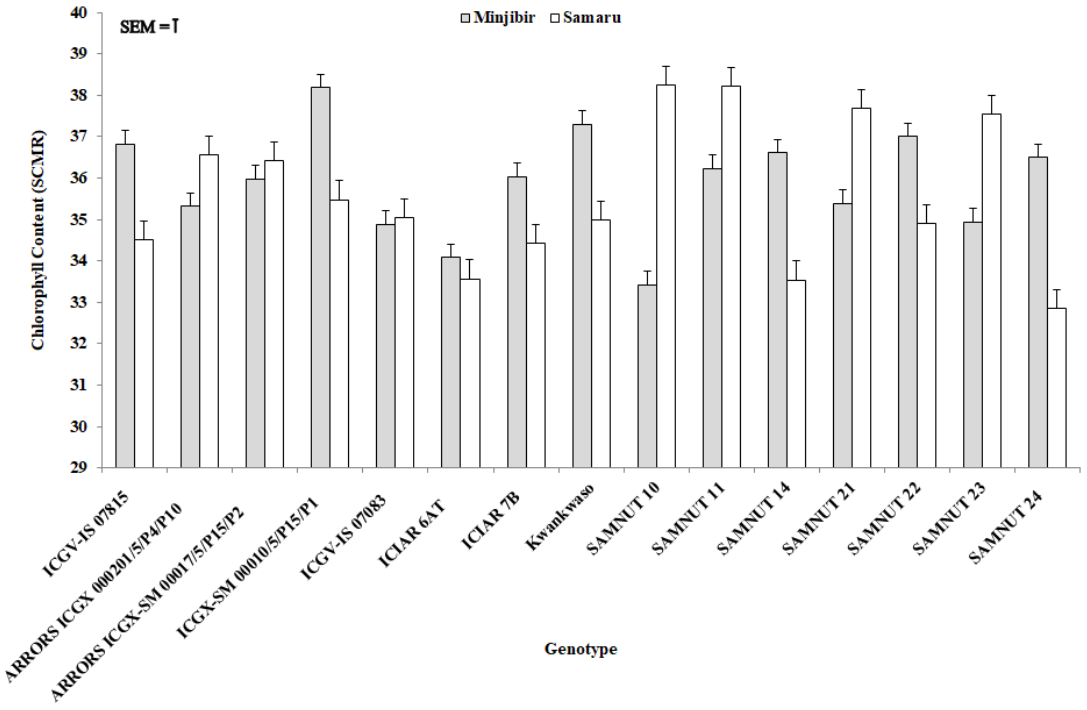



Figure 4.54: Genotype by location interaction on chlorophyll content of groundnuts in the 2015 field trial

### *4.8.2.5 Genotype by location interaction on chlorophyll content (SCMR) of groundnuts in the 2016 field trial*

The groundnut genotypes were significantly ($P \leq 0.01$) different in terms of genotype against location interaction on the chlorophyll content (CC) measured in the 2016 trial season (Figure 4.55). In that, ICGV-IS 07083 in Samaru had the highest CC record of 39.10 SCMR. It was followed by SAMNUT 10 (37.79 SCMR), in Minjibir, and some other genotypes across both locations. The lowest CC was, however, recorded for SAMNUT 24, both in Samaru (32.47 SCMR) and Minjibir (32.50 SCMR), but they were also statistically akin to some of the genotypes across the locations (Figure 4.55). The Minjibir location had the highest number of genotypes (60%) that had good CC records. The Samaru location followed with only about 27% genotypes.

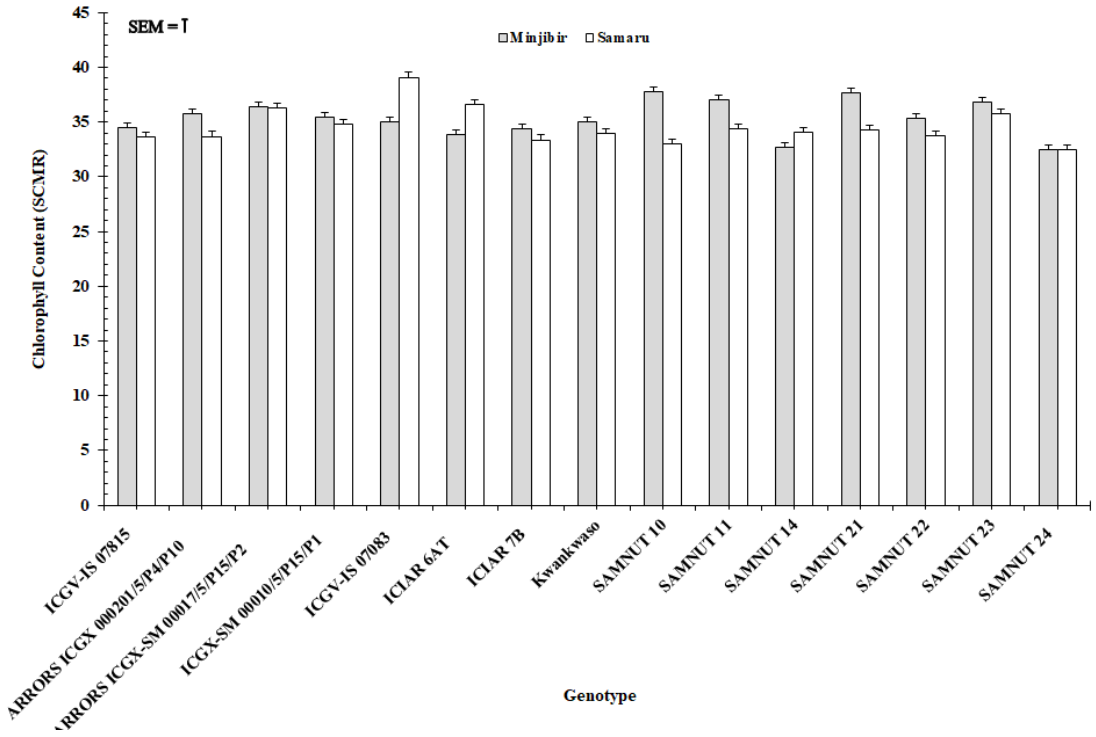



Figure 4.55: Genotype by location interaction on chlorophyll content of the groundnuts in the 2016 field trial

### *4.8.2.6 Genotype by location interaction on chlorophyll content (SCMR) of the groundnuts in the mean field trials across the seasons*

A significant ($P \leq 0.01$) difference between the genotypes in terms of genotype by location interaction on their chlorophyll content (CC) was observed in the mean across the two trial seasons (Figure 4.56). Genotypes ICGX-SM 00010/5/$P_{15}$/$P_1$ (36.83 SCMR), SAMNUT 11 (36.62 SCMR), SAMNUT 21 (36.53 SCMR), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (36.20 SCMR), SAMNUT 22 (36.18 SCMR) and Kwankwaso (36.14 SCMR) all in Minjibir; and ICGV-IS 07083 (37.07 SCMR), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (36.36 SCMR) and SAMNUT 11 (36.28 SCMR), all in Samaru, were statistically similar and had the highest CC record. SAMNUT 24 (32.66 SCMR) in Samaru, had the lowest CC but was similar to many other genotypes across both locations (Figure 4.56). All the genotypes (100%) in Minjibir and 93% in Samaru had good CC records during mean of the seasons.

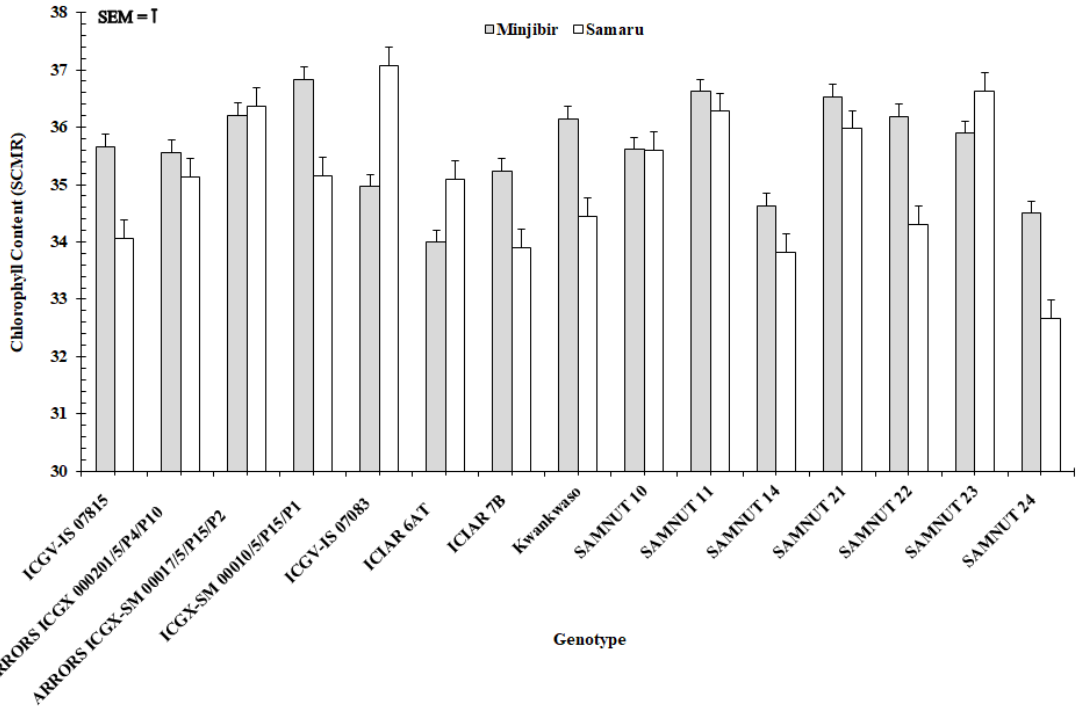



Figure 4.56: Genotype by location interaction on chlorophyll content of the groundnuts in the field trials mean across the seasons

### *4.8.2.7 Genotype by phosphorus versus location interaction on chlorophyll content of groundnuts in the 2015 field trial*

The genotype by P source versus location interaction, on the chlorophyll content (CC) of the genotypes in the 2015 trial season (Figure 4.57), was observed to be significant ($P \leq 0.01$). As such, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, under the control in Samaru (41.39 SCMR), had the highest CC record of all the genotypes. However, this did not differ significantly from many other genotypes under the other P sources and across the locations. The lowest CC, on the other hand, was recorded for SAMNUT 24 under SSP in Samaru (30.33 SCMR). The highest number of genotypes (100%) that performed well, in terms of CC measurement, was observed under SRP in Samaru. This was followed by SSP (in the same Samaru) and control P (in Minjibir), with a record of 93% genotypes each. About 87% of the genotypes under each of SSP and the control P sources, respectively, in Minjibir and Samaru also performed well. About 80% of the genotypes, however, performed well under the SRP in Minjibir (Figure 4.57).

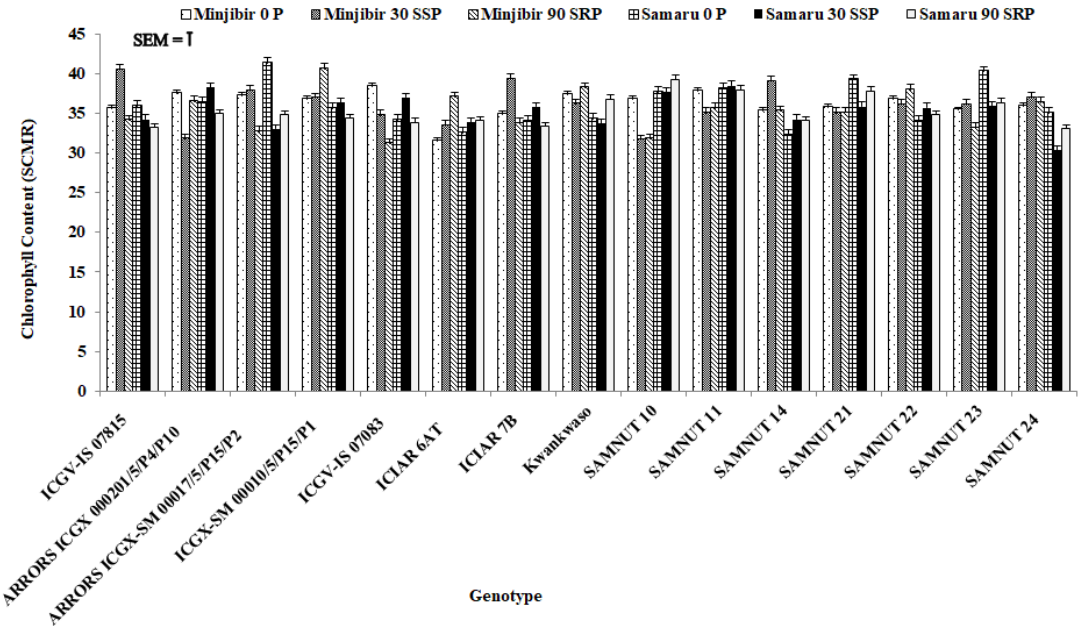



Figure 4.57: Genotype by phosphorus versus location interaction on chlorophyll content of groundnuts in the 2015 field trial

### *4.8.2.8 Genotype by phosphorus versus location interaction on chlorophyll content of the groundnuts in the 2016 field trial*

A significant ($P \leq 0.01$) difference was observed between the genotypes, on the basis of genotype versus P source by location interaction on the chlorophyll content (CC) of the genotypes in the 2016 trial season (Figure 4.58). SAMNUT 11 under control in Minjibir (42.08 SCMR) had the highest CC. It was, however, followed by ICGV-IS 07083 (41.39 SCMR) and SAMNUT 11 (40.31 SCMR), respectively under the control and SRP, both in Minjibir. The lowest CC of 30.33 SCMR and 30.43 SCMR was recorded for SAMNUT 23 and SAMNUT 24 in Samaru respectively, under SRP and SSP (Figure 4.58). The SRP P in Minjibir had the highest number of genotypes (80%) observed to perform well, during the 2016 trial season, in terms of CC. The relatively low number of 53% was observed under the same SRP in Samaru. Conversely, the genotypes performed better in Samaru under the control and SSP P sources. In that, 73% and about 67% of the genotypes were better under SSP respectively in Samaru and Minjibir. Under the control, about 67% and 60% of the genotypes performed well in Samaru and Minjibir respectively.

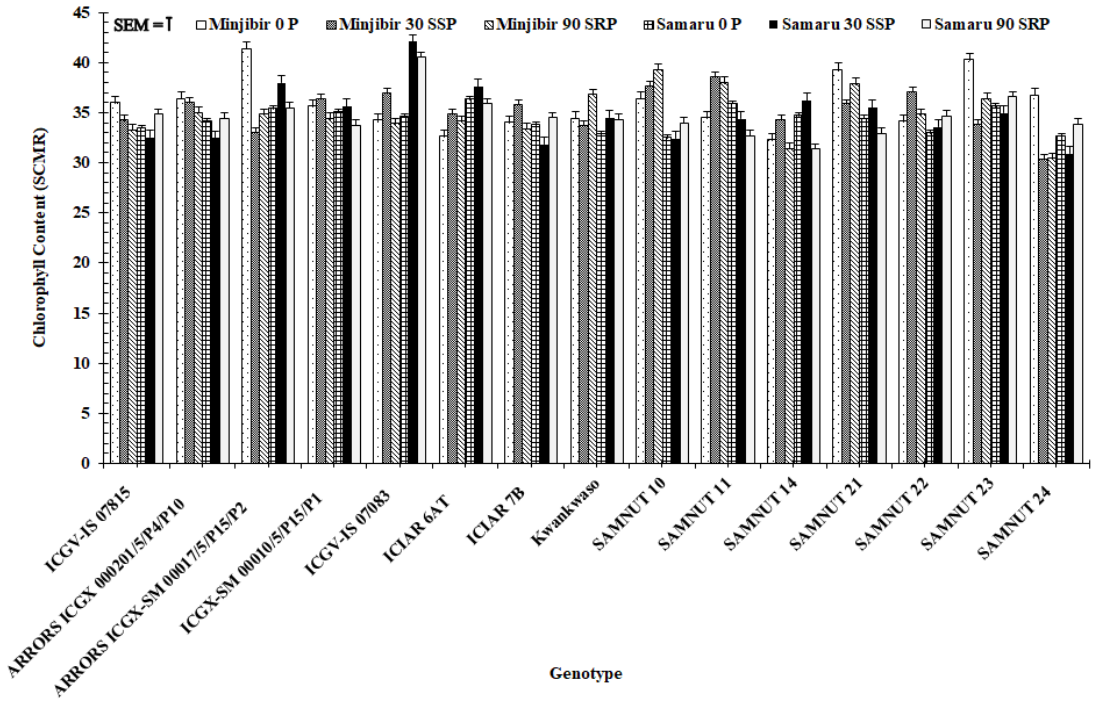



Figure 4.58: Genotype by phosphorus versus location interaction on chlorophyll content of the groundnuts in 2016 field trial

## 4.9 Pearson Correlation Coefficients of Selected Parameters in the 2015 and 2016 Field Trials and Mean across the Seasons

### 4.9.1 Pearson correlation coefficients of selected parameters in the 2015 field trial

The Pearson correlation (*i.e.*, interdependence, also called Pearson product-moment correlation or correlation coefficient) analysis results in 2015 showed positive and significant ($P \leq 0.001$) correlations between the dry haulm and pod yields ($r = 0.19$), dry haulm and dry matter yields ($r = 0.99$) and dry matter and pod yields ($r = 0.19$), as indicated in Table 4.7. There was, however, no significant ($P > 0.05$) correlation between these crop yield parameters and chlorophyll content during the same trial season. This correlation, therefore, indicated directly proportional relationships between the yields parameters considered. That is, the dry haulm yield was responsible for the dry matter and, consequently, the pod yields recorded.

The findings, therefore, suggested a possibility of developing groundnut genotypes capable of combining high pod and haulm yields. There was, however, no significant ($P > 0.05$) interdependence between the SCMR versus dry haulm ($r = 0.01$) and dry matter ($r = 0.01$) yields. There was also no interdependence between the SCMR and pod yield ($r = 0$) in the 2015 trial season. Güler and Özçelik (2007), in their study, also concluded

that neither low leaf SPAD chlorophyll content values are indicative of poor yield nor does higher SCMR values at some stages are of higher yields. Silveira *et al*. (2003) also reported non-significant correlations between SPAD CC and yields of some dry beans cultivars. This is basically, according to them, due to the conversion of $N_2$ into organic compounds through BNF process of legumes. This made Güler and Özçelik (2007) to recommend further elaborate investigation into the issue. Although the SPAD chlorophyll readings are closely related with yield in most studies (*e.g.*, Boggs *et al*., 2003; Güler *et al*., 2006), Güler and Özçelik (2007), attributed their rather contradictory observed scenario to measurement period. Varietal differences, time of measurement and fertiliser management are also suggested to influence similar unexpected correlations as observed in a study with some groundnut cultivars by Sheshshayee *et al.* (2006).

All positive correlations, significant or non-significant, are indicative of directly proportional relationships between any given parameters. That is, as one of two parameters increases, the other also increases, and vice-versa. Negative correlations are, on the other hand, the reverse case, that is, it is an indication of an inversely related situation in which an increase in one of the parameters makes the other decrease, and vice-versa (Manisha *et al*., 2018; Walle *et al*., 2018). Positive and negative correlations can either be significant or non-significant. They are significant when the relationship is meaningfully compelling and not significant if not.

This correlation partly tallied with the findings of Nigam and Blummel (2010) in their work with groundnut genotypes, as cited by Oteng-Frimpong *et al*. (2017). Nigam and Blummel (2010) also observed a significant positive correlation between haulm N content (and hence crude protein, by extension) and pod yield and between haulm N content and haulm yield. They did not, however, observe any inverse relationship between either haulm quality and haulm yield, or pod yield and haulm quality. There was also a significant ($P < 0.001$) and positive correlation between pod and dry haulm yields of groundnuts in a study by Ahounou *et al*. (2017). Dapaah *et al*. (2014) also had a similar report for the many groundnut genotypes they tested in their study.

Table 4.7: Pearson correlation coefficients for Minjibir and Samaru field trials for 2015 trial season

| Parameters | Dry Haulm Yield (kg ha$^{-1}$) | Pod Yield (kg ha$^{-1}$) | Dry Matter Yield (kg ha$^{-1}$) | Harvest Index (%) | Chlorophyll Content (SCMR) |
|---|---|---|---|---|---|
| Dry Haulm Yield (kg ha$^{-1}$) | 1.00 | | | | |
| Pod Yield (kg ha$^{-1}$) | 0.19$^{**}$ | 1.00 | | | |
| Dry Matter Yield (kg ha$^{-1}$) | 0.99$^{**}$ | 0.19$^{**}$ | 1.00 | | |
| Harvest Index (%) | 0.12* | 0.69** | 0.12* | 1.00 | |
| Chlorophyll Content (SCMR) | 0.01$^{NS}$ | 0.00$^{NS}$ | 0.01$^{NS}$ | 0.07$^{NS}$ | 1.00 |

Df=178; SCMR=SPAD Chlorophyll Meter Reading, **=Significant at 1% probability level; NS=Not Significant at 5% probability level

Table 4.8: Pearson Correlation Coefficients for Minjibir and Samaru Field Trials of 2016 trial season

| Parameters | Dry Haulm Yield (kg ha$^{-1}$) | Pod Yield (kg ha$^{-1}$) | Dry Matter Yield (kg ha$^{-1}$) | Harvest Index (%) | Chlorophyll Content (SCMR) |
|---|---|---|---|---|---|
| Dry Haulm Yield (kg ha$^{-1}$) | 1.00 | | | | |
| Pod Yield (kg ha$^{-1}$) | 0.39** | 1.00 | | | |
| Dry Matter Yield (kg ha$^{-1}$) | 0.39** | 0.99** | 1.00 | | |
| Harvest Index (%) | 0.06 $^{NS}$ | 0.08$^{NS}$ | 0.08$^{NS}$ | 1.00 | |
| Chlorophyll Content (SCMR) | -0.08$^{NS}$ | -0.11* | -0.11$^{*}$ | 0.15$^{**}$ | 1.000 |

Df=178; SCMR=SPAD Chlorophyll Meter Reading, **=Significant at 1% probability level; NS=Not Significant at 5% probability level

Table 4.9: Pearson correlation coefficients for Minjibir and Samaru in the 2015 and 2016 trials means

| Parameters | Dry Haulm Yield (kg ha$^{-1}$) | Pod Yield (kg ha$^{-1}$) | Dry Matter Yield (kg ha$^{-1}$) | Harvest Index (%) | Chlorophyll Content (SCMR) |
|---|---|---|---|---|---|
| Dry Haulm Yield (kg ha$^{-1}$) | 1.00 | | | | |
| Pod Yield (kg ha$^{-1}$) | 0.55** | 1.00 | | | |
| Dry Matter Yield (kg ha$^{-1}$) | 0.88** | 0.67** | 1.00 | | |
| Harvest Index (%) | -0.06$^{NS}$ | 0.17** | -0.13$^{**}$ | 1.00 | |
| Chlorophyll Content (SCMR) | -0.05$^{NS}$ | 0.05$^{NS}$ | 0.10$^{**}$ | 0.08$^{*}$ | 1.00 |

Df=178; SCMR=SPAD Chlorophyll Meter Reading, **=Significant at 1% probability level; NS=Not Significant at 5% probability level

Significant positive correlations were observed between HI of the genotypes and their dry haulm ($r = 0.12$, $P \leq 0.05$), pod ($r = 0.70$, $P \leq 0.01$) and dry matter ($r = 0.12$, $P \leq 0.05$) yields during the 2015 season trial, and not with their CC ($r = 0.07$, $P > 0.05$). This suggested for a directly proportional association between the HI of the genotypes, their yield parameters and, to a certain extent, their CC. Significant, but weak, correlations of SCMR were, however, observed with haulm and total dry matter yields in a study by Lal' *et al*. (2005).

### 4.9.2 Pearson correlation coefficients of selected parameters in the 2016 field trial

The Pearson correlation analysis results in the 2016 trial season also indicated positive and significant ($P \leq 0.001$) correlations between all the yield parameters. That is, between the dry haulm and pod yields ($r = 0.39$), dry haulm and dry matter yields ($r = 0.39$); and dry matter and pod yields ($r = 0.99$) observed during the trial season, as indicated in Table 4.8 (above). This indicated a directly proportional relationship between the dry haulm, pod and dry matter yields. Higher photosynthetic rates would be expected in plants with more number of leaves, which is also expected to contribute to the haulm yield. Higher photosynthetic rates would be expected to be translated into various plant yields. There were non-significant ($P > 0.05$) positive correlations of HI with dry haulm ($r = 0.06$), pod ($r = 0.08$) and dry matter ($r = 0.46$) yields but a significant ($P < 0.01$) correlation with CC ($r = 0.15$). This indicated an inversely proportional association between HI and dry haulm, pod and DM yields; and a directly proportional one between the HI and CC during the 2016 trial season. There were also non-significant ($P > 0.05$) negative correlations between the CC (SCMR) and dry haulm ($r = - 0.08$) and dry matter ($r = - 0.11$) yields. The Pearson correlation coefficient between the SCMR and pod yield was also observed to be negative but significant ($r = - 0.11$, $P \leq 0.05$) thereby indicating a mild significant inverse relationship between the two parameters.

Conversely, a mild (*i.e.*, non-significant) inverse relationship between the dry haulm yield and SCMR was observed in the 2016 trial season. Varietal differences were observed between groundnut genotypes in terms of their SCMR and plant biomass in a study conducted by Singh and Joshi (1993).

### 4.9.3 Pearson correlation coefficients of selected parameters in the field trials as mean across the seasons

The Pearson correlation analysis results for the 2015 and 2016 as mean across the seasons indicated significantly ($P \leq 0.01$) positive correlations between all the yield parameters (*i.e.*, dry haulm, pod and dry matter yields). However, exceptions were the negative correlations observed in HI versus DHY ($r = - 0.06$), which was non-significant; and with DMY ($r = - 0.13$), which was significant ($P \leq 0.01$) as indicated by Table 4.9. In that, there were strong Pearson correlation coefficients between dry matter and pod ($r = 0.68$) yields and dry haulm and dry matter ($r = 0.89$) yields. The correlation coefficient (r) between the dry haulm and pod yields was observed to be 0.55, indicating a relatively lesser interdependence than that of the immediately preceded yields. This indicated a significant ($P \leq 0.01$) directly proportional increase between the yield parameters in the mean across the seasons. There were also significant ($P \leq 0.01$) positive correlations between the CC (SCMR) versus dry matter yield ($r = 0.09$), pod yield ($r = 0.05$) and HI ($r = 0.08$). The correlations were, however, not significant ($P > 0.05$) and positive with DHY ($r = 0.05$) as indicated by Table 4.9 (above).

There was a non-significant ($P > 0.05$) negative correlation between HI and dry haulm ($r = 0.06$) and a significant ($P < 0.01$) positive correlation with pod ($r = 0.17$) yields. The correlation was, however, significantly negative with dry matter yield ($r = - 0.13$, $P \leq 0.01$) in the mean across the seasons. A similar observation between the three yield components was, therefore, made. Higher impact ($r = 0.88$) was, however, observed for the correlation between dry haulm and dry matter yields. There was also a, relatively, similar significant ($P \leq 0.01$) impact in the correlation between dry matter and pod yields ($r = 0.67$). There were positive correlations between the CC (SCMR) with all the yield parameters. The interdependence was, however, significant ($P \leq 0.01$) with DMY and HI; and non-significant ($P > 0.05$) with dry haulm and pod yields (Table 4.9). The correlations between CC (SCMR) versus dry haulm yield ($r = 0.05$), pod yield ($r = 0.05$) and HI ($r = 0.07$) were relatively weak in the mean across the seasons (Table 4.9).

## 4.10 Effects of Genotype, Phosphorus and Location on $N_2$-fixation, Ndfa and N Uptake of the Groundnuts

### 4.10.1 Effects of genotype, phosphorus and location on $N_2$-fixation, Ndfa, and N uptake of the groundnuts

The individual contribution of location, genotype and P source was significant ($P \leq 0.01$). This was in terms of the atmospheric nitrogen ($N_2$) fixed, N derived from the atmosphere (Ndfa) and N uptake of the groundnut genotypes observed in both locations (Table 4.10). There was also a significant ($P \leq 0.01$) difference between the two locations in terms of the $N_2$-fixed, Ndfa and N uptake observed for the groundnut genotypes (Table 4.10). There was also a significant ($P \leq 0.05$) difference between the genotypes in terms of the three aforementioned parameters (*i.e.*, $N_2$-fixation, Ndfa and N uptake). Genotype SAMNUT 21 was observed to have outperformed all the other genotypes in all the parameters. It was followed by SAMNUT 10 and SAMNUT 22, which were statistically similar to ARRORS ICGX 000201/5/$P_4$/$P_{10}$, SAMNUT 24 and SAMNUT 14 in terms of the $N_2$-fixed. ICGX-SM 00010/5/$P_{15}$/$P_1$, Kwankwaso, ICGV-IS 07083, SAMNUT 11 and SAMNUT 23 had the statistically lowest $N_2$-fixation record of all the genotypes.

Although less than what was obtained in a work by Gabasawa (2011), a similar $N_2$ fixation trend was, however, observed in this study between the IAR released genotypes. In that, SAMNUT 21 outperformed all other genotypes in terms of the parameter and was followed by SAMNUT 10, which was statistically at par with SAMNUT 22. In a similar study, SAMNUT 23 was observed to have recorded the lowest $N_2$ fixation among the IAR released genotypes. On another hand, SAMNUT 24, which did not feature in that work, was observed to statistically not be different from SAMNUT 22, SAMNUT 10 and SAMNUT 14 in terms of $N_2$ fixation as observed in this study.

In terms of the Ndfa, SAMNUT 21 was, however, statistically similar to SAMNUT 22, SAMNUT 10, SAMNUT 24, ARRORS ICGX 000201/5/$P_4$/$P_{10}$, ICGV-IS 07815 and ICIAR 6AT. SAMNUT 14 and ICIAR 7B followed those and were followed by SAMNUT 23, which was similar to SAMNUT 11, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ and Kwankwaso. Significantly lowest Ndfa was recorded in ICGX-SM 00010/5/$P_{15}$/$P_1$, which was statistically at par with ICGV-IS 07083. The significantly highest SAMNUT

21 was, also, statistically similar to SAMNUT 22, in terms of N uptake both of which were also similar to SAMNUT 10, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-IS 07815. ICGX-SM 00010/5/$P_{15}$/$P_1$, although statistically similar to ICGV-IS 07083, Kwankwaso, SAMNUT 14, SAMNUT 23 and SAMNUT 11, had the significantly lowest N uptake record of all the genotypes.

Table 4.10: Effects of genotype, phosphorus and location on $N_2$-fixed, Ndfa and N uptake of the groundnuts

| Treatment | $N_2$-fixed (kg ha$^{-1}$) | Ndfa (%) | N Uptake (kg ha$^{-1}$) |
|---|---|---|---|
| **Location (L)** | | | |
| Minjibir | 17.32$^{a}$ | 30.25$^{a}$ | 32.23$^{a}$ |
| Samaru | 3.08$^{b}$ | -13.36$^{b}$ | 15.78$^{b}$ |
| SE± | 0.374 | 1.209 | 0.409 |
| **Genotype (G)** | | | |
| ICGV-IS 07815 | 1.61$^{c-e}$ | 25.33$^{ab}$ | 26.71$^{a-c}$ |
| ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 14.6$^{b-d}$ | 30.17$^{ab}$ | 26.83$^{ab}$ |
| ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 8.39$^{e}$ | -22.73$^{c-e}$ | 23.71$^{c-e}$ |
| ICGX-SM 00010/5/$P_{15}$/$P_1$ | 0.89$^{f}$ | -36.24$^{e}$ | 17.92$^{f}$ |
| ICGV-IS 07083 | 1.98$^{f}$ | -31.09$^{de}$ | 19.50$^{ef}$ |
| ICIAR 6AT | 10.79$^{de}$ | 25.73$^{ab}$ | 25.71$^{b-d}$ |
| ICIAR 7B | 9.05$^{e}$ | 21.52$^{b}$ | 24.21$^{b-e}$ |
| Kwankwaso | 1.21$^{f}$ | -24.66$^{c-e}$ | 19.25$^{ef}$ |
| SAMNUT 10 | 17.14$^{b}$ | 35.10$^{ab}$ | 29.25$^{ab}$ |
| SAMNUT 11 | 3.10$^{f}$ | -16.94$^{cd}$ | 20.50$^{d-f}$ |
| SAMNUT 14 | 12.91$^{b-e}$ | 23.01$^{b}$ | 19.58$^{ef}$ |
| SAMNUT 21 | 24.4$^{a}$ | 39.48$^{a}$ | 31.71$^{a}$ |
| SAMNUT 22 | 16.96$^{b}$ | 36.42$^{ab}$ | 31.46$^{a}$ |
| SAMNUT 23 | 3.38$^{f}$ | -9.68$^{c}$ | 20.00ef |
| SAMNUT 24 | 16.45$^{bc}$ | 31.29$^{ab}$ | 23.75c-e |
| SE± | 1.024 | 3.309 | 1.119 |
| **Phosphorus Source (P, kg $P_2O_5$ ha$^{-1}$)** | | | |
| 0 | 1.65$^{b}$ | -19.96$^{b}$ | 21.60$^{b}$ |
| 30 SSP | 14.17$^{a}$ | 21.66$^{a}$ | 24.84$^{a}$ |
| 90 SRP | 14.79$^{a}$ | 23.64$^{a}$ | 25.58$^{a}$ |
| SE± | 0.458 | 1.480 | 0.501 |
| **Interactions** | | | |
| Lx G | ** | ** | ** |
| L x P | ** | ** | ** |
| G x P | ** | ** | ** |
| L x G x P | ** | ** | ** |

Ndfa = Nitrogen derived from the atmosphere; NS = Not Significant at 5% level of probability; ** = Sig at 1% level of probability; Means followed by same letter(s) within a treatment in a column do n significantly according to Tukey's honest significant difference (HSD).

The contributions of single superphosphate (SSP) and Sokoto rock phosphate (SRP) were statistically similar in terms of the $N_2$-fixed, Ndfa and N uptake by the genotypes. Significantly highest $N_2$-fixation, N derived from the atmosphere and N uptake were recorded in Minjibir than Samaru. All the interactions recorded, for all the parameters, were significant at 1% level of probability as indicated in Table 4.10 (above). There were generally low $N_2$-fixation and Ndfa records for the genotypes due to the commensurate lower yield obtained, which was directly related to these parameters. The low yield, on the other hand, may be due to many possible factors, including: climatic factors (*e.g.,* Appendix V, Appendix VI and Appendix VII), notably precipitation and temperature (Kowal and Knabe, 1972; Murthy and Rao, 1986), the inherent fertility of the soil (Sanginga *et al*., 1997) and the crop management method employed (Okogun *et al*., 2005). More so, Yakubu *et al*. (2010) reported that an application of 40 kg P $ha^{-1}$ increased the quantity of $N_2$ fixed by groundnut over a control in soils of Sudano-Sahelian zone of Nigeria. In this study, however, the SSP P source was lower, whereas the solubility constraint, inherent in the SRP, remained a stumbling block even after the addition of a few folds above the more readily soluble SSP.

### 4.10.2 Genotype by phosphorus versus location interaction on $N_2$-fixed, Ndfa and N uptake of the groundnuts

*4.10.2.1 Genotype by location interaction on $N_2$-fixed by the groundnuts*

A significant ($P < 0.01$) interaction of location versus genotype on the $N_2$-fixation of the genotypes was observed (Table 4.10 and Figure 4.59). Generally, the highest $N_2$ was fixed by SAMNUT 21 (39.47 kg $ha^{-1}$) in Minjibir and was followed by ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (27.30 kg $ha^{-1}$), which was statistically at par with SAMNUT 24 (24.01 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (21.99 kg $ha^{-1}$), all in Minjibir and SAMNUT 10 (25.02 kg $ha^{-1}$) in Samaru. Significantly lowest $N_2$ was fixed, in Samaru location, by all other genotypes, which were statistically similar, except SAMNUT 22 (17.35 kg $ha^{-1}$) which was at par with the SAMNUT 10. Other exceptions were the statistically similar genotypes [that included ICGX-SM 00010/5/$P_{15}$/$P_1$ (-11.14 kg $ha^{-1}$), ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (-10.52 kg $ha^{-1}$), ICGV-IS 07083 (-9.29 kg $ha^{-1}$), Kwankwaso (-9.25 kg $ha^{-1}$), SAMNUT 23 (-6.99 kg $ha^{-1}$) and SAMNUT 11 (-5.87 kg $ha^{-1}$)] all of which aided in a net $N_2$ loss as depicted by Figure 4.59 (below).

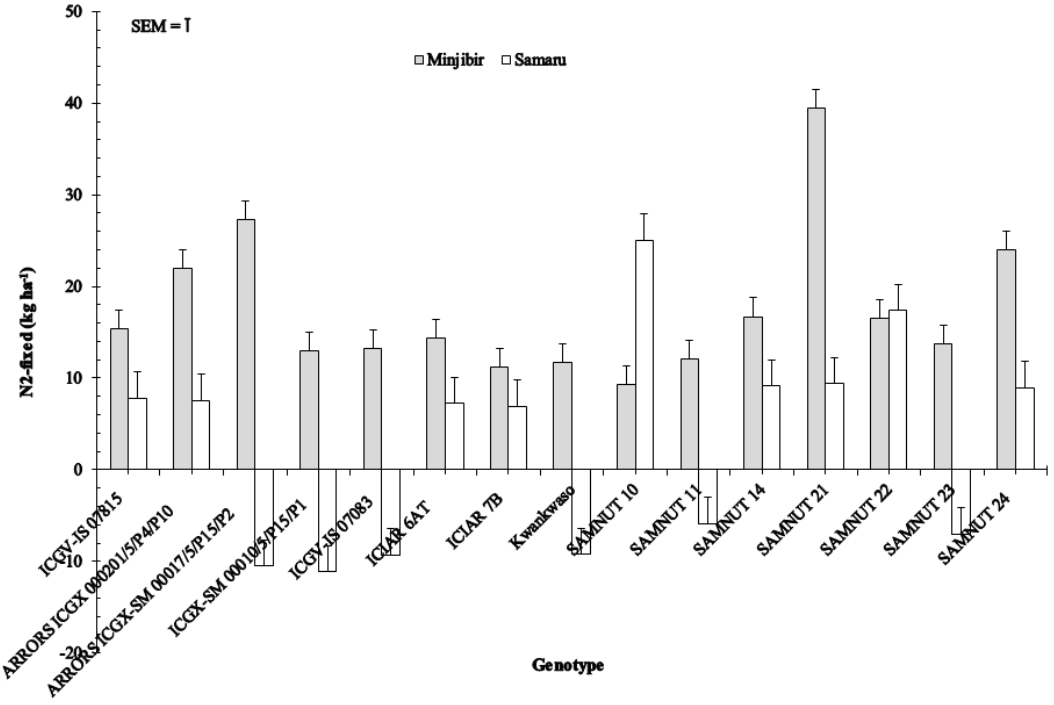



Figure 4.59: Genotype by location interaction on $N_2$-fixed by the groundnuts

*4.10.2.2 Phosphorus by location interaction on $N_2$-fixed by the groundnuts*

There was also a significant ($P < 0.01$) interaction of location by P source on the $N_2$-fixation of the genotypes. Hence, the significantly highest $N_2$-fixation of 24.95 kg $ha^{-1}$ was recorded for SRP, which was followed by SSP (21.14 kg $ha^{-1}$), both in Minjibir agro-ecology. The significantly lowest $N_2$-fixation was, on the other hand, recorded for SRP (4.64 kg $ha^{-1}$) in Samaru location, which was statistically not different from SSP (7.19 kg $ha^{-1}$) in Samaru and control (5.89 kg $ha^{-1}$) in Minjibir. A net $N_2$ loss of -2.58 kg $ha^{-1}$ was, however, recorded under the control in Samaru location as indicated in Figure 4.60 (also Table 4.10).

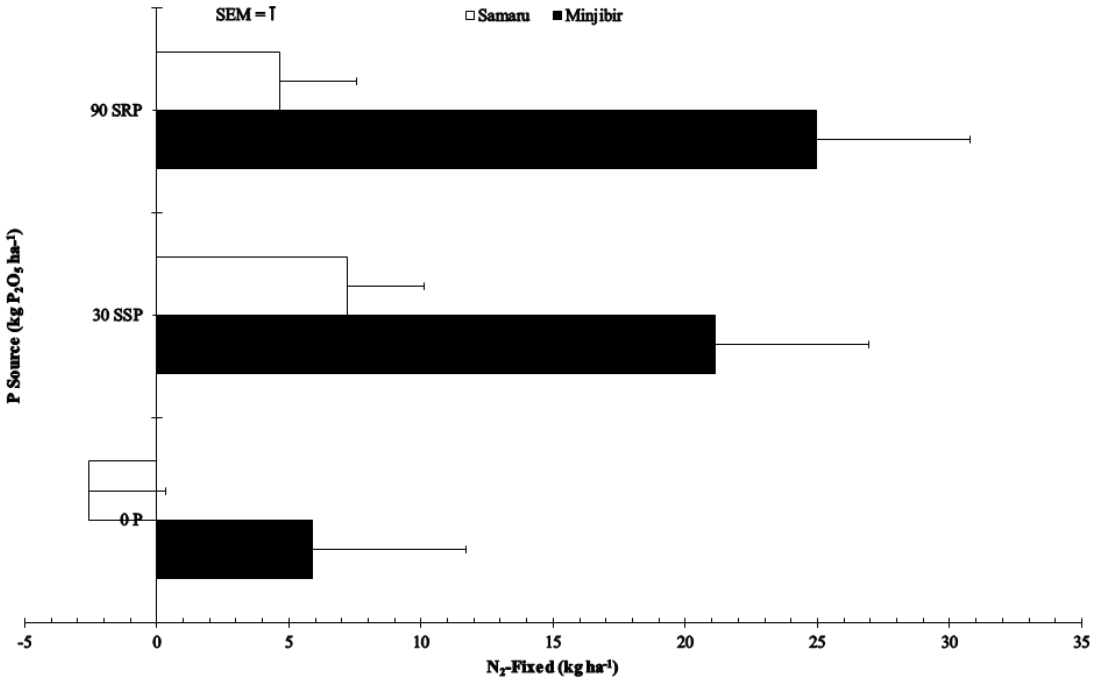



Figure 4.60: Phosphorus by location interaction on $N_2$-fixed by the groundnuts

*4.10.2.3 Genotype by phosphorus interaction on $N_2$-fixed by the groundnuts*

There was also a significant ($P < 0.01$) interaction of genotype versus P source on the $N_2$-fixation of the genotypes (Figure 4.61). Hence, the significantly highest $N_2$-fixation of 34.29 kg $ha^{-1}$ was recorded in SAMNUT 21 under the influence of SRP. Statistically at par with SAMNUT 21, however, were SAMNUT 14 (29.03 kg $ha^{-1}$) and SAMNUT 21 (26.32 kg $ha^{-1}$) both under SSP; and SAMNUT 24 (28.40 kg $ha^{-1}$) and SAMNUT 22 (27.08 kg $ha^{-1}$) both SRP-fertilised. These were followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (20.07 kg $ha^{-1}$) under SRP; and SAMNUT 10 (23.49 kg $ha^{-1}$) and SAMNUT 24 (19.75 kg $ha^{-1}$) both SSP-fertilised. Other than genotypes that were observed as having contributed to N loss, the significantly lowest fixation was, however, observed in SAMNUT 24 (1.21 kg $ha^{-1}$) under the control. SAMNUT 24 was, however, statistically at par with at least two genotypes under each of control and SSP, but not SRP. ARRORS ICGX 000201/5/$P_4$/$P_{10}$, although did not highly fix $N_s$, was observed to have fixed $N_2$ under both P sources and the control as depicted in Figure 4.61.

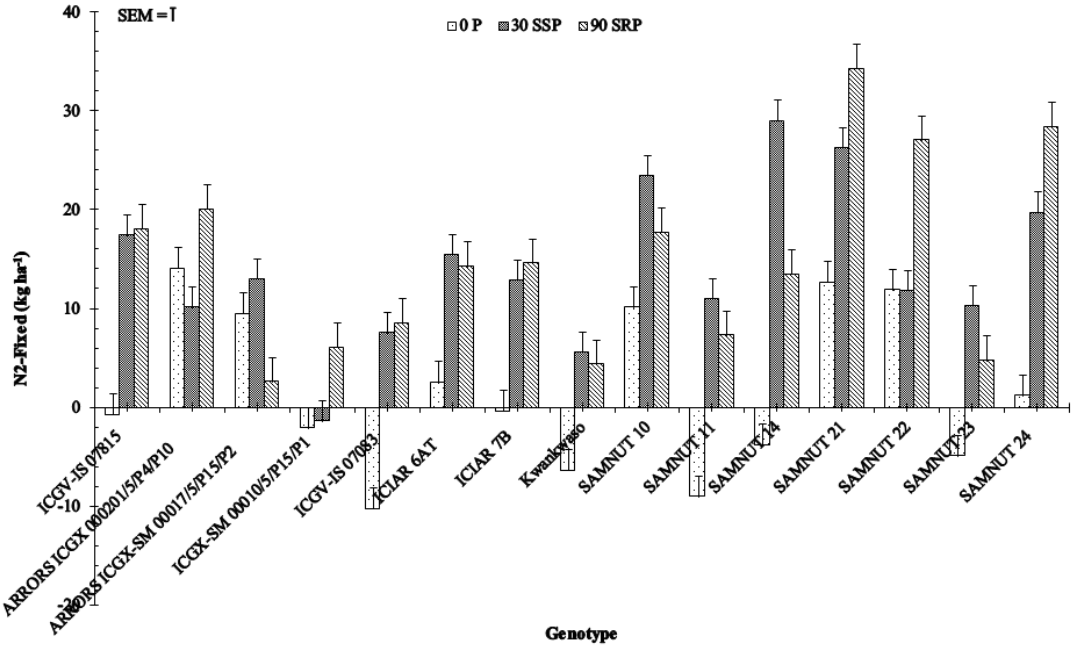



Figure 4.61: Genotype by phosphorus interaction on $N_2$-fixed by the groundnuts

#### *4.10.2.4 Genotype by phosphorus versus location interaction on $N_2$-fixed by the groundnuts*

There was, equally, a significant difference between the genotypes in terms of their $N_2$-fixation performance on the basis of location versus genotype by P source interaction (Figure 4.62). In this regards, therefore, SAMNUT 21, under SRP in Minjibir, was observed to have fixed 52.21 kg $ha^{-1}$, thereby outperforming all other genotypes under both P sources and the control in both agro-ecological locations. However, SAMNUT 24 (41.35 kg $ha^{-1}$) under SRP and SSP-fertilised SAMNUT 21 (40.83 kg $ha^{-1}$), in the same Minjibir were statistically similar to SRP-fertilised SAMNUT 21. They were followed by ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ under SSP in Minjibir (35.84 kg $ha^{-1}$), which was statistically akin to genotypes ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$) under the control, SAMNUT 14, SAMNUT 24 and SAMNUT 23 under SSP; and SAMNUT 22, ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and ICGV-IS 07815 under SRP in Minjibir; and SAMNUT 10 under SSP in Samaru. However, some genotypes contributed to net $N_2$ losses under most of the P sources across the locations while some had the significantly lowest $N_2$-fixation record. Notably amongst these genotypes were SAMNUT 11 (0.34 kg $ha^{-1}$), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (0.54 kg $ha^{-1}$) and SAMNUT 24 (0.79 kg $ha^{-1}$), respectively under SSP P source and control all in Samaru location. Other genotypes,

under the P sources across both locations were, however, at par with these in terms of the parameter.

Forty percent (40%) of the genotypes in Minjibir were observed to contribute to net N loss and were under the control. Conversely, in Samaru, 33% of the genotypes (ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, ICGX-SM 00010/5/$P_{15}$/$P_1$, ICGV-IS 07083, Kwankwaso and SAMNUT 23) were observed to have contributed to the net loss under both P sources and the control. Generally, SAMNUT 23 was observed as having predominantly contributed to net N loss in all but under SSP and SRP in Minjibir (Figure 4.62).

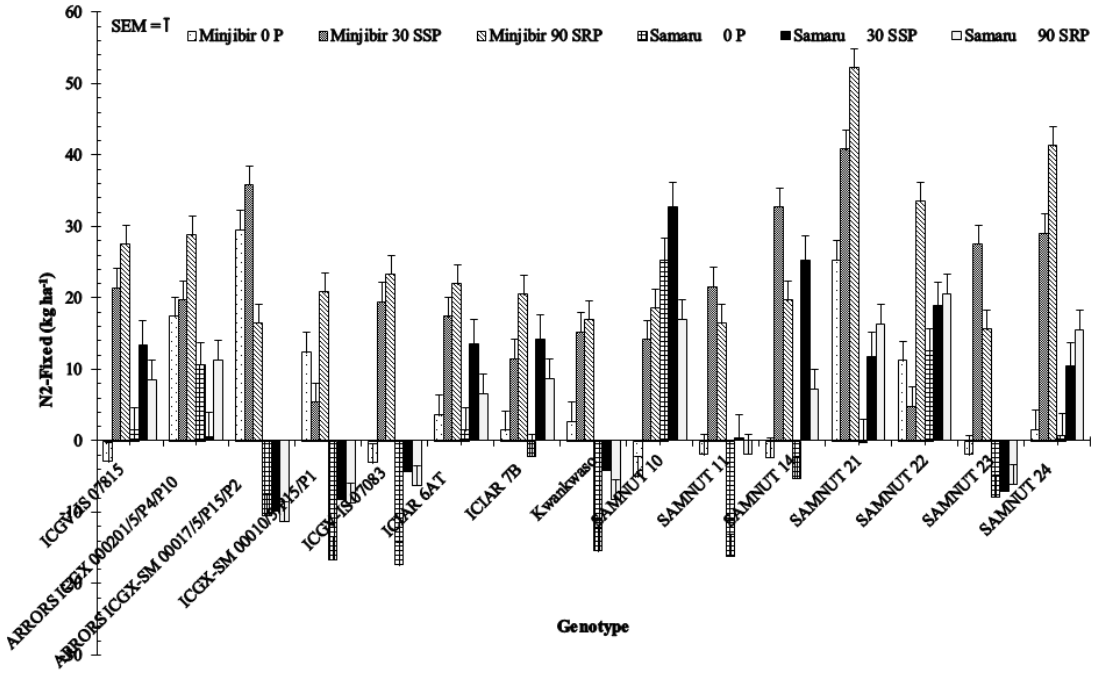



Figure 4.62: Genotype by phosphorus versus location interaction on $N_2$-fixed by the groundnuts

In a study, Moji *et al*. (2020) found fixed $N_2$ by groundnut genotypes that ranged between 5.30 kg ha$^{-1}$ and 94.73 kg ha$^{-1}$ in a Sudan savannah with a mean value of 44.10 kg ha$^{-1}$. In Samaru, the northern Guinea savannah however, the researchers observed the genotypes as having fixed a range of 5.23 kg ha$^{-1}$ to 140.27 kg ha$^{-1}$ with a mean value of 58.30 kg ha$^{-1}$, which was greater than the values reported by Agah *et al*. (2016) (*i.e.*, 20.71 kg ha$^{-1}$ and 11.24 kg ha$^{-1}$) and Okito *et al*. (2004) (*i.e.*, 40.9 kg ha$^{-1}$). The values were, however, lower than 96 kg ha$^{-1}$ that was reported by Burris, (1994). The amount of $N_2$-fixed in Moji *et al*. (2020)'s study, however, fell within the range of 17-200 kg N

$ha^{-1}$ for groundnut as in a report by Peoples *et al*. (2008) and Peoples and Craswell (1992). Same result was, however, in disagreement with Dakora (1997)'s who reported up to 134 kg N $ha^{-1}$ being the highest BNF value estimated as been fixed by legume crops contrary to the Moji *et al*. (2020)'s value of 140.27 kg N $ha^{-1}$ record. Other researchers (Patterson and La Rue, 1983; Hardarson *et al*., 1984) previously also reported significant variations in $N_2$ fixation between various groups of soya bean genotypes, but attributed the variations to host plant characteristic, which is principally controlled by the nitrogenase enzyme. Also, the wide variations observed in the amount of $N_2$ fixed by different groundnut genotypes depends on $N_2$ fixing capacity of the genotypes, the native fertility of the soil (Sanginga *et al*., 1997), the indigenous *rhizobia* spp. and the method of crop management (Okogun *et al*., 2005). This, partly, makes it clear that variations from optimum $N_2$ fixation, and Ndfa, recordable observations are very common.

Studies, conducted in the Nigerian savannah regions, indicated that P application at the rate 20 - 40 kg $ha^{-1}$ significantly improved groundnut' performances (Balasubramanian and Nnadi, 1980), however, general information on legumes' P requirements for optimum $N_2$-fixation in Sudano-Sahelian agro-ecological zone is lacking (Yakubu *et al*., 2010). Giller (2001) reported the N-fixing potential of cowpea, groundnut and soybean as 9 - 201; 21 - 206 and 55 - 188 kg N $ha^{-1}$ $year^{-1}$, respectively. However, low phosphorus content of the soil in Sudano-Sahelian region may restrict *rhizobia* population and legume root development, which in turn can affect their $N_2$ fixing potential (Kwari, 2005).

*4.10.2.5 Genotype by location interaction on Ndfa of the groundnuts*

There was a significant ($P \leq 0.01$) interaction of location by genotype on the N derived from the atmosphere (Ndfa) by the genotypes (Figure 4.63). Genotype SAMNUT 21 in Minjibir (52.70%), although statistically at par with some other genotypes across the two locations, significantly had the highest Ndfa. The lowest Ndfa was, however, recorded in SAMNUT 10 (18.87%), ICIAR 7B (23.09%), SAMNUT 11 (24.12%) and ICGV-IS 07083 (24.88%) in Minjibir; SAMNUT 14 (18.20%), ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (21%), ICIAR 6AT (22.84%) and ICGV-IS 07815 (23.38%) in Samaru; and ICIAR 7B in both Samaru (19.95% and Minjibir (23.09%). Whereas 40% of the genotypes [ICGX-SM 00010/5/$P_{15}$/$P_1$ (-99.48%), ARRORS ICGX-SM

00017/5/$P_{15}$/$P_2$ (-88.38%), ICGV-IS 07083 (-87.07%), Kwankwaso (-74.44%), SAMNUT 11 (-58.01%) and SAMNUT 23 (-44.97%) in Samaru contributed to net N losses and none was in Minjibir (Figure 4.63). Unlike ICIAR 7B, SAMNUT 22 performed significantly well in both locations especially Samaru where only 13% of the genotypes derived a significant N from the atmosphere. Up to 60% of the genotypes, however, significantly had a high Ndfa record as shown in Figure 4.63 (below).

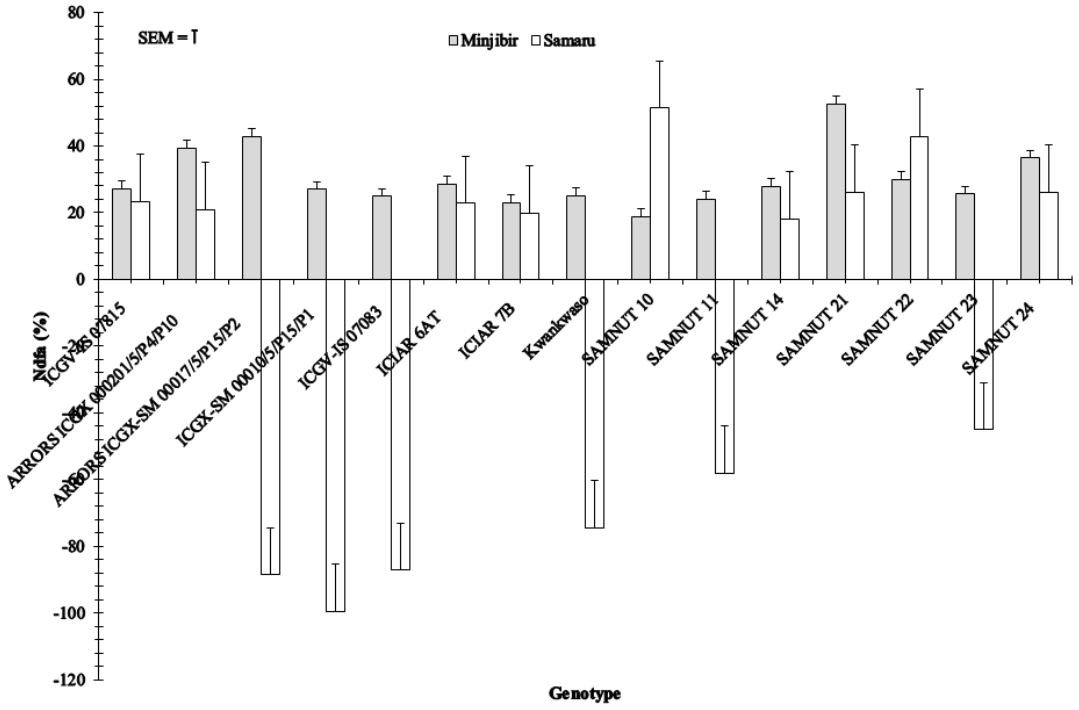



Figure 4.63: Genotype by location interaction on Ndfa of the groundnuts

*4.10.2.6 Phosphorus by location interaction on Ndfa of the groundnuts*

A significant ($P \leq 0.05$) location by P source interaction on the N derived from the atmosphere (Ndfa) by the genotypes was observed (Figure 4.64). Hence, the significantly highest N derived from the atmosphere under SRP (46%) followed by SSP (36%), both in Minjibir. The significantly lowest control (9%), in the same location, was statistically similar to the Ndfa in Samaru under SSP (7%) and SRP (2%). A net N loss of -49% was, however, observed under the control P source in Samaru location (Figure 4.64).

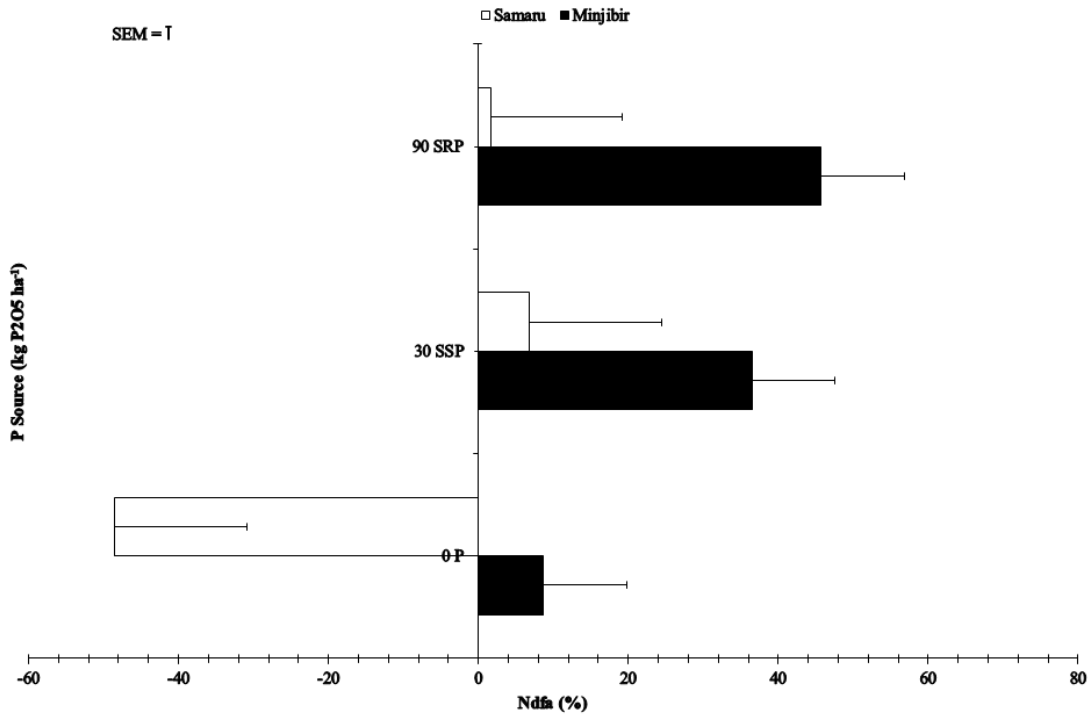



Figure 4.64: Phosphorus by location interaction on Ndfa of the groundnuts

*4.10.2.7 Genotype by phosphorus interaction on Ndfa of the groundnuts*

A significant ($P \leq 0.05$) genotype by P source interaction on the N derived from the atmosphere (Ndfa) by the genotypes was observed (Figure 4.65). Hence, the significantly highest N was observed to be derived from the atmosphere by SAMNUT 21 under SRP (53.62%). The genotype was at par with some other genotypes, in terms of the parameter, notably SAMNUT 22 (51.65%) and SAMNUT 24 (50.86%), both under SRP. Whereas only about 7% of the genotypes was observed to have a significant Ndfa under the control, up to 60% was observed under each of SSP and SRP. Conversely, up to 60% of them, under the control, aided in net N loss, whereas 20% and 13% were observed under SSP and SRP, respectively (Figure 4.65). This, therefore, buttressed the importance of P in Ndfa of the groundnut genotypes.

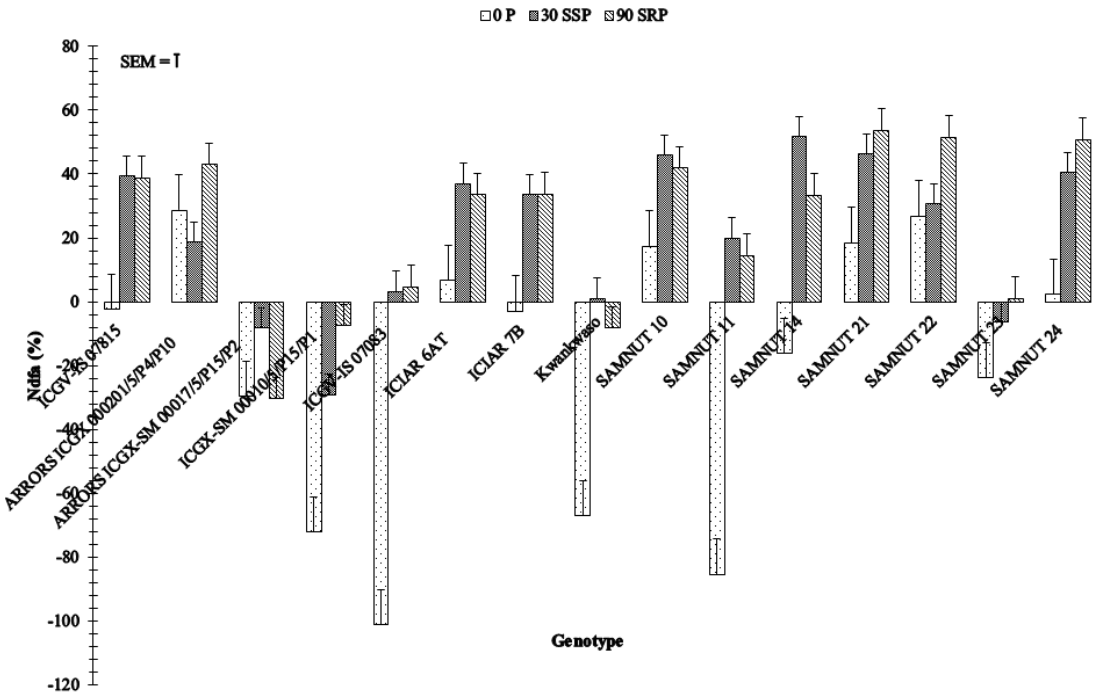



Figure 4.65: Genotype by phosphorus interaction on Ndfa of the groundnuts

*4.10.2.8 Genotype by phosphorus versus location interaction on Ndfa of the groundnuts*

There was a significant ($P \leq 0.05$) location by genotype versus P source interaction on the N derived from the atmosphere (Ndfa) by the genotypes (Figure 4.66) during the trial season. SAMNUT 21 (65.40%) under SRP in Minjibir derived the highest N from the atmosphere amongst the genotypes. The genotype was statistically at par with some other genotypes under the P sources across the agro-ecological locations. Notably amongst these genotypes were SSP-fertilised SAMNUT 10 (62.11%) and SRP-fertilised SAMNUT 24 (60.87%) in Samaru and Minjibir respectively. Also, 33% and 20% of the genotypes under the control, up to 93% and 53% under SSP; and 100% and 60% under SRP, respectively at Minjibir and Samaru, performed significantly ($P \leq 0.01$) well in terms of Ndfa. Generally, 33% of the genotypes performed well in both locations, and under all but one P source. About 27% of the genotypes (namely, ARRORS ICGX 000201/5/$P_4$/$P_{10}$, ICIAR 6AT, SAMNUT 22 and SAMNUT 24) contributed to a net N loss under at least two of the P sources. About 27% of the genotypes (namely, ICGV-IS 07815, ICIAR 7B, SAMNUT 10 and SAMNUT 21) contributed to a net N loss under at least one of the two P sources and the control as depicted by Figure 4.66.

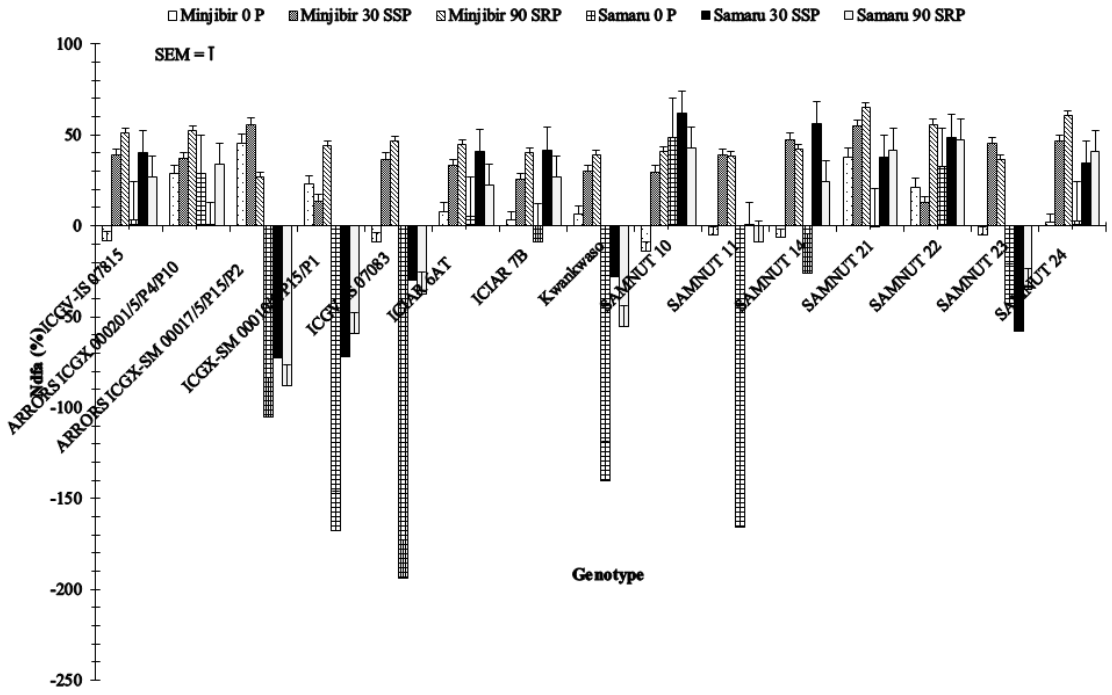



Figure 4.66: Genotype by phosphorus versus location interaction on Ndfa of the groundnuts

The negative $N_2$-fixation and Ndfa values observed in some genotypes was indicative of low responsive nature of the given soil to exogenous P application. This means that the BNF/Ndfa performance of such genotypes was not affected irrespective of P application (*i.e.*, with or without). This was vis-à-vis other location-specific factors, as Samaru had the highest record of genotypes with negative values of the two parameters. The soil in Minjibir was therefore more responsive to the applied P and hence the predominantly positive values observed in the genotypes' BNF and Ndfa records. The negative N parameters' scenario is, however, usually associated with marginal areas of the tropics, thereby causing a net mining of soil nutrients (*e.g.*, N) (Wani *et al*., 1995). This is usually due, mainly, to low levels of nutrients (N in this case), crop removal, leaching, *et cetera* (Sanchez, 1994). In addition to these, however, inherent $N_2$-fixing ability of the genotypes is also important (Kumar Rao, *et al*., 1996), which is partly due to maturity period difference (Yusuf *et al*., 2008).

*4.10.2.9 Genotype by location interaction on N uptake of the groundnuts*

The location by genotype interaction, on the N uptake of the groundnut genotypes, was significant ($P < 0.01$) as shown by Table 4.10 and Figure 4.67. Significantly more N uptake was observed for the genotypes in Minjibir than in Samaru. Hence, the highest N uptake record of 41.44% was observed, in Minjibir, for SAMNUT 21. It was, however,

statistically similar to ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (37.40%) in the same location. Following genotypes with the highest N uptake was ICGV-IS 07815 (31.31%), which was statistically similar to ICGX-SM 00010/5/$P_{15}$/$P_1$, ICGV-IS 07083, ICIAR 6AT, Kwankwaso, SAMNUT 10 and SAMNUT 11. These were followed by the control in Minjibir, and which was followed by SRP in Samaru.

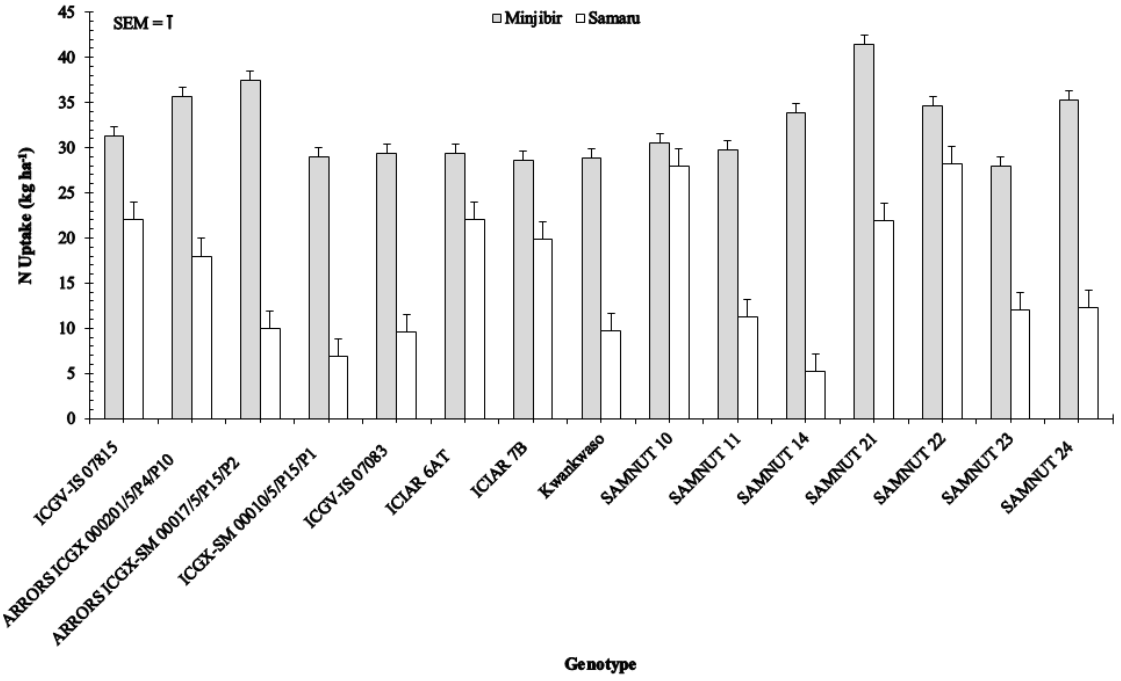



Figure 4.67: Genotype by location interaction on N uptake of the groundnuts

The overall significantly lowest N uptake was recorded in Samaru in SAMNUT 14 (5.37 kg $ha^{-1}$). This genotype was, however, statistically similar to some other genotypes, such as ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, ICGX-SM 00010/5/$P_{15}$/$P_1$, SAMNUT 11 and SAMNUT 24, as also indicated by Figure 4.67 (above).

*4.10.2.10 Phosphorus by location interaction on N uptake of the groundnuts*

There was a significant ($P < 0.01$) interaction of location and P source on the N uptake of the genotypes (Table 4.10 and below). The SSP and SRP P sources in Minjibir were statistically similar and had the highest contribution to the genotypes in terms of their N uptake. These were followed by the control P source at the same Minjibir and were followed by SRP P source in Samaru. The least contribution was made by SSP and control P sources, both in Samaru (Figure 4.68 below).

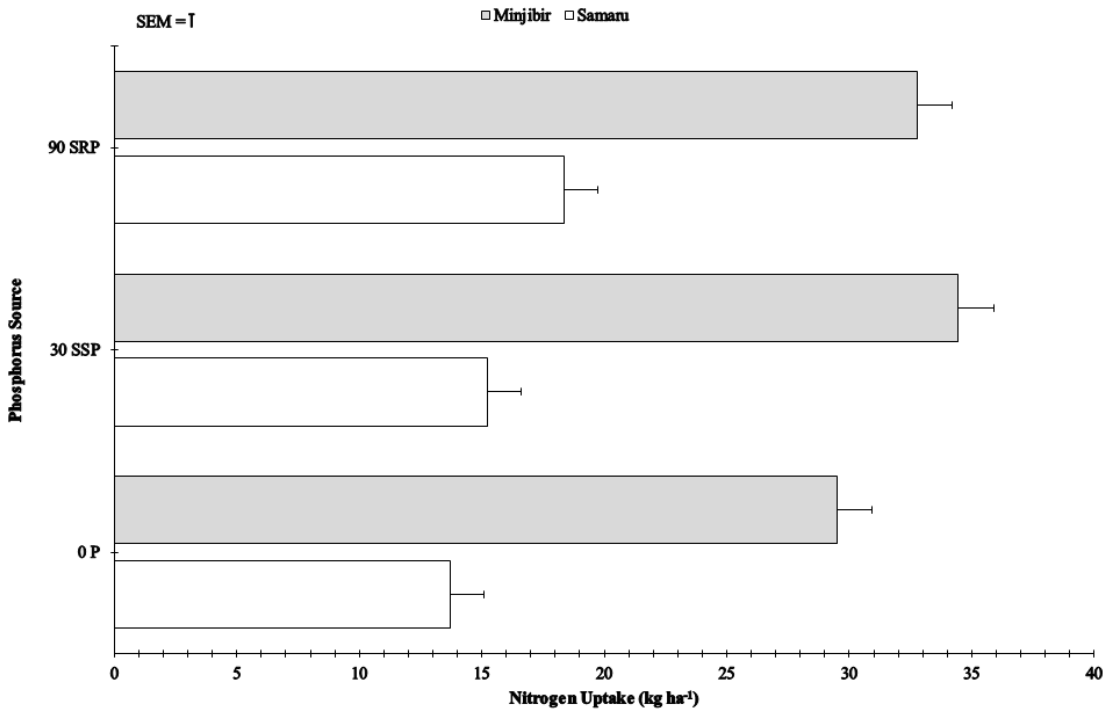



Figure 4.68: Phosphorus by location interaction on N uptake of the groundnuts

*4.10.2.11 Genotype by phosphorus interaction on N uptake of the groundnuts*

The interaction of genotype versus P source on the N uptake of the genotypes was significantly ($P \leq 0.05$) different. SAMNUT 22 (36.28kg $ha^{-1}$) under SRP had the highest N uptake and was statistically similar to many other genotypes across all P sources. ICGV-IS 07083, however, had the lowest N uptake, although also at similar to some other genotypes (Table 4.10 and Figure 4.69).

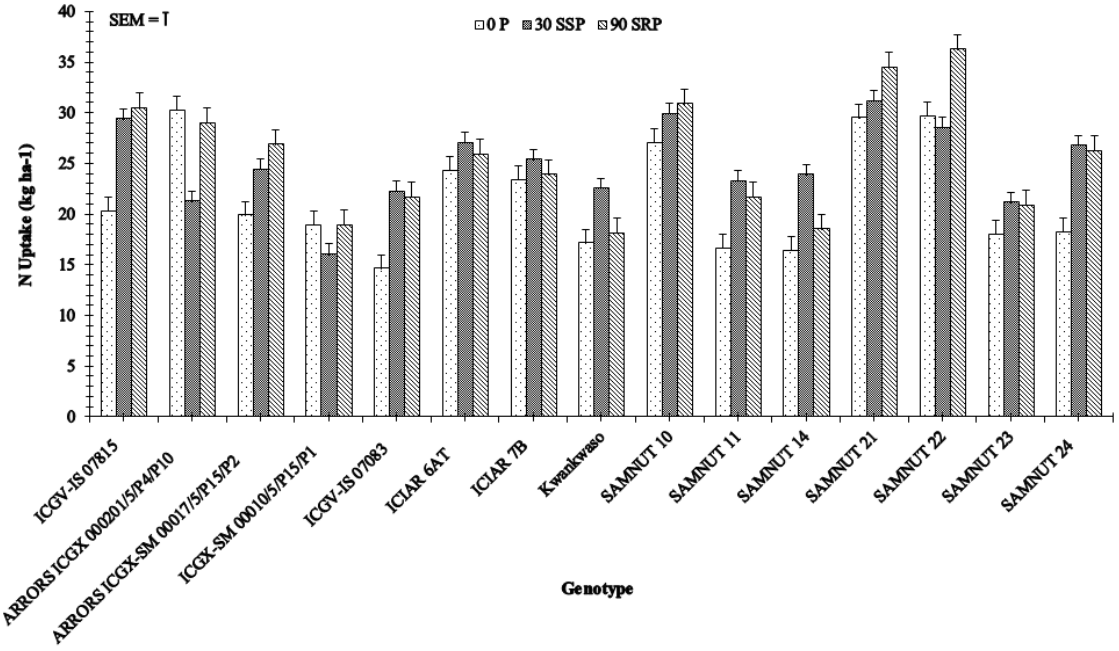



Figure 4.69: Genotype by phosphorus interaction on N uptake of the groundnuts

#### *4.10.2.12 Genotype by phosphorus versus location interaction on N uptake of the groundnuts*

Significant ($P \leq 0.01$) interaction of location, genotype and P source was observed in terms of N uptake by the genotypes in both locations (Figure 4.70**)**. Although SAMNUT 21 was statistically similar to many other genotypes, it had the highest numerical value of $N_2$ fixation recorded in Minjibir under SRP. SAMNUT 14 in Samaru under the control had the overall least $N_2$ fixation record, although still at par with many other genotypes under all the P sources, specifically, in Samaru (Figure 4.70).

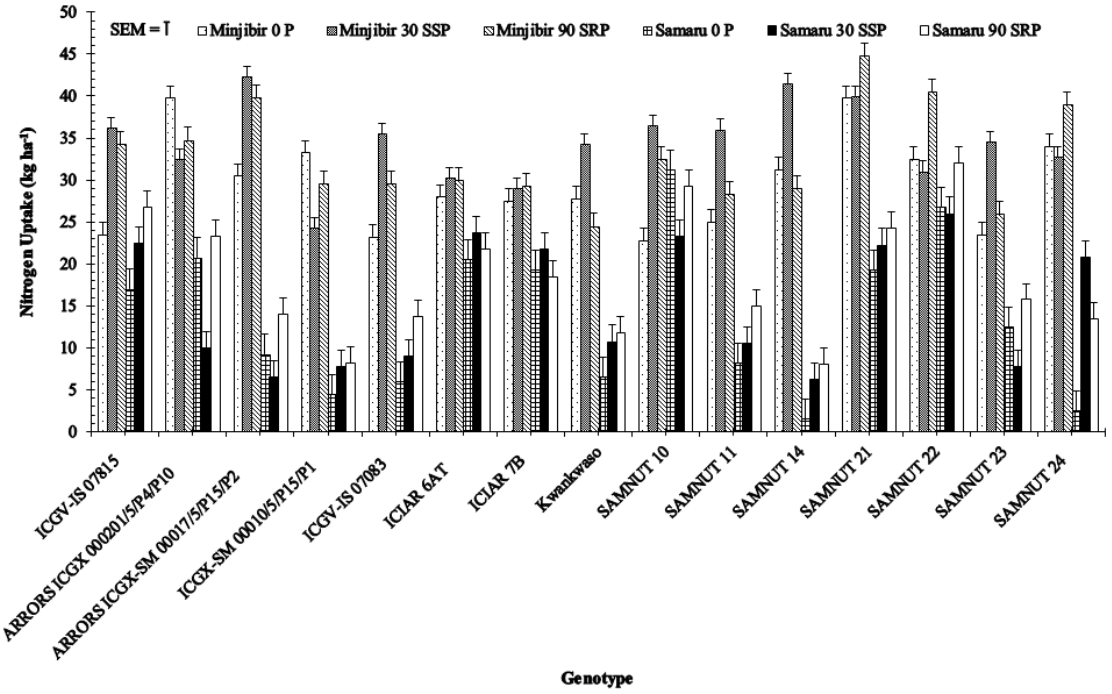



Figure 4.70: Genotype by phosphorus versus location interaction on N uptake of the groundnuts

## 4.11 Effects of Location, Genotype and Phosphorus on the Activities of Amidohydrolase (Urease) and Phosphomonoesterases in the Soils

### 4.11.1 Effects of location, genotype and phosphorus on the activities of amidohydrolase (urease) and phosphomonoesterases in the soils

There were significant ($P \leq 0.01$) contributions of location, genotype and P source on the activities of amidohydrolase (urea) and phosphomonoesterases (acid and alkaline phosphatases). Activities of the enzymes, urease, acid phosphatase (AcPhase) and alkaline phosphatase (AkPhase) were observed to be significantly higher ($P \leq 0.05$) in Minjibir than Samaru (Table 4.11). This may partly be due to the relatively higher organic carbon content in the Minjibir, compared to Samaru, soil. This further translated to organic matter content difference between the two soils, which was relatively higher in Minjibir (Table 4.11), thereby ensuring the higher urease (Özdemir *et al*., 2000) and phosphomonoesterases (Reddy *et al*., 2020) contents in Minjibir than Samaru soils. Urease enzyme activities were also observed by Dkhar and Mishra (1983) to always be higher in soils of relatively continuous cropping, like as in Minjibir, than those in shifting agriculture. Also, Agbenin (1995) explained that quantitative and qualitative C

distribution in soils is a precondition to such soil physicochemical properties as bulk density, cation exchange capacity (CEC), and availability of N, P, sulphur (S), *et cetera*.

Kwankwaso recorded the highest urease activity of 430.67 mg $NH_4^+$-N $l^{-1}$ and it was followed by ICIAR 7B (399.46 mg $NH_4^+$-N $l^{-1}$), which was in turn followed by SAMNUT 24 (379.38 mg $NH_4^+$-N $l^{-1}$) and SAMNUT 23 (378.00 mg $NH_4^+$-N $l^{-1}$) (Table 4.11). The genotype ICGV-IS 07815 (-11.79 mg $NH_4^+$-N $l^{-1}$), followed by ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (163.17 mg $NH_4^+$-N $l^{-1}$), however, recorded the least activity of the enzyme. The genotypes Kwankwaso (191.25 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and ICGV-IS 07083 (187.58 µg *p*NPP $g^{-1}$soil $hr^{-1}$) outperformed all the other genotypes in soil AcPhase activity (Table 4.11). They were followed by SAMNUT 23, which was statistically similar to ICIAR 6AT, ICIAR 7B and SAMNUT 24. ARRORS ICGX 000201/5/$P_4$/$P_{10}$ had the lowest soil AcPhase activity of 109.78 µg *p*NPP $g^{-1}$soil $hr^{-1}$ and was statistically similar to ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (118.93 µg *p*NPP $g^{-1}$soil $hr^{-1}$). In terms of AkPhase, SAMNUT 24 (375.51 µg *p*NPP $g^{-1}$soil $hr^{-1}$) outperformed all other genotypes and was followed by SAMNUT 23 (290.30 µg *p*NPP $g^{-1}$soil $hr^{-1}$). The least genotype was SAMNUT 22 (with 135.69 µg *p*NPP $g^{-1}$soil $hr^{-1}$).

The contributions of SSP and SRP sourced P to all the soil enzymatic activities were significantly different. Highest urease activity, of 283.73 mg $NH_4^+$-N $l^{-1}$, was recorded under the control, followed by SSP (275.38 mg $NH_4^+$-N $l^{-1}$) and then by SRP (260.08 mg $NH_4^+$-N $l^{-1}$) P sources. This agrees with Baligar *et al*. (2005) who reported that an increase in a fertiliser P level, applied resulted into a decrease in urease activity. There was also no significant difference between the P sources in terms of AcPhase activity, as all the sources were statistically at par with SSP. Soil treated with SRP had the lowest AcPhase activity (Table 4.11). Significantly highest AkPhase activity was observed under SRP (192.64 µg *p*NPP $g^{-1}$soil $hr^{-1}$). It was followed by the control (182.51 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and SSP had the lowest (178.94 µg *p*NPP $g^{-1}$soil $hr^{-1}$) (Table 4.11). All the interactions, for all the enzymes observed, were significant at $P \leq 0.01$ probability levels (Table 4.11).

### 4.11.2 Genotype by phosphorus versus location interaction on the activities of an amidohydrolase (urease) and phosphomonoesterases

*4.11.2.1 Genotype by location interaction on urease activity*

There was a significant ($P \leq 0.01$) difference between the genotypes in terms of location versus genotype interaction in the urease activity of soils. In that, Kwankwaso, in Samaru, had the highest record of urease activity.

Table 4.11: Effects of location, genotype and P source on the activities of an amidohydrolase (urease) and phosphomonoesterases

| Treatment | Urease (mg $NH_4^+$-N $l^{-1}$) | Acid Phosphatase (µg *p*NPP $g^{-1}$soil $hr^{-1}$) | Alkaline Phosphatase (µg *p*NPP $g^{-1}$soil $hr^{-1}$) |
|---|---|---|---|
| **Location (L)** | | | |
| Minjibir | 291.79$^{a}$ | 153.12$^{a}$ | 188.50$^{a}$ |
| Samaru | 254.32$^{b}$ | 143.26$^{b}$ | 180.89$^{b}$ |
| SE± | 0.377 | 0.819 | 0.459 |
| **Genotype (G)** | | | |
| ICGV-IS 07815 | -11.42$^{m}$ | 144.67$^{de}$ | 164.11$^{e}$ |
| ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 163.17$^{m}$ | 109.78$^{g}$ | 153.44$^{f}$ |
| ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 196.92$^{i}$ | 118.93$^{fg}$ | 162.85$^{e}$ |
| ICGX-SM 00010/5/$P_{15}$/$P_1$ | 281.46$^{g}$ | 147.38$^{de}$ | 160.00$^{e}$ |
| ICGV-IS 07083 | 283.75$^{g}$ | 187.58$^{a}$ | 200.85$^{c}$ |
| ICIAR 6AT | 363.13$^{d}$ | 161.09$^{bc}$ | 164.08$^{e}$ |
| ICIAR 7B | 399.46$^{b}$ | 155.40$^{b-d}$ | 150.81$^{f}$ |
| Kwankwaso | 430.67$^{a}$ | 191.25$^{a}$ | 196.43$^{c}$ |
| SAMNUT 10 | 171.58$^{k}$ | 148.65$^{de}$ | 143.42$^{g}$ |
| SAMNUT 11 | 180.88$^{j}$ | 141.21$^{e}$ | 148.03$^{fg}$ |
| SAMNUT 14 | 254.42$^{h}$ | 147.69$^{de}$ | 151.41$^{f}$ |
| SAMNUT 21 | 293.75$^{f}$ | 127.88$^{f}$ | 173.53$^{d}$ |
| SAMNUT 22 | 330.75$^{e}$ | 126.20$^{f}$ | 135.69$^{h}$ |
| SAMNUT 23 | 378.00$^{c}$ | 163.76$^{b}$ | 290.30$^{b}$ |
| SAMNUT 24 | 379.38$^{c}$ | 151.35$^{b-d}$ | 375.51$^{a}$ |
| SE± | 1.033 | 2.243 | 1.257 |
| **Phosphorus Source (P, kg $P_2O_5$ $ha^{-1}$)** | | | |
| 0 P | 283.73$^{a}$ | 149.71$^{a}$ | 182.51$^{b}$ |
| 30 SSP | 275.38$^{b}$ | 148.54$^{ab}$ | 178.94$^{c}$ |
| 90 SRP | 260.08$^{c}$ | 146.31$^{b}$ | 192.64$^{a}$ |
| SE± | 0.462 | 1.003 | 0.562 |
| **Interactions** | | | |
| L x G | ** | ** | ** |
| L x P | ** | ** | ** |
| G x P | ** | ** | ** |
| L x G x P | ** | ** | ** |

**=Significant at 1% level of probability; Means followed by same letter(s) within a treatment in a column do not differ significantly according to Tukey's honest significant difference (HSD).

It was followed by SAMNUT 23 in Minjibir, which was in turn followed by ICIAR 7B in Samaru. Significantly lowest soil urease activity was recorded in ICGV-IS 07815 in Samaru (-21.69 mg $NH_4^+$-N $l^{-1}$) followed by the same genotype in Minjibir (-1.07 mg $NH_4^+$-N $l^{-1}$) as shown in Figure 4.71.

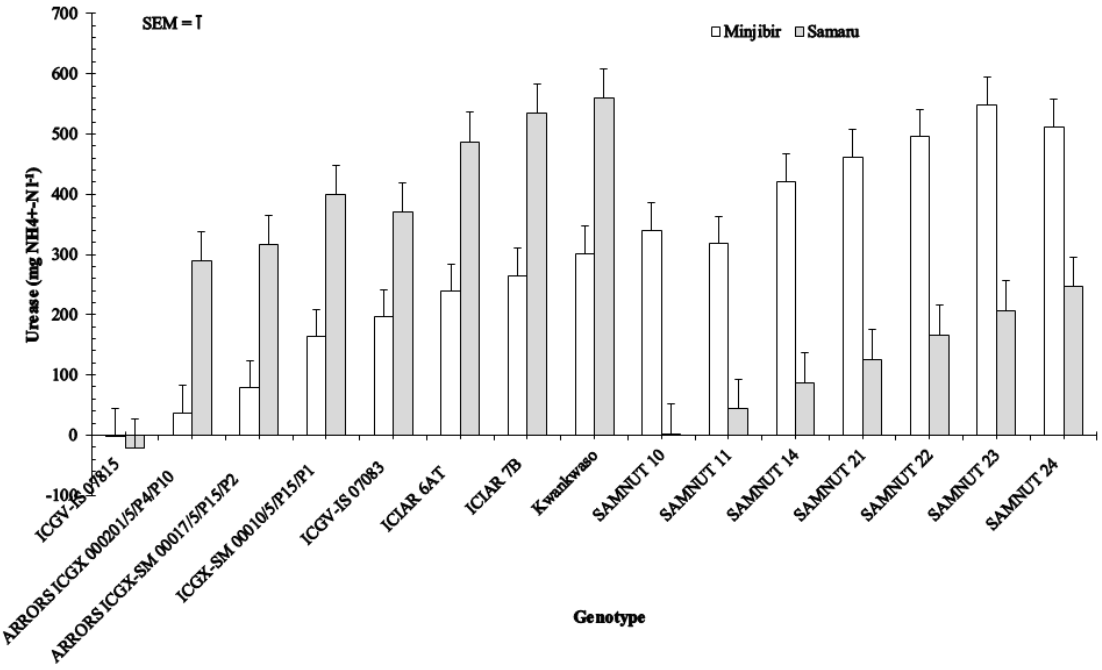



Figure 4.71: Genotype by location interaction on urease activity

*4.11.2.2 Phosphorus by location interaction on urease activity*

There was also a significant ($P \leq 0.01$) location by P source interaction on the genotypes in terms of soil urease activity (Figure 4.72). Hence, a significantly highest activity of the enzyme was observed in Minjibir under the control (306.81 mg $NH_4^+$-N $l^{-1}$), which was followed by SSP (290.47 mg $NH_4^+$-N $l^{-1}$) and lastly by SRP (277.67 mg $NH_4^+$-N $l^{-1}$). These were followed by statistically similar control and SSP P sources (260.40 and 259.98 mg $NH_4^+$-N $l^{-1}$, respectively) in Samaru. The least urease activity was, however, recorded in Samaru under SRP (Figure 4.72).

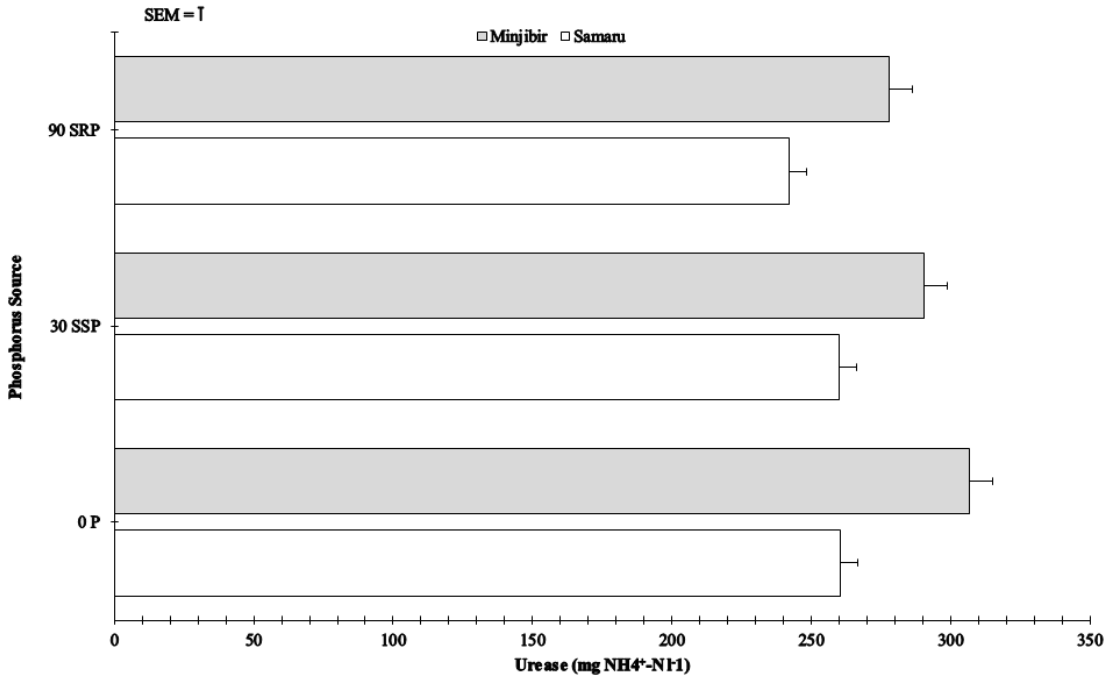



Figure 4.72: Phosphorus by location interaction on urease activity

*4.11.2.3 Genotype by phosphorus interaction on urease activity*

The genotype by P source interaction on the soil urease activity was significant ($P \leq 0.01$) as indicated in Table 4.11. Hence, Kwankwaso had the highest values of 432.28, 429.94 and 429.47 mg $NH_4^+$-N $l^{-1}$, respectively under the control, SRP and SSP; and SAMNUT 24, under the control and SSP (Figure 4.73). ICIAR 7B under the control (405.44 mg $NH_4^+$-N $l^{-1}$) and SSP (398.06 mg $NH_4^+$-N $l^{-1}$), but were statistically similar to what was recorded for the same ICIAR 7B under SRP (394.19 mg $NH_4^+$-N $l^{-1}$). ICGV-IS 07815, under all the P sources (*i.e.*, -19.22, -8.82 and -6.09 mg $NH_4^+$-N $l^{-1}$, respectively under SRP, the control and SSP P source) had the least urease activity recorded (Figure 4.73).

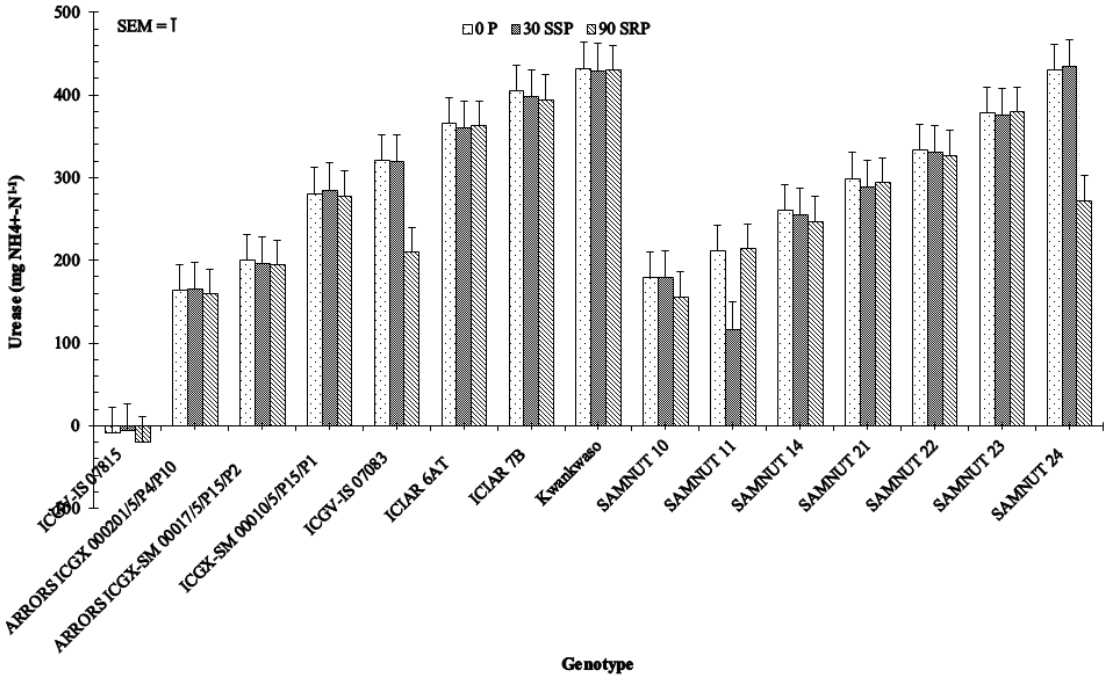



Figure 4.73: Genotype by phosphorus interaction on urease activity

*4.11.2.4 Genotype by phosphorus versus location interaction on urease activity*

There was a significant ($P \leq 0.01$) location by genotype versus P source interaction on the genotypes in terms of the soil enzyme, urease (Table 4.11). SAMNUT 24, under SSP (624.50 mg $NH_4^+$-N $l^{-1}$) and the control (616.63 mg $NH_4^+$-N $l^{-1}$) both in Minjibir, outperformed all other genotypes under all the P sources (Figure 4.74). Following SAMNUT 24 under these P sources (control and SSP) was Kwankwaso in Samaru under all the sources of P (560.60, 560.00 and 558.69 SSP (624.50 mg $NH_4^+$-N $l^{-1}$), under SSP, the control and SRP, respectively). Kwankwaso, under those P sources, was similar to SAMNUT 23 under SRP (550.94 SSP (624.50 mg $NH_4^+$-N $l^{-1}$) and 0 (552.06 SSP (624.50 mg $NH_4^+$-N $l^{-1}$) sources of P. The lowest soil urease activity was observed for ICGV-IS 07815 under SSP (-18.00 mg $NH_4^+$-N $l^{-1}$) and the control (-25.06 mg $NH_4^+$-N $l^{-1}$) in Samaru; and under SRP in Samaru (-22.00 mg $NH_4^+$-N $l^{-1}$) and Minjibir (-16.44 mg $NH_4^+$-N $l^{-1}$) (Figure 4.74).

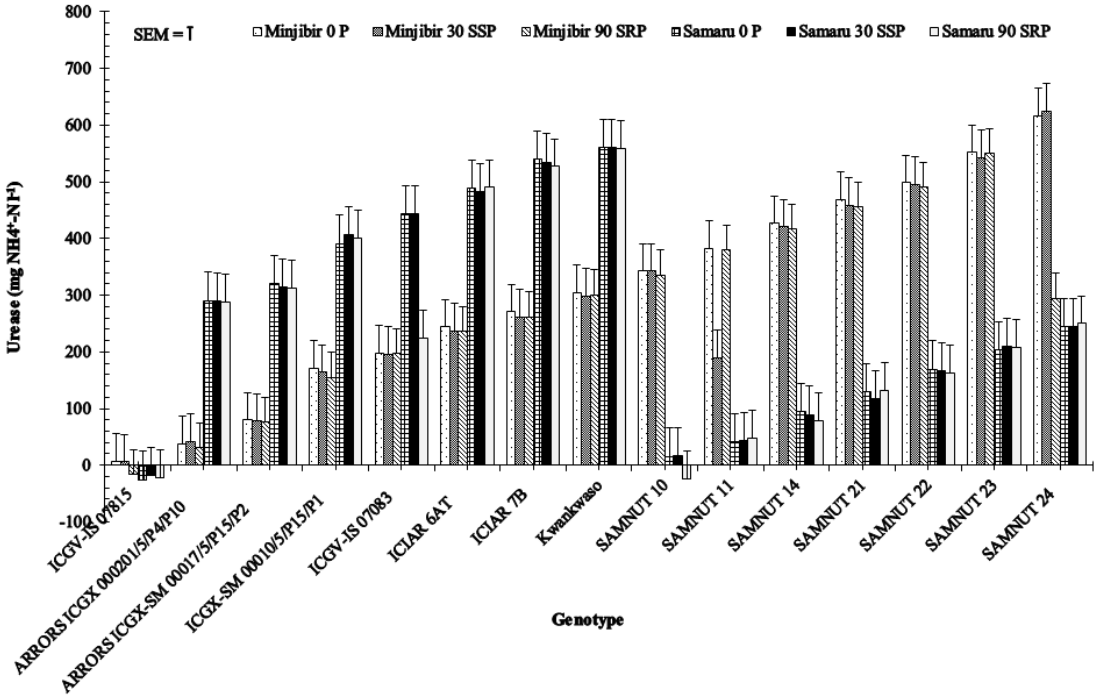



Figure 4.74: Genotype by phosphorus versus location interaction on urease activity

*4.11.2.5 Genotype by location interaction on AcPhase activity*

There was a significant ($P \leq 0.01$) location versus genotype interaction on the genotypes in terms of soil acid phosphatase (AcPhase) activity (Table 4.11 and Figure 4.75). In that, SAMNUT 23, SAMNUT 24 and ICGV-IS 07083 in Minjibir, and Kwankwaso, in Samaru, outperformed all other genotypes, and were followed by SAMNUT 22 in Minjibir, which was statistically similar to Kwankwaso in Minjibir; and ICGV-IS 07083, ICIAR 6AT, ICIAR 7B and SAMNUT 10 in Samaru. The lowest AcPhase activity was, however, recorded for SAMNUT 22 in Samaru (Figure 4.75).

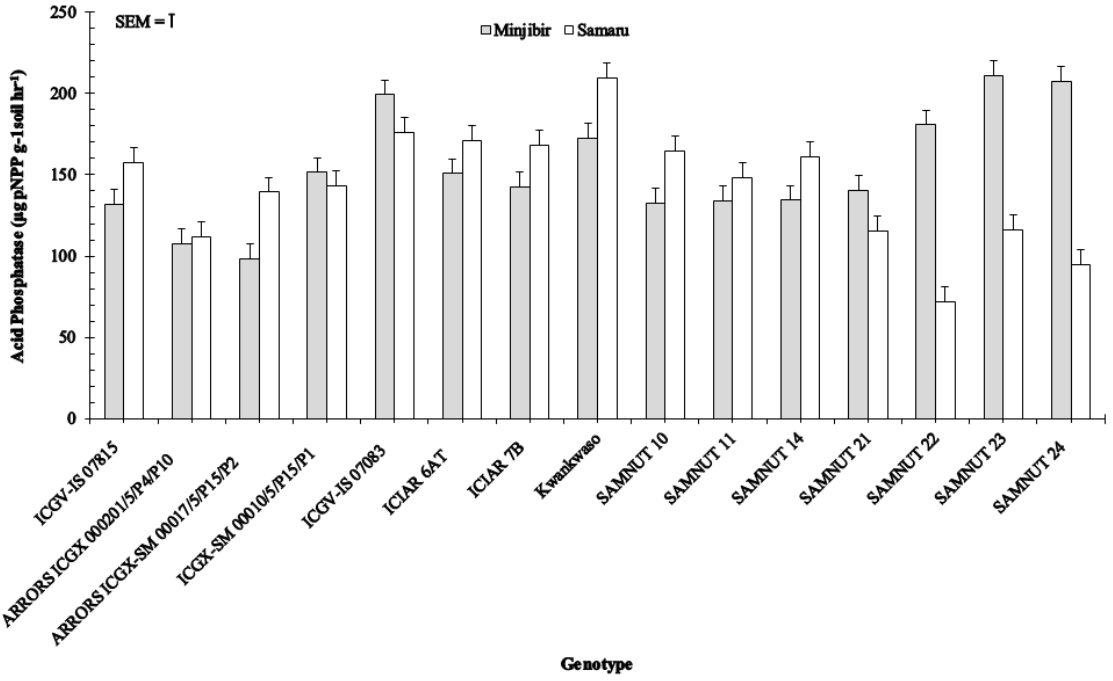



Figure 4.75: Genotype by location interaction on AcPhase activity

*4.11.2.6 Phosphorus by location interaction on AcPhase activity*

There was also a significant ($P \leq 0.01$) location by P source interaction on the genotypes in terms of soil AcPhase activity (Table 4.11). Higher AcPhase activity was, generally, observed in Minjibir than Samaru. More activity was numerically observed in Minjibir (155.49 µg *p*NPP $g^{-1}$soil $hr^{-1}$) under SSP, although was statistically similar with the two other P sources in the location. The lowest activity was, however, observed under SRP (141.15 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Samaru, although it was statistically at par with the other sources in that location (Table 4.11 and Figure 4.76 ).

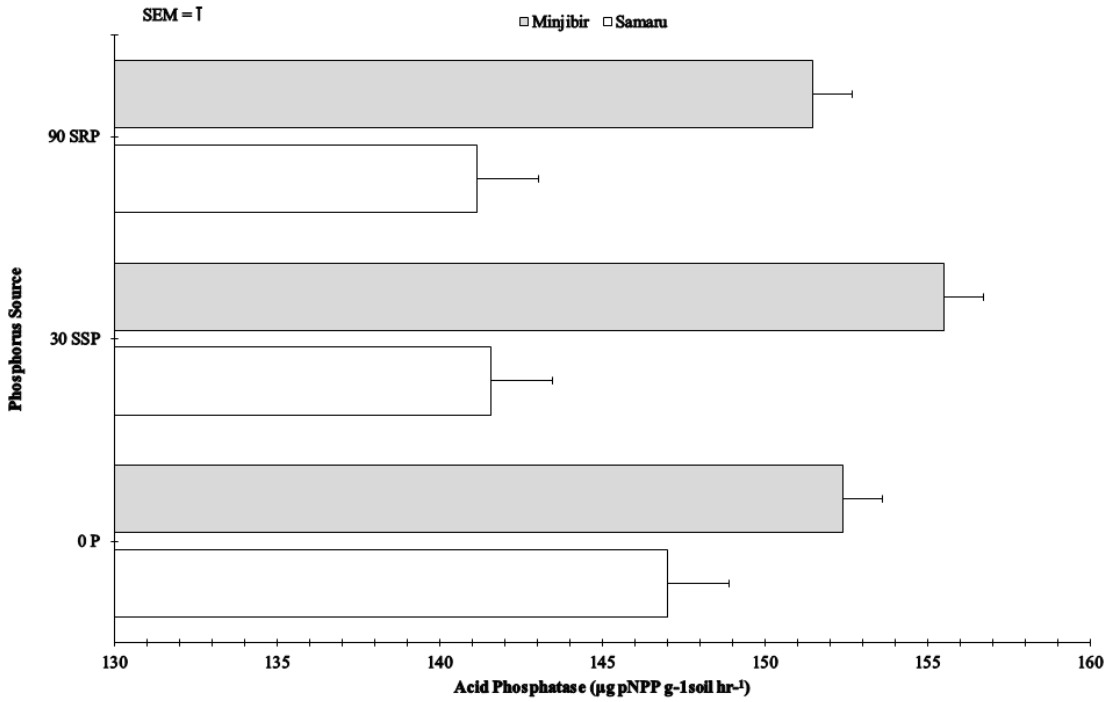



Figure 4.76: Phosphorus by location interaction on AcPhase activity

*4.11.2.7 Genotype by phosphorus interaction on AcPhase activity*

Significant ($P \leq 0.01$) genotype by P source interaction was observed, in terms of the AcPhase recorded, for the genotypes (Table 4.11). The statistically similar SAMNUT 24 (230.94 µg *p*NPP $g^{-1}$soil $hr^{-1}$) under SSP and ICGV-IS 07083 under the control (220.35 µg *p*NPP $g^{-1}$soil $hr^{-1}$), which in turn was similar to ICGV-IS 07083 under SRP (218.29 µg *p*NPP $g^{-1}$soil $hr^{-1}$) outperformed all the genotypes in the soils' AcPhase activity (Figure 4.77). The lowest AcPhase activity was, however, recorded in ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (90.89 µg *p*NPP $g^{-1}$soil $hr^{-1}$) under the control source, which was statistically not different from ARRORS ICGX 000201/5/$P_4$/$P_{10}$ under SRP (106.31 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and; ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ (100.97 µg *p*NPP $g^{-1}$soil $hr^{-1}$), under SSP; and SAMNUT 22 (111.25 µg *p*NPP $g^{-1}$soil $hr^{-1}$), SAMNUT 23 (106.94 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and SAMNUT 24 (102.21 µg *p*NPP $g^{-1}$soil $hr^{-1}$) all under SRP (Figure 4.77).

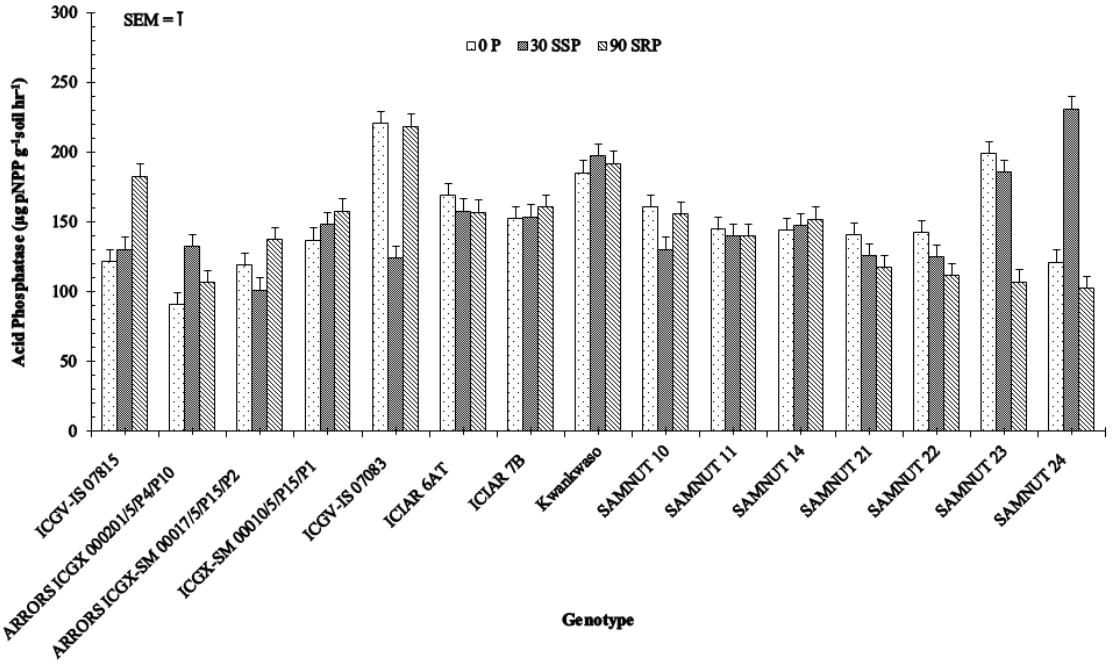



Figure 4.77: Genotype by phosphorus interaction on AcPhase activity

*4.11.2.8 Genotype by phosphorus versus location interaction on AcPhase activity*

A significant ($P \leq 0.01$) location and genotype versus P source interaction, in terms of AcPhase, was observed (Table 4.11). SAMNUT 24, under SSP (358.64 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Minjibir, outperformed all other genotypes under all the P sources (Figure 4.78) and was followed by SAMNUT 23, also under SSP (267.75 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and ICGV-IS 07083, under the control (260.96 µg *p*NPP $g^{-1}$soil $hr^{-1}$). These were statistically non-different from ICGV-IS 07083 under SRP (257.67 µg *p*NPP $g^{-1}$soil $hr^{-1}$), both in Minjibir. The lowest AcPhase activity of 67.45 µg *p*NPP $g^{-1}$soil $hr^{-1}$ was recorded in ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ in Minjibir, under SSP Figure 4.78). This same genotype (ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$) under SSP in Minjibir was also statistically akin to ICGV-IS 07815 and ARRORS ICGX 000201/5/$P_4$/$P_{10}$ under the control and SRP; and ICGV-IS 07083 under SSP, all in Minjibir; and same ARRORS ICGX 000201/5/$P_4$/$P_{10}$, SAMNUT 22 and SAMNUT 24 under the control, SAMNUT 22 under SSP and SAMNUT 21, SAMNUT 22, SAMNUT 23 and SAMNUT 24, all under SRP and in Samaru (Figure 4.78).

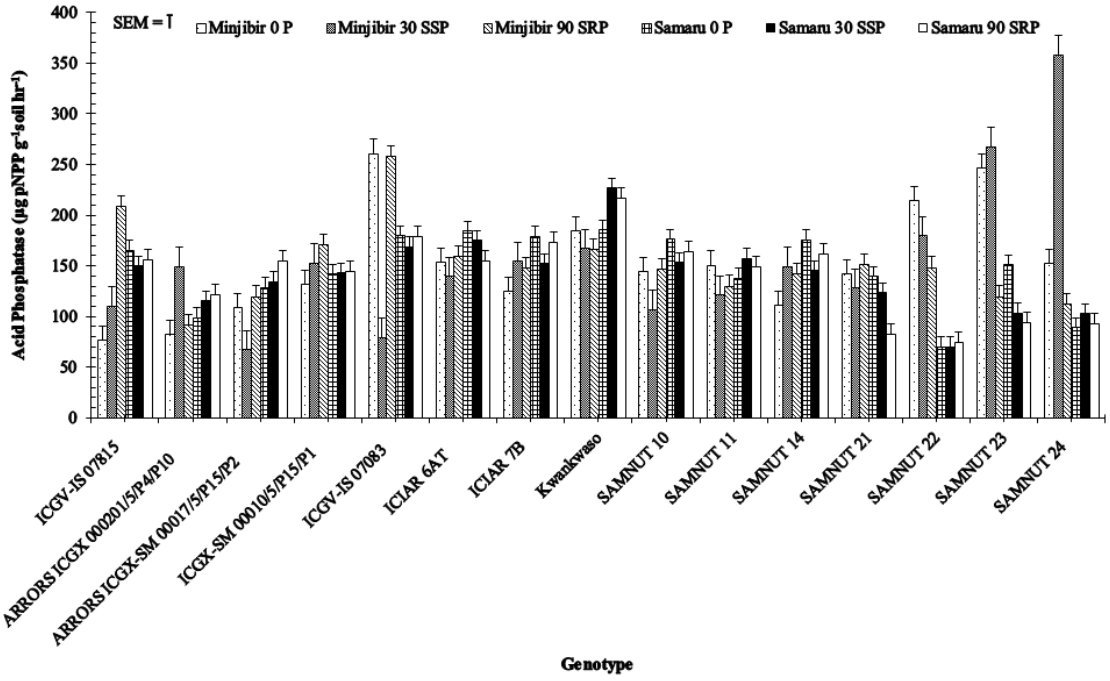



Figure 4.78: Genotype by phosphorus versus location interaction on AcPhase activity

*4.11.2.9 Genotype by location interaction on AkPhase activity*

The location by genotype interaction on the genotypes in terms of soil alkaline phosphatase (AkPhase) activity was also significant ($P \leq 0.01$) (Figure 4.79). Therefore, SAMNUT 24 (562.78 µg *p*NPP $g^{-1}$soil $hr^{-1}$) outperformed all the other genotypes and was followed by SAMNUT 23 (452.14 µg *p*NPP $g^{-1}$soil $hr^{-1}$). The lowest AkPhase activity was, however, recorded in ICIAR 7B also in Minjibir (108.44 µg *p*NPP $g^{-1}$soil $hr^{-1}$), which was statistically similar to SAMNUT 10 (111.25 µg *p*NPP $g^{-1}$soil $hr^{-1}$), also in Minjibir. None of the genotypes in Samaru was statistically comparable to its highest performed Minjibir counterpart (Figure 4.79). However, Kwankwaso in Samaru (265.58 µg *p*NPP $g^{-1}$soil $hr^{-1}$) followed the second highest genotype in Minjibir (SAMNUT 23, 452.14 µg *p*NPP $g^{-1}$soil $hr^{-1}$). SAMNUT 21 (127.36 µg *p*NPP $g^{-1}$soil $hr^{-1}$) was the lowest in Samaru (Figure 4.79).

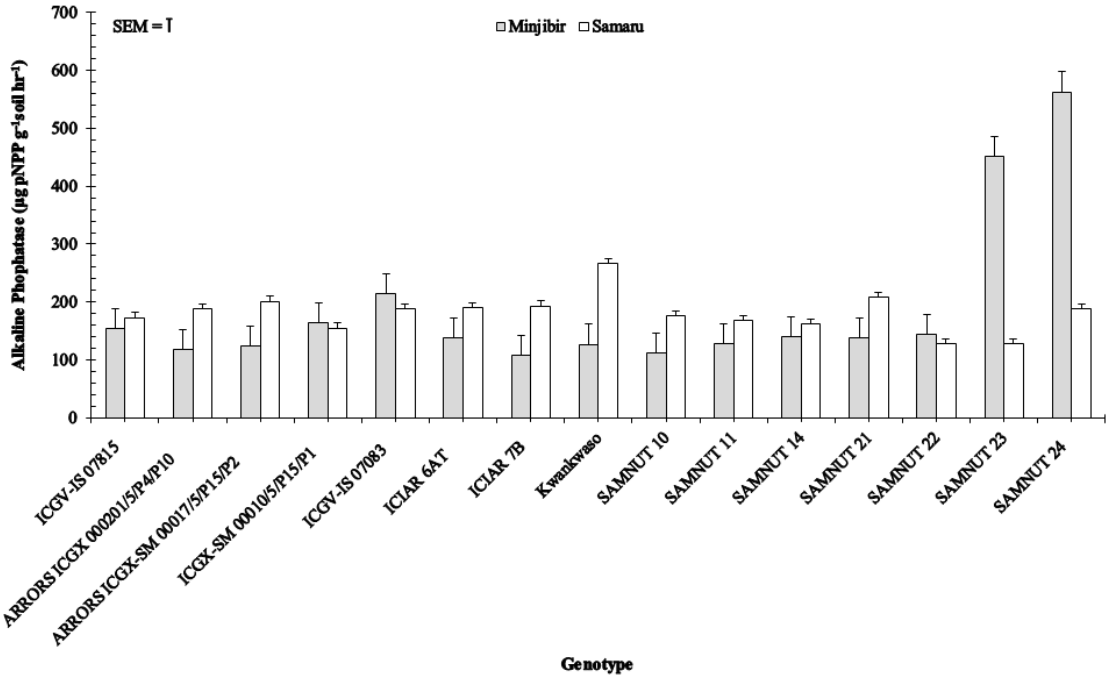



Figure 4.79: Genotype by location interaction on AkPhase activity

#### *4.11.2.10 Phosphorus by location interaction on AkPhase activity*

There was significant ($P \leq 0.01$) location by P source interaction on the genotypes in terms of soil AkPhase activity (Table 4.11). Highest AkPhase activity was recorded under SRP (208.29 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Minjibir. It was followed by statistically similar control P (182.55 µg *p*NPP $g^{-1}$soil $hr^{-1}$), in Minjibir; and control (182.47 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and SSP (183.21 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Samaru. Statistically lowest AkPhase activity was recorded in statistically similar, SSP (174.67 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Minjibir and SRP (176.98 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Samaru (Figure 4.80).

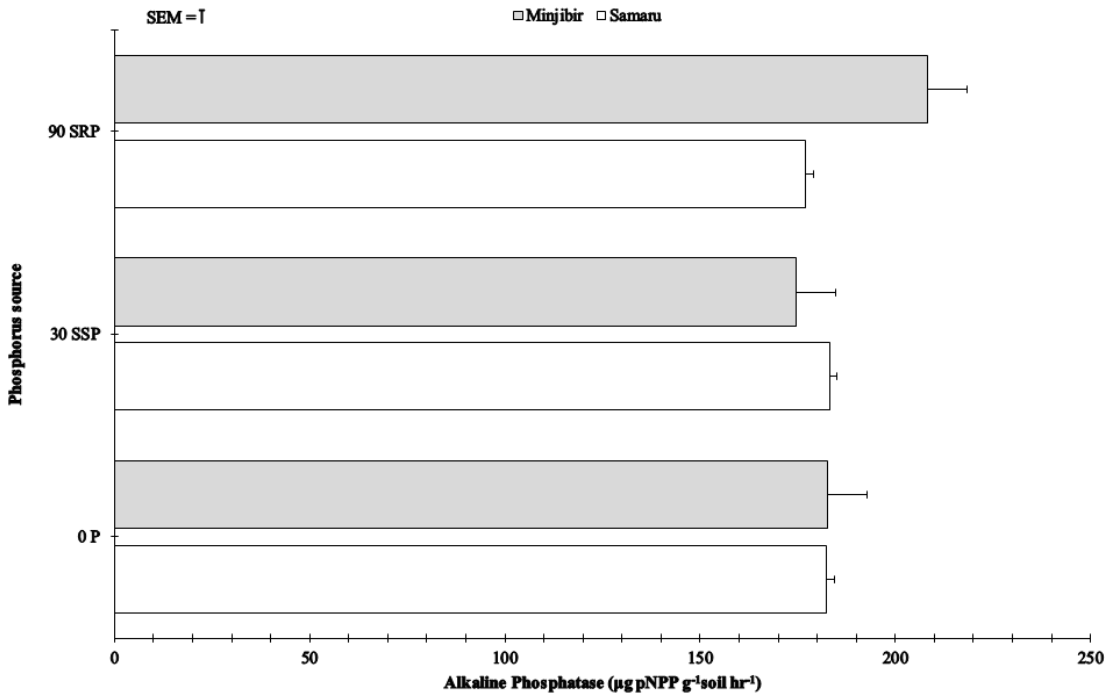



Figure 4.80: Phosphorus by location interaction on AkPhase activity

*4.11.2.11 Genotype by phosphorus interaction on AkPhase activity*

Statistically significant ($P \leq 0.01$) genotype by P source interaction was observed amongst the genotypes in terms of AkPhase activity of the soils (Table 4.11). In that, SAMNUT 24 under all the P sources (*i.e.,* 377.87, 374.54 and 374.07 µg *p*NPP $g^{-1}$soil $hr^{-1}$), respectively, under the control, SSP and SRP) outperformed all other genotypes. SAMNUT 23 followed the SAMNUT 24, in which, it had the second (335.82 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and third (268.16 and 266.93 µg *p*NPP $g^{-1}$soil $hr^{-1}$) preponderance in the enzyme record, respectively under SRP and; control and SSP sources of P (Figure 4.81). SAMNUT 23, under the control and SSP was, however, not significantly different ($P \geq 0.05$) from ICGV-IS 07083 under SRP (268.24 µg *p*NPP $g^{-1}$soil $hr^{-1}$), which, under SSP (127.81 µg *p*NPP $g^{-1}$soil $hr^{-1}$), was at par with ICIAR 7B under SSP P source and had lowest AkPhase activity of 127.29 µg *p*NPP $g^{-1}$soil $hr^{-1}$ (Figure 4.81). In a study by Gabasawa *et al*. (2012), SAMNUT 23 was observed to be not significantly different from SAMNUT 10 and SAMNUT 11 in terms of AcPhase activity but it followed the two genotypes in terms of AkPhase activity.

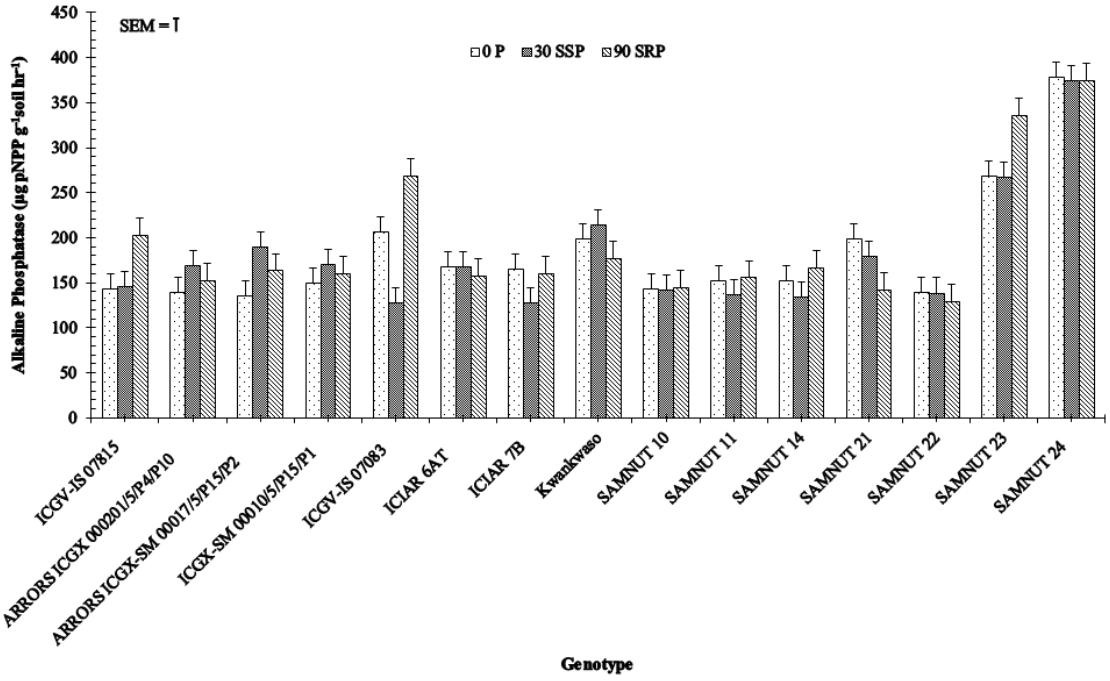



Figure 4.81: Genotype by phosphorus interaction on AkPhase activity

*4.11.2.12 Genotype by phosphorus versus location interaction on AkPhase activity*

There was also a significant ($P \leq 0.01$) difference between the genotypes, based on the location and genotype versus P source interaction, in terms of AkPhase (Table 4.11). SAMNUT 24, under the control (567.79 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and SRP (573.34 µg *p*NPP $g^{-1}$soil $hr^{-1}$), at par with SAMNUT 23 under SRP (556.06 µg *p*NPP $g^{-1}$soil $hr^{-1}$) in Minjibir, outperformed all other genotypes under all the P sources (Figure 4.82) and was followed by SAMNUT 24, under SSP (547.22 µg *p*NPP $g^{-1}$soil $hr^{-1}$), which was in turn followed by SAMNUT 23 under control (405.53 µg *p*NPP $g^{-1}$soil $hr^{-1}$) and SSP (394.84 µg *p*NPP $g^{-1}$soil $hr^{-1}$) P sources in Minjibir. The lowest AkPhase activity of 87.22 and 87.40 µg *p*NPP $g^{-1}$soil $hr^{-1}$ was recorded in ARRORS ICGX 000201/5/$P_4$/$P_{10}$ under the control and ICGV-IS 07083 under SSP P sources in Minjibir (Figure 4.82).

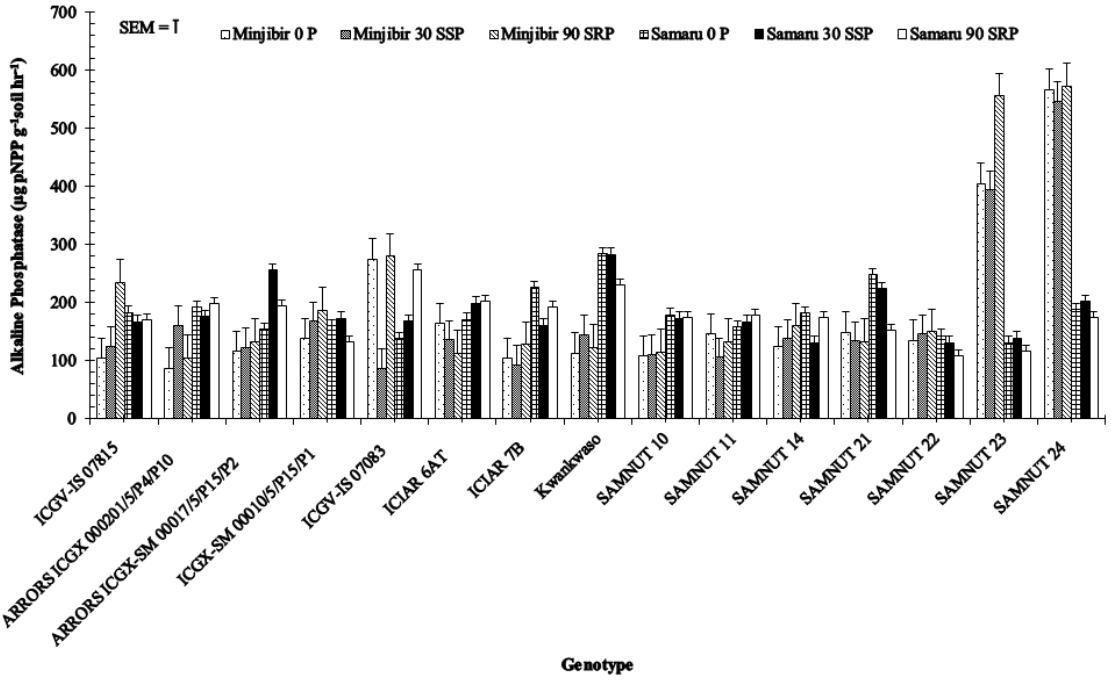



Figure 4.82: Genotype by phosphorus versus location interaction on AkPhase activity

## 4.12 Pearson Correlations Analysis of Yield, $N_2$-fixation and Enzyme Activities

The Pearson correlation matrix, between some of the observed groundnut yield and soil biochemical parameters, was carried out to examine the direction and strength of their interdependence. The Pearson correlation coefficients observed during the field experiment were as presented in Table 4.12. It indicated a significant ($P \leq 0.01$) positive correlation between dry haulm yield (DHY) and pod yield ($r = 0.20$), dry matter yield (DMY) ($r = 0.99$), $N_2$-fixed ($r = 0.67$) and N derived from the atmosphere (Ndfa) ($r = 0.65$). The interdependence was, however, positive but non-significant ($P > 0.05$) with chlorophyll content (CC), urease and AkPhase (each $r = 0.01$). The DHY was, however, negatively correlated with AcPhase ($r = - 0.04$) in addition to also being non-significant ($P > 0.05$). This revealed that there was a reasonable directly proportional relationship between DHY and pod yield, DMY, $N_2$-fixed and Ndfa. The relationships were also directly proportional, though non-significantly, with CC, urease and AkPhase. Conversely, AcPhase was inversely related with DHY. This inverse relation was also not significant ($P > 0.05$).

Table 4.12: Pearson correlation coefficients of yield, $N_2$-fixation and enzyme activities

| | Dry Haulm Yield (kg $ha^{-1}$) | Pod yield (kg $ha^{-1}$) | DMY (kg $ha^{-1}$) | $N_2$-fixed (kg $ha^{-1}$) | Ndfa (%) | Chlorophyll (SCMR) | Urease (mg $NH_4^+$-N $l^{-1}$) | AcPhase (µg *p*NPP $g^{-1}$ soil $hr^{-1}$) | AkPhase (µg *p*NPP $g^{-1}$ soil $hr^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Dry Haulm Yield (kg $ha^{-1}$) | 1.000 | | | | | | | | |
| Pod yield (kg $ha^{-1}$) | $0.204^{**}$ | 1.000 | | | | | | | |
| DMY (kg $ha^{-1}$) | $0.999^{**}$ | $0.204^{**}$ | 1.000 | | | | | | |
| $N_2$-fixed (kg $ha^{-1}$) | $0.668^{**}$ | $0.244^{**}$ | $0.667^{**}$ | 1.000 | | | | | |
| Ndfa (%) | $0.649^{**}$ | $0.302^{**}$ | $0.649^{**}$ | $0.828^{**}$ | 1.000 | | | | |
| Chlorophyll (SCMR) | $0.013^{NS}$ | $0.027^{NS}$ | $0.012^{NS}$ | $0.018^{NS}$ | $-0.007^{NS}$ | 1.000 | | | |
| Urease (mg $NH_4^+$-N $l^{-1}$) | $0.013^{NS}$ | $0.007^{NS}$ | $0.013^{NS}$ | $-0.127^{*}$ | $-0.177^{**}$ | $-0.088^{NS}$ | 1.000 | | |
| AcPhase (µg *p*NPP $g^{-1}$soil $hr^{-1}$) | $-0.041^{NS}$ | $0.037^{NS}$ | $-0.042^{NS}$ | $-0.075^{NS}$ | $-0.092^{NS}$ | $0.016^{NS}$ | $0.380^{**}$ | 1.000 | |
| AkPhase (µg *p*NPP $g^{-1}$soil $hr^{-1}$) | $0.009^{NS}$ | $0.331^{**}$ | $0.008^{NS}$ | $0.021^{NS}$ | $0.006^{NS}$ | $-0.031^{NS}$ | $0.384^{**}$ | $0.453^{**}$ | 1.000 |

DF = 190, DMY= Dry matter yield, Ndfa = $N_2$ derived from the atmosphere, SCMR = SPAD Chlorophyll Meter Reading, AcPhase = Acid phosphate, AkPhase = Alkaline phosphatase

There was also a significant ($P \leq 0.01$) positive correlation between the pod yield and DMY recorded (r = 0.20), $N_2$-fixed (r = 0.67), Ndfa (r = 0.65) and AkPhase (r = 0.33). There was, however, positive but non-significant ($P > 0.05$) interdependence of pod yield and CC (0.03), urease (0.01) and AcPhase (r = 0.04). This showed a reasonably directly proportional relationship between the pod yield and DMY, $N_2$-fixed, Ndfa and AkPhase. The relationship was also non-significantly directly proportional with CC, urease and AcPhase. The DMY, on the other hand, was positively and significantly ($P \leq 0.01$) correlated only with the $N_2$-fixed (r = 0.67) and Ndfa (r = 0.65) by the genotypes. All the other parameters were also not significant ($P > 0.05$) and positively correlated with DMY, each at r = 0.01, except AcPhase which was negatively correlated (r = - 0.04). The DMY was, therefore, significantly influenced by $N_2$-fixed and Ndfa of the groundnuts, and vice-versa. The interrelation was, non-significantly, inverse with AcPhase as depicted in Table 4.12 on page 212 (above).

Also, $N_2$-fixed by the groundnuts was observed to significantly ($P \leq 0.01$) correlate positively with Ndfa (r = 0.83) and negatively with urease ($P \leq 0.05$, r = - 0.13). The interdependence between the $N_2$-fixed by the genotypes was, conversely, not significant ($P > 0.05$) and positive with CC and AkPhase (r = 0.02 each); and negative with AcPhase ($P > 0.05$, r = -008). This indicated a non-significant, respective, directly and inversely proportional interdependence, as also indicated by Table 4.12. Nitrogen derived from the atmosphere was positively correlated only with AkPhase ($P > 0.05$, r = 0.01) and significantly ($P \leq 0.01$), though negatively, only with urease (r = - 0.18). The interdependence was also non-significant ($P > 0.05$) and negative with CC (r = - 0.01) and AcPhase (r = - 0.09). Chlorophyll content recorded was generally not significantly ($P > 0.05$) correlated with urease (r = - 0.09), AkPhase (r = - 0.03), which were negatively correlated and AcPhase (r = 0.02), which was positively correlated (Table 4.12).

There was a significant ($P \leq 0.01$) positive interdependence between urease enzyme and the two phosphomonoesterase enzymes (r = 0.38 each), as also between AcPhase and AkPhase ($P \leq 0.01$, r = 0.45). The correlation between pod yield and dry haulm yield was also observed to be positive and significant ($P < 0.001$) in a study by Ahounou *et al*. (2017). Kandeler *et al*. (1999) also reported a significant positive correlation between urease and AkPhase enzymes in their study. A similar correlation coefficient

between AcPhase and AkPhase was also reported in a work by Furtak *et al*. (2020). Significantly ($P \leq 0.01$) positive correlations were observed between urease and AcPhase ($r = 0.85$) and AkPhase ($r = 0.82$); and AcPhase versus AkPhase ($r = 0.90$) in a study by Liang *et al*. (2014). An ecological significance of distinct soil enzymes activities is still subject to debate (Nannipieri *et al*., 1990). It was also shown that the activity of some enzymes (phosphatase, invertase, urease and β-glucosidase) correlates with crop yields and with the content of organic matter in the soil and its pH. Processes of P transformations were reported, by Acosta-Martinez and Tabatabai (2011), to be mediated and/or controlled by Acid and alkaline phosphatases. However, several studies still clearly show the roles of soil management in enzyme activities (Kandeler *et al*., 1999; Bandick and Dick, 1999). Hence, physical and chemical changes in soils may also result in the increase in soil enzyme activities (Nannipieri *et al*., 1990). For example, an increase in soil enzyme activities due to minimum to zero tillage can, consequently improve the soil microbial habitat. Also, long-term tillage is reported to alter soil structure and can trigger organic matter losses, as tillage disrupts soil aggregates thereby exposing more organic matter to attack by soil microbes (Beare *et al*., 1994). Forgone may partly be the reason behind the differences in AcPhase and AkPhase observed in soils of the two locations. More so for Minjibir soil as was fallowed for a long time before conducting this study thereon, unlike the Samaru's.

In a personal communication with Mary Ann Bruns, a Professor of Soil Microbiology with Pennsylvania State University, she explained that it is usually common for multiple soil enzyme tests to vary widely due to high temporal and spatial soil variability. This is not to mention management histories of the sites involved. Correlating enzyme test results with "soil health" can, therefore, sometimes be relatively problematic.

## 4.13 Partial Economic Analysis on Investment of Growing Groundnut Genotypes Using SSP and SRP Fertilisers in Minjibir and Samaru

### 4.13.1 Partial economic analyses of groundnut yield in Minjibir in 2015 and 2016 cropping seasons

The result of gross margin analysis of groundnut yield recorded in Minjibir in the 2015 cropping season ( Table 4.13) indicated that ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$, grown without any fertiliser P application (0 kg $P_2O_5$ $ha^{-1}$), gave an overall highest gross return or revenue (GR) of ₦ 770, 625 with a gross margin (GM) of ₦ 690, 892 and a profit of ₦ 8.67 per Naira (₦$^{-1}$) invested. The single superphosphate followed the control by having recorded a GR of ₦ 649,575 with a GM of ₦ 552,425 and a profit of ₦ 5.69 ₦$^{-1}$ invested on SAMNUT 11. A GR of ₦ 427,725, with a GM of ₦ 330,575 and a profit of ₦ 3.40 ₦$^{-1}$ invested was realised with ICIAR 7B grown with Sokoto rock phosphate (SRP).

Similarly, during 2016 cropping season, at the same Minjibir location, 0 kg $P_2O_5$ $ha^{-1}$ also had the overall highest GR (₦ 4,833,338), GM (₦ 4,746,228) and profit (₦ 54.49 ₦$^{-1}$ invested) record with SAMNUT 22 grown ( Table 4.15). It was closely followed by SAMNUT 24 (GR, ₦ 4,129,200; GM, ₦ 4,042,090; and profit (₦ 46.40 ₦$^{-1}$ invested) and SMNUT 23 (GR, ₦ 4,112,475; GM, ₦ 4,025,365 and profit (₦ 46.21 ₦$^{-1}$ invested), both also under the control (0 kg $P_2O_5$ $ha^{-1}$). Kwankwaso, under SSP followed those with the GR (of ₦ 4,433,325), with a GM of ₦ 4,334,315 and a profit of ₦ 43.78 ₦$^{-1}$ invested. The influence of SRP finally followed all those by raising SAMNUT 14 to record a GR of ₦ 2,995,838, with a GM of ₦ 2,896,828 and a profit that stood at ₦ 29.26 ₦$^{-1}$ invested. Some other fertiliser P sources were, however, observed to have also influenced the closely high GR and GM values; and net profit margins recorded for some other genotypes grown under them, as indicated in the corresponding Tables ( Table 4.13 and Table 4.14).

Table 4.13: Partial economic analysis on growing groundnut using P fertiliser at Minjibir in 2015 cropping season

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦ $^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| 0 P | ICGV-IS 07815 | 79733 | 335 | 900 | 301500 | 221767 | 2.78 |
| 0 P | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 79733 | 266 | 900 | 239625 | 159892 | 2.01 |
| 0 P | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 79733 | 856 | 900 | 770625 | 690892 | 8.67 |
| 0 P | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 79733 | 229 | 900 | 206100 | 126367 | 1.58 |
| 0 P | ICGV-IS 07083 | 79733 | 306 | 900 | 275625 | 195892 | 2.46 |
| 0 P | ICIAR 6AT | 79733 | 158 | 900 | 142650 | 62917 | 0.79 |
| 0 P | ICIAR 7B | 79733 | 352 | 900 | 316800 | 237067 | 2.97 |
| 0 P | Kwankwaso | 79733 | 255 | 900 | 229500 | 149767 | 1.88 |
| 0 P | SAMNUT 10 | 79733 | 842 | 900 | 758025 | 678292 | 8.51 |
| 0 P | SAMNUT 11 | 79733 | 386 | 900 | 347175 | 267442 | 3.35 |
| 0 P | SAMNUT 14 | 79733 | 333 | 900 | 299475 | 219742 | 2.76 |
| 0 P | SAMNUT 21 | 79733 | 136 | 900 | 122625 | 42892 | 0.54 |
| 0 P | SAMNUT 22 | 79733 | 211 | 900 | 189900 | 110167 | 1.38 |
| 0 P | SAMNUT 23 | 79733 | 269 | 900 | 242100 | 162367 | 2.04 |
| 0 P | SAMNUT 24 | 79733 | 257 | 900 | 231300 | 151567 | 1.90 |
| SSP | ICGV-IS 07815 | 97150 | 559 | 900 | 503100 | 405950 | 4.18 |
| SSP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 97150 | 380 | 900 | 342225 | 245075 | 2.52 |
| SSP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 97150 | 661 | 900 | 594450 | 497300 | 5.12 |
| SSP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 97150 | 261 | 900 | 235125 | 137975 | 1.42 |
| SSP | ICGV-IS 07083 | 97150 | 180 | 900 | 161775 | 64625 | 0.67 |
| SSP | ICIAR 6AT | 97150 | 205 | 900 | 184275 | 87125 | 0.90 |
| SSP | ICIAR 7B | 97150 | 181 | 900 | 162675 | 65525 | 0.67 |
| SSP | Kwankwaso | 97150 | 436 | 900 | 392175 | 295025 | 3.04 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| SSP | SAMNUT 10 | 97150 | 246 | 900 | 221400 | 124250 | 1.28 |
| SSP | SAMNUT 11 | 97150 | 722 | 900 | 649575 | 552425 | 5.69 |
| SSP | SAMNUT 14 | 97150 | 217 | 900 | 195525 | 98375 | 1.01 |
| SSP | SAMNUT 21 | 97150 | 406 | 900 | 365625 | 268475 | 2.76 |
| SSP | SAMNUT 22 | 97150 | 209 | 900 | 187875 | 90725 | 0.93 |
| SSP | SAMNUT 23 | 97150 | 360 | 900 | 324225 | 227075 | 2.34 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source | Genotype | | | | | | |
| SSP | SAMNUT 24 | 97150 | 276 | 900 | 248175 | 151025 | 1.55 |
| SRP | ICGV-IS 07815 | 97150 | 358 | 900 | 321975 | 224825 | 2.31 |
| SRP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 97150 | 393 | 900 | 353250 | 256100 | 2.64 |
| SRP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 97150 | 284 | 900 | 255375 | 158225 | 1.63 |
| SRP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 97150 | 387 | 900 | 348300 | 251150 | 2.59 |
| SRP | ICGV-IS 07083 | 97150 | 364 | 900 | 327375 | 230225 | 2.37 |
| SRP | ICIAR 6AT | 97150 | 372 | 900 | 334575 | 237425 | 2.44 |
| SRP | ICIAR 7B | 97150 | 475 | 900 | 427725 | 330575 | 3.40 |
| SRP | Kwankwaso | 97150 | 268 | 900 | 241200 | 144050 | 1.48 |
| SRP | SAMNUT 10 | 97150 | 437 | 900 | 393525 | 296375 | 3.05 |
| SRP | SAMNUT 11 | 97150 | 347 | 900 | 312075 | 214925 | 2.21 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | | Gross Margin ₦ $^{-1}$ Invested |
|---|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | | |
| SRP | SAMNUT 14 | 97150 | 265 | 900 | 238275 | 141125 | 1.45 | |
| SRP | SAMNUT 21 | 97150 | 281 | 900 | 252675 | 155525 | 1.60 | |
| SRP | SAMNUT 22 | 97150 | 372 | 900 | 334800 | 237650 | 2.45 | |
| SRP | SAMNUT 23 | 97150 | 396 | 900 | 356625 | 259475 | 2.67 | |
| SRP | SAMNUT 24 | 97150 | 285 | 900 | 256725 | 159575 | 1.64 | |

SSP = Single superphosphate, SRP = Sokoto rock phosphate

Table 4.14: Partial economic analysis on growing groundnut using P fertiliser in Minjibir in the 2016 cropping season

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| 0 P | ICGV-IS 07815 | 87110 | 1047 | 1500 | 1,570,838 | 1483728 | 17.03 |
| 0 P | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 87110 | 1375 | 1500 | 2,062,538 | 1975428 | 22.68 |
| 0 P | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 87110 | 769 | 1500 | 1,154,213 | 1067103 | 12.25 |
| 0 P | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 87110 | 2467 | 1500 | 3,700,050 | 3612940 | 41.48 |
| 0 P | ICGV-IS 07083 | 87110 | 2064 | 1500 | 3,095,850 | 3008740 | 34.54 |
| 0 P | ICIAR 6AT | 87110 | 933 | 1500 | 1,399,988 | 1312878 | 15.07 |
| 0 P | ICIAR 7B | 87110 | 1411 | 1500 | 2,116,650 | 2029540 | 23.30 |
| 0 P | Kwankwaso | 87110 | 1178 | 1500 | 1,766,663 | 1679553 | 19.28 |
| 0 P | SAMNUT 10 | 87110 | 556 | 1500 | 833,325 | 746215 | 8.57 |
| 0 P | SAMNUT 11 | 87110 | 626 | 1500 | 938,888 | 851778 | 9.78 |
| 0 P | SAMNUT 14 | 87110 | 1389 | 1500 | 2,083,313 | 1996203 | 22.92 |
| 0 P | SAMNUT 21 | 87110 | 453 | 1500 | 679,200 | 592090 | 6.80 |
| 0 P | SAMNUT 22 | 87110 | 3222 | 1500 | 4,833,338 | 4746228 | 54.49 |
| 0 P | SAMNUT 23 | 87110 | 2742 | 1500 | 4,112,475 | 4025365 | 46.21 |
| 0 P | SAMNUT 24 | 87110 | 2753 | 1500 | 4,129,200 | 4042090 | 46.40 |
| SSP | ICGV-IS 07815 | 99010 | 1344 | 1500 | 2,016,638 | 1917628 | 19.37 |
| SSP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 99010 | 2042 | 1500 | 3,062,513 | 2963503 | 29.93 |
| SSP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 99010 | 1461 | 1500 | 2,191,688 | 2092678 | 21.14 |
| SSP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 99010 | 1553 | 1500 | 2,329,200 | 2230190 | 22.52 |
| SSP | ICGV-IS 07083 | 99010 | 1772 | 1500 | 2,658,338 | 2559328 | 25.85 |
| SSP | ICIAR 6AT | 99010 | 1033 | 1500 | 1,549,988 | 1450978 | 14.65 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| SSP | ICIAR 7B | 99010 | 622 | 1500 | 933,338 | 834328 | 8.43 |
| SSP | Kwankwaso | 99010 | 2956 | 1500 | 4,433,325 | 4334315 | 43.78 |
| SSP | SAMNUT 10 | 99010 | 314 | 1500 | 470,813 | 371803 | 3.76 |
| SSP | SAMNUT 11 | 99010 | 361 | 1500 | 541,688 | 442678 | 4.47 |
| SSP | SAMNUT 14 | 99010 | 1333 | 1500 | 1,999,988 | 1900978 | 19.20 |
| SSP | SAMNUT 21 | 99010 | 881 | 1500 | 1,320,863 | 1221853 | 12.34 |
| SSP | SAMNUT 22 | 99010 | 461 | 1500 | 691,650 | 592640 | 5.99 |
| SSP | SAMNUT 23 | 99010 | 800 | 1500 | 1,200,000 | 1100990 | 11.12 |
| SSP | SAMNUT 24 | 99010 | 707 | 1500 | 1,060,425 | 961415 | 9.71 |
| SRP | ICGV-IS 07815 | 99010 | 1678 | 1500 | 2,516,700 | 2417690 | 24.42 |
| SRP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 99010 | 428 | 1500 | 641,663 | 542653 | 5.48 |
| SRP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 99010 | 1372 | 1500 | 2,058,338 | 1959328 | 19.79 |
| SRP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 99010 | 361 | 1500 | 540,863 | 441853 | 4.46 |
| SRP | ICGV-IS 07083 | 99010 | 347 | 1500 | 520,838 | 421828 | 4.26 |
| SRP | ICIAR 6AT | 99010 | 1183 | 1500 | 1,774,988 | 1675978 | 16.93 |
| SRP | ICIAR 7B | 99010 | 739 | 1500 | 1,108,350 | 1009340 | 10.19 |
| SRP | Kwankwaso | 99010 | 497 | 1500 | 745,875 | 646865 | 6.53 |
| SRP | SAMNUT 10 | 99010 | 547 | 1500 | 820,838 | 721828 | 7.29 |
| SRP | SAMNUT 11 | 99010 | 606 | 1500 | 908,325 | 809315 | 8.17 |
| SRP | SAMNUT 14 | 99010 | 1997 | 1500 | 2,995,838 | 2896828 | 29.26 |
| SRP | SAMNUT 21 | 99010 | 1294 | 1500 | 1,941,638 | 1842628 | 18.61 |
| SRP | SAMNUT 22 | 99010 | 1061 | 1500 | 1,591,650 | 1492640 | 15.08 |
| SRP | SAMNUT 23 | 99010 | 1422 | 1500 | 2,133,338 | 2034328 | 20.55 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| SRP | SAMNUT 24 | 99010 | 1594 | 1500 | 2,391,675 | 2292665 | 23.16 |

SSP = Single superphosphate, SRP = Sokoto rock phosphate

### 4.13.2 Partial economic analysis of groundnut yield in Samaru in 2015 and 2016 cropping seasons

The result of partial budget analysis of groundnut yield in Samaru in the 2015 cropping season was as depicted on Table 4.15). It showed that an application of SRP sourced fertiliser P to SAMNUT 23 resulted in the highest GR (₦ 1,023,225), GM (₦ 922,375) and profit (₦ 9.15 $₦^{-1}$ invested) of the season. This was followed by the effect of SSP P source on ICIAR 7B. It had the second overall highest GR (₦ 915,338), GM (₦ 832,088) and profit (₦ 10 $₦^{-1}$ invested). Following these was ARRORS ICGX 000201/5/$P_4$/$P_{10}$ without any P application having recorded a gross return of ₦ 560,700 with gross margin of ₦ 477,450 and a profit of ₦ 5.74 $₦^{-1}$ invested.

Somewhat conversely in the 2016 cropping season, the control (zero) P application to SAMNUT 10 gave the highest economic returns in the Samaru location (Table 4.16). The record indicated a GR of ₦ 3,190,509, with a GM of ₦ 3,104,399 and a profit of ₦ 36.05 per naira invested. Also, ICGX-SM 00010/5/$P_{15}$/$P_1$ (GR, ₦ 3,131,987; GM, ₦ 3,045,877 and profit, ₦ 35.37 $₦^{-1}$ invested) had a good record under the control P source. ARRORS ICGX 000201/5/$P_4$/$P_{10}$, under SRP sourced P followed those with a GR of ₦ 2,578,473, having a GM of ₦ 2,480,463 and a profit of ₦ 25.31 $₦^{-1}$ invested. This was somewhat close to what was recorded for the same genotype (ARRORS ICGX 000201/5/$P_4$/$P_{10}$, GR, ₦ 2,245,482; GM, ₦ 2,159,372 and profit, ₦ 25.08 $₦^{-1}$ invested) under control P source. Both P sources were followed by SSP P applied to SAMNUT 14. It recorded a GR of ₦ 2,321,987, with a GM of ₦ 2,223,977 and a profit of ₦ 22.69 $₦^{-1}$ invested. Also in Samaru, some other fertiliser P sources were variously observed to have influenced other genotypes. This was through the similarly high GR, GM and net profit margin values recorded for some of the genotypes grown under the P sources as indicated in the corresponding Table 4.15 and Table 4.16.

The record indicated a GR of ₦ 3,190,509, with a GM of ₦ 3,104,399 and a profit of ₦ 36.05 per naira invested. Also, ICGX-SM 00010/5/$P_{15}$/$P_1$ (GR, ₦ 3,131,987; GM, ₦ 3,045,877 and profit, ₦ 35.37 $₦^{-1}$ invested) had a good record under the control P source. ARRORS ICGX 000201/5/$P_4$/$P_{10}$, under SRP sourced P followed those with a GR of ₦ 2,578,473, having a GM of ₦ 2,480,463 and a profit of ₦ 25.31 $₦^{-1}$ invested. This was somewhat close to what was recorded for the same genotype (ARRORS ICGX 000201/5/$P_4$/$P_{10}$, GR, ₦ 2,245,482; GM, ₦ 2,159,372 and profit, ₦ 25.08 $₦^{-1}$ invested) under control P source. Both P sources were followed by SSP P applied to SAMNUT 14. It recorded a GR of ₦ 2,321,987, with a GM of ₦ 2,223,977 and a profit

of ₦ 22.69 ₦$^{-1}$ invested. Also in Samaru, some other fertiliser P sources were variously observed to have influenced other genotypes. This was through the similarly high GR, GM and net profit margin values recorded for some of the genotypes grown under the P sources as indicated in the corresponding Table 4.15 and Table 4.16.

Table 4.15: Partial economic analysis on growing groundnut using P fertiliser in Samaru in 2015 cropping season

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| 0 P | ICGV-IS 07815 | 83250 | 192 | 1050 | 201600 | 118350 | 1.42 |
| 0 P | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 83250 | 534 | 1050 | 560700 | 477450 | 5.74 |
| 0 P | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 83250 | 466 | 1050 | 489563 | 406313 | 4.88 |
| 0 P | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 83250 | 454 | 1050 | 477120 | 393870 | 4.73 |
| 0 P | ICGV-IS 07083 | 83250 | 341 | 1050 | 358313 | 275063 | 3.30 |
| 0 P | ICIAR 6AT | 83250 | 790 | 1050 | 829500 | 746250 | 8.96 |
| 0 P | ICIAR 7B | 83250 | 872 | 1050 | 915338 | 832088 | 10.00 |
| 0 P | Kwankwaso | 83250 | 501 | 1050 | 525788 | 442538 | 5.32 |
| 0 P | SAMNUT 10 | 83250 | 464 | 1050 | 486675 | 403425 | 4.85 |
| 0 P | SAMNUT 11 | 83250 | 580 | 1050 | 608738 | 525488 | 6.31 |
| 0 P | SAMNUT 14 | 83250 | 476 | 1050 | 500063 | 416813 | 5.01 |
| 0 P | SAMNUT 21 | 83250 | 388 | 1050 | 407400 | 324150 | 3.89 |
| 0 P | SAMNUT 22 | 83250 | 239 | 1050 | 250425 | 167175 | 2.01 |
| 0 P | SAMNUT 23 | 83250 | 557 | 1050 | 584850 | 501600 | 6.03 |
| 0 P | SAMNUT 24 | 83250 | 746 | 1050 | 782775 | 699525 | 8.40 |
| SSP | ICGV-IS 07815 | 100850 | 259 | 1050 | 271950 | 171100 | 1.70 |
| SSP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 100850 | 328 | 1050 | 344400 | 243550 | 2.41 |
| SSP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 100850 | 498 | 1050 | 522900 | 422050 | 4.18 |
| SSP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 100850 | 168 | 1050 | 175875 | 75025 | 0.74 |
| SSP | ICGV-IS 07083 | 100850 | 318 | 1050 | 333900 | 233050 | 2.31 |
| SSP | ICIAR 6AT | 100850 | 360 | 1050 | 378000 | 277150 | 2.75 |
| SSP | ICIAR 7B | 100850 | 558 | 1050 | 585375 | 484525 | 4.80 |
| SSP | Kwankwaso | 100850 | 367 | 1050 | 385613 | 284763 | 2.82 |
| SSP | SAMNUT 10 | 100850 | 290 | 1050 | 304238 | 203388 | 2.02 |
| SSP | SAMNUT 11 | 100850 | 583 | 1050 | 611888 | 511038 | 5.07 |
| SSP | SAMNUT 14 | 100850 | 614 | 1050 | 644175 | 543325 | 5.39 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| SSP | SAMNUT 21 | 100850 | 340 | 1050 | 357263 | 256413 | 2.54 |
| SSP | SAMNUT 22 | 100850 | 801 | 1050 | 840788 | 739938 | 7.34 |
| SSP | SAMNUT 23 | 100850 | 770 | 1050 | 808763 | 707913 | 7.02 |
| SSP | SAMNUT 24 | 100850 | 966 | 1050 | 1014038 | 913188 | 9.05 |
| SRP | ICGV-IS 07815 | 100850 | 268 | 1050 | 281663 | 180813 | 1.79 |
| SRP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 100850 | 343 | 1050 | 359888 | 259038 | 2.57 |
| SRP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 100850 | 414 | 1050 | 434438 | 333588 | 3.31 |
| SRP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 100850 | 276 | 1050 | 290063 | 189213 | 1.88 |
| SRP | ICGV-IS 07083 | 100850 | 263 | 1050 | 275625 | 174775 | 1.73 |
| SRP | ICIAR 6AT | 100850 | 583 | 1050 | 611888 | 511038 | 5.07 |
| SRP | ICIAR 7B | 100850 | 543 | 1050 | 570413 | 469563 | 4.66 |
| SRP | Kwankwaso | 100850 | 252 | 1050 | 264075 | 163225 | 1.62 |
| SRP | SAMNUT 10 | 100850 | 347 | 1050 | 363825 | 262975 | 2.61 |
| SRP | SAMNUT 11 | 100850 | 833 | 1050 | 874388 | 773538 | 7.67 |
| SRP | SAMNUT 14 | 100850 | 694 | 1050 | 728438 | 627588 | 6.22 |
| SRP | SAMNUT 21 | 100850 | 205 | 1050 | 214988 | 114138 | 1.13 |
| SRP | SAMNUT 22 | 100850 | 243 | 1050 | 255150 | 154300 | 1.53 |
| SRP | SAMNUT 23 | 100850 | 975 | 1050 | 1023225 | 922375 | 9.15 |
| SRP | SAMNUT 24 | 100850 | 426 | 1050 | 446775 | 345925 | 3.43 |

SSP = Single superphosphate, SRP = Sokoto rock phosphate

Table 4.16: Partial economic analysis on growing groundnut using P fertiliser in Samaru in 2016 cropping season

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| 0 P | ICGV-IS 07815 | 86110 | 389 | 1620 | 629,978 | 543,868 | 6.32 |
| 0 P | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 86110 | 1386 | 1620 | 2,245,482 | 2,159,372 | 25.08 |
| 0 P | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 86110 | 1617 | 1620 | 2,619,014 | 2,532,904 | 29.41 |
| 0 P | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 86110 | 1933 | 1620 | 3,131,987 | 3,045,877 | 35.37 |
| 0 P | ICGV-IS 07083 | 86110 | 1364 | 1620 | 2,209,478 | 2,123,368 | 24.66 |
| 0 P | ICIAR 6AT | 86110 | 1703 | 1620 | 2,758,536 | 2,672,426 | 31.04 |
| 0 P | ICIAR 7B | 86110 | 817 | 1620 | 1,323,014 | 1,236,904 | 14.36 |
| 0 P | Kwankwaso | 86110 | 1411 | 1620 | 2,285,942 | 2,199,832 | 25.55 |
| 0 P | SAMNUT 10 | 86110 | 1969 | 1620 | 3,190,509 | 3,104,399 | 36.05 |
| 0 P | SAMNUT 11 | 86110 | 858 | 1620 | 1,390,487 | 1,304,377 | 15.15 |
| 0 P | SAMNUT 14 | 86110 | 1178 | 1620 | 1,907,997 | 1,821,886 | 21.16 |
| 0 P | SAMNUT 21 | 86110 | 883 | 1620 | 1,431,027 | 1,344,917 | 15.62 |
| 0 P | SAMNUT 22 | 86110 | 667 | 1620 | 1,080,054 | 993,944 | 11.54 |
| 0 P | SAMNUT 23 | 86110 | 383 | 1620 | 621,027 | 534,917 | 6.21 |
| 0 P | SAMNUT 24 | 86110 | 622 | 1620 | 1,008,005 | 921,895 | 10.71 |
| SSP | ICGV-IS 07815 | 98010 | 578 | 1620 | 935,996 | 837,986 | 8.55 |
| SSP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 98010 | 1340 | 1620 | 2,170,476 | 2,072,466 | 21.15 |
| SSP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 98010 | 1211 | 1620 | 1,962,023 | 1,864,013 | 19.02 |
| SSP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 98010 | 758 | 1620 | 1,228,527 | 1,130,517 | 11.53 |
| SSP | ICGV-IS 07083 | 98010 | 819 | 1620 | 1,327,509 | 1,229,499 | 12.54 |
| SSP | ICIAR 6AT | 98010 | 614 | 1620 | 994,518 | 896,508 | 9.15 |
| SSP | ICIAR 7B | 98010 | 556 | 1620 | 899,991 | 801,981 | 8.18 |
| SSP | Kwankwaso | 98010 | 644 | 1620 | 1,044,009 | 945,999 | 9.65 |
| SSP | SAMNUT 10 | 98010 | 819 | 1620 | 1,327,509 | 1,229,499 | 12.54 |
| SSP | SAMNUT 11 | 98010 | 483 | 1620 | 782,987 | 684,977 | 6.99 |
| SSP | SAMNUT 14 | 98010 | 1433 | 1620 | 2,321,987 | 2,223,977 | 22.69 |
| SSP | SAMNUT 21 | 98010 | 825 | 1620 | 1,336,500 | 1,238,490 | 12.64 |
| SSP | SAMNUT 22 | 98010 | 947 | 1620 | 1,534,464 | 1,436,454 | 14.66 |

| Treatments | | Total Variable Cost (₦ $ha^{-1}$) | Yield (kg $ha^{-1}$) | Average Price (₦ 100 $kg^{-1}$ Sack) | Gross Revenue (₦ $ha^{-1}$) | Gross Margin | Gross Margin ₦$^{-1}$ Invested |
|---|---|---|---|---|---|---|---|
| P Source (P, kg $P_2O_5$ $ha^{-1}$) | Genotype | | | | | | |
| SSP | SAMNUT 23 | 98010 | 1411 | 1620 | 2,285,982 | 2,187,972 | 22.32 |
| SSP | SAMNUT 24 | 98010 | 772 | 1620 | 1,251,005 | 1,152,995 | 11.76 |
| SRP | ICGV-IS 07815 | 98010 | 925 | 1620 | 1,498,500 | 1,400,490 | 14.29 |
| SRP | ARRORS ICGX 000201/5/$P_4$/$P_{10}$ | 98010 | 1592 | 1620 | 2,578,473 | 2,480,463 | 25.31 |
| SRP | ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ | 98010 | 1461 | 1620 | 2,366,982 | 2,268,972 | 23.15 |
| SRP | ICGX-SM 00010/5/$P_{15}$/$P_1$ | 98010 | 592 | 1620 | 958,514 | 860,504 | 8.78 |
| SRP | ICGV-IS 07083 | 98010 | 1406 | 1620 | 2,277,032 | 2,179,022 | 22.23 |
| SRP | ICIAR 6AT | 98010 | 1319 | 1620 | 2,137,509 | 2,039,499 | 20.81 |
| SRP | ICIAR 7B | 98010 | 522 | 1620 | 845,964 | 747,954 | 7.63 |
| SRP | Kwankwaso | 98010 | 789 | 1620 | 1,278,018 | 1,180,008 | 12.04 |
| SRP | SAMNUT 10 | 98010 | 914 | 1620 | 1,480,518 | 1,382,508 | 14.11 |
| SRP | SAMNUT 11 | 98010 | 558 | 1620 | 904,487 | 806,477 | 8.23 |
| SRP | SAMNUT 14 | 98010 | 1347 | 1620 | 2,182,464 | 2,084,454 | 21.27 |
| SRP | SAMNUT 21 | 98010 | 664 | 1620 | 1,075,478 | 977,468 | 9.97 |
| SRP | SAMNUT 22 | 98010 | 542 | 1620 | 877,473 | 779,463 | 7.95 |
| SRP | SAMNUT 23 | 98010 | 608 | 1620 | 985,527 | 887,517 | 9.06 |
| SRP | SAMNUT 24 | 98010 | 975 | 1620 | 1,579,500 | 1,481,490 | 15.12 |

SSP = Single superphosphate, SRP = Sokoto rock phosphate

# CHAPTER FIVE

# 5 SUMMARY, CONCLUSION AND RECOMMENDATION

## 5.1 Summary

Phosphorus (P) is the second most important nutrient elements for plant growth and is largely unavailable in the soil solution for plant uptake. Reports have shown that the P statuses of well above 90% of the Nigerian arable lands surveyed in savannah agro-ecologies were below a critical value that makes P fertiliser application, for an improved crop yield, a necessity. These much needed P fertilisers for groundnut production are, on the other hand, usually very scarce and where relatively available are not timely accessible and premium priced for the smallholder farmers. This particularly presents a serious constraint to those farmers in terms of boom harvests. A thoughtful choice and application of P fertilisers, vis-à-vis increased nutrient use efficiency, can ultimately harness the menace to the barest minimum. This is more especially when such leguminous crops as groundnut are in cultivation. More so, available knowledge on the extent of genotypic differences among existing groundnut genotypes is a vital and primary stride that can relatively put the hitch to rest. Therefore, screening/selection of P-efficient, groundnut genotypes with an enhanced yield under some P fertiliser sources is, therefore, of an immense practical importance. Fortunately, however, phosphate rock or phosphorites, which refers to a mineral assemblage occurring naturally and having an exceptionally high concentration of phosphate minerals is reserved in Sokoto deposited in an estimated five million tonnes. Apart from their uses as food and fodder, legumes, like groundnuts, have a very significant contribution to the maintenance of soil fertility. This is, partly, through fixation of atmospheric nitrogen, thereby adding to soil N fertility/availability, reconstructing the soil structure and adding organic matter. Since it relatively requires low fertilisers, and other inputs, groundnut crop is economically highly profitable. It also improves environmental quality, like its other legumes counterparts. This is basically in the form of, amongst others, the fixation of atmospheric nitrogen ($N_2$), which reduces the need for synthetic fertilisers, which in turn, according to the FAO, assists in a decrease of greenhouse gas emissions released into the environment.

Field experiments were conducted during the 2015 and 2016 cropping seasons in each of two agro-ecological zones of Nigeria as thus: Sudan savannah (Minjibir) and northern Guinea savannah (Samaru). The study sought to identify promising groundnut genotypes, grown on P-deficient soils which were of the highest level of biological nitrogen fixation (BNF) and yield under the various P sources applied in the two agro-ecological zones. The experiments were laid out in a split plot design with P fertiliser sources (control P, SSP and SRP) in the main- and the 16 groundnut genotypes in the sub-plots. The yield, and most of yield components, was observed to be significantly higher in Minjibir site than Samaru. However, the genotypes responded, differently, to the application of P fertiliser from the two P sources evaluated and the control (inherent soil P) in both agro-ecological locations. This was attributable to the soil enzyme activities, soil solution P availability in, vis-à-vis its adsorption/desorption cycles and some weather conditions, notably temperature and precipitation. Under the control (0 P) P source, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ had highest values of 29.5 kg $ha^{-1}$ and 46%, respectively for $N_2$-fixed and Ndfa in Minjibir during the 2015 trial season. ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and SAMNUT 21 had the highest N uptake of 40 kg ha-1 each, at the same P source, location and season. SAMNUT 21 had the highest $N_2$-fixation record, under both SSP (41 kg $ha^{-1}$) and SRP (52 kg $ha^{-1}$) in the same Minjibir location. In Samaru location, however, the highest $N_2$ fixation under both the control (25 kg $ha^{-1}$) and SSP (33 kg $ha^{-1}$) P sources was observed for SAMNUT 10. Highest N uptake of 27 kg $ha^{-1}$, 26 kg $ha^{-1}$ and 32 kg $ha^{-1}$, respectively under the control, SSP and SRP P sources, was observed for SAMNUT 22 tested at the location. There were also higher activities of the enzymes amidohydrolase (urease) and phosphomonoestrases (acid and alkaline phosphatases) observed in soil of Minjibir than that of Samaru. This is a soil factor that partly caused the observed yield variations between the two locations. The economic analysis for both locations, especially Minjibir, indicated that profitable groundnut crop production can be achieved without addition of fertiliser P most likely due the enzymatic activities. Maintenance application of fertiliser P would, however, be routinely required. It can however, also be produced in the order of SSP > SRP. In the 2015 season, in Samaru location, however, fertilization with SRP gave higher net return than SSP.

## 5.2 Conclusion

The following conclusions could be deduced from this study, based on the objectives considered:

1. That some of the genotypes performed well irrespective of fertiliser P source. In that, ARRORS ICGX-SM 00017/5/$P_{15}$/$P_2$ had the highest $N_2$-fixation (29.5 kg $ha^{-1}$) and Ndfa (46%) records in Minjibir during 2015 trial season. ARRORS ICGX 000201/5/$P_4$/$P_{10}$ and SAMNUT 21 had the highest N uptake of 40 kg $ha^{-1}$ each, under the same (control) P source, in the same Minjibir location and during the same season. The same SAMNUT 21, on the other hand, had the highest $N_2$-fixation recorded under both SSP (41 kg $ha^{-1}$) and SRP (52 kg $ha^{-1}$) P sources at the same location. The highest $N_2$ fixation, under the control (25 kg $ha^{-1}$) and SSP (33 kg $ha^{-1}$), was both observed for SAMNUT 10 in Samaru, whereas highest N uptake, under the control (27 kg $ha^{-1}$), SSP (26 kg $ha^{-1}$) and SRP (32 kg $ha^{-1}$) sources, was observed for SAMNUT 22 tested at the same location in Samaru.

2. There was generally a more preponderant activity of, the soil enzyme, alkaline phosphatase in soils of both locations. However, greater activities of both phosphomonoesterases (acid and alkaline phosphatases), and the amidohydrolase (urease) enzyme, were observed within the soil of Minjibir than that of Samaru. This partly suggested for the rationales behind the disparity of the locations in terms of the yield, and yield components observed, especially under prevailing P-constrained soil conditions.

3. There was an observed significant ($P < 0.01$) influence of SRP on the $N_2$-fixation, Ndfa and N uptake recorded for some of the genotypes. The values recorded were, respectively, 24.95 kg $ha^{-1}$, 45.68 kg $ha^{-1}$ and 32.70 kg $ha^{-1}$, which were the highest and observed for the SRP P source in Minjibir. The P sourced from SSP followed SRP, in terms of $N_2$-fixation and Ndfa. It (SSP) was statistically similar with SRP in terms of the N uptake observed, whereas both were followed by the control P source in Minjibir. The control P source, in Minjibir had, however, a significantly more N uptake record than all the other P sources in Samaru, including the SRP P source.

4. The result of the mean across the seasons data analysed from both study locations indicated differences in, pod and dry haulm yield response due to P fertiliser source. This variability was, partly, due to the variations in soil biotic and abiotic gradients existing between the two site locations. The highest pod yield of 2032 kg $ha^{-1}$ (ICGV-IS 07083) was

recorded in Minjibir and the lowest was 286 kg $ha^{-1}$ (Kwankwaso), respectively under the control and SRP P sources. The highest recorded in Samaru was 1297 kg $ha^{-1}$ (ARRORS ICGX 000201/5/$P_4$/$P_{10}$) also under the control fertiliser P source. Kwankwaso was also the lowest in Samaru under the control (416 kg $ha^{-1}$) and SSP (418 kg $ha^{-1}$) P sources. Highest and lowest dry haulm yields in Minjibir were recorded for ARRORS ICGX 000201/5/$P_4$/$P_{10}$ (2256 kg $ha^{-1}$) and SAMNUT 24 (886 kg $ha^{-1}$) under SSP and control P sources respectively. The highest dry haulm yield in Samaru was recorded under SSP (2097 kg $ha^{-1}$) for ICIAR 7B. The lowest was under SRP under the ICIAR 6AT (102 kg $ha^{-1}$). The highest dry matter yield of 4095 kg $ha^{-1}$ (Kwankwaso) and 3105 kg $ha^{-1}$ (ICIAR 7B) were respectively recorded in Minjibir and Samaru locations. The lowest for the respective locations were 716 kg $ha^{-1}$ (SAMNUT 10) and 471 kg $ha^{-1}$ (ICIAR 7B) under SRP and control P sources.

5. The partial economic analysis of the Minjibir trial revealed that the gross returns and profits margins were both achieved variously with SSP, SRP and, especially, the control P sources and in both agro-ecological locations and in both trial seasons.

### 5.3 Recommendations

The use of different P sources in both Sudan and northern Guinea savannahs of Nigeria displayed a distinct and active effect of location. This, therefore, hinted for a need for a clarion call for more in-depth evaluation of Sokoto phosphate rock in various agro-ecologies of Nigeria with similar soil properties. For example, application of different rates, and granule sizes (textures), of SRP should be tested. More studies on more numbers of groundnut genotypes, being mostly grown by our farmers, on the basis of high and, especially, low P status would be of invaluable significance. This would be of more interest if a thorough P sorption/desorption study is carried out in conjunction. The genotypes reported here could, appropriately, be recommended for diverse cropping/farming systems, especially following the outcome of the immediate preceded recommendation. Also, some of the genotypes and P source(s) combinations when judiciously utilised will assist to achieve an effective biological $N_2$-fixation that would consequently see to the possibilities of greater cost-benefit ratio advantages. Finally, there is a need for a synergy, in form of interdisplinary research, between soil microbiologists and (legumes) plant breeders. This

will assist in releasing high $N_2$-fixing legumes that can perform under relatively wider P sources and availability.

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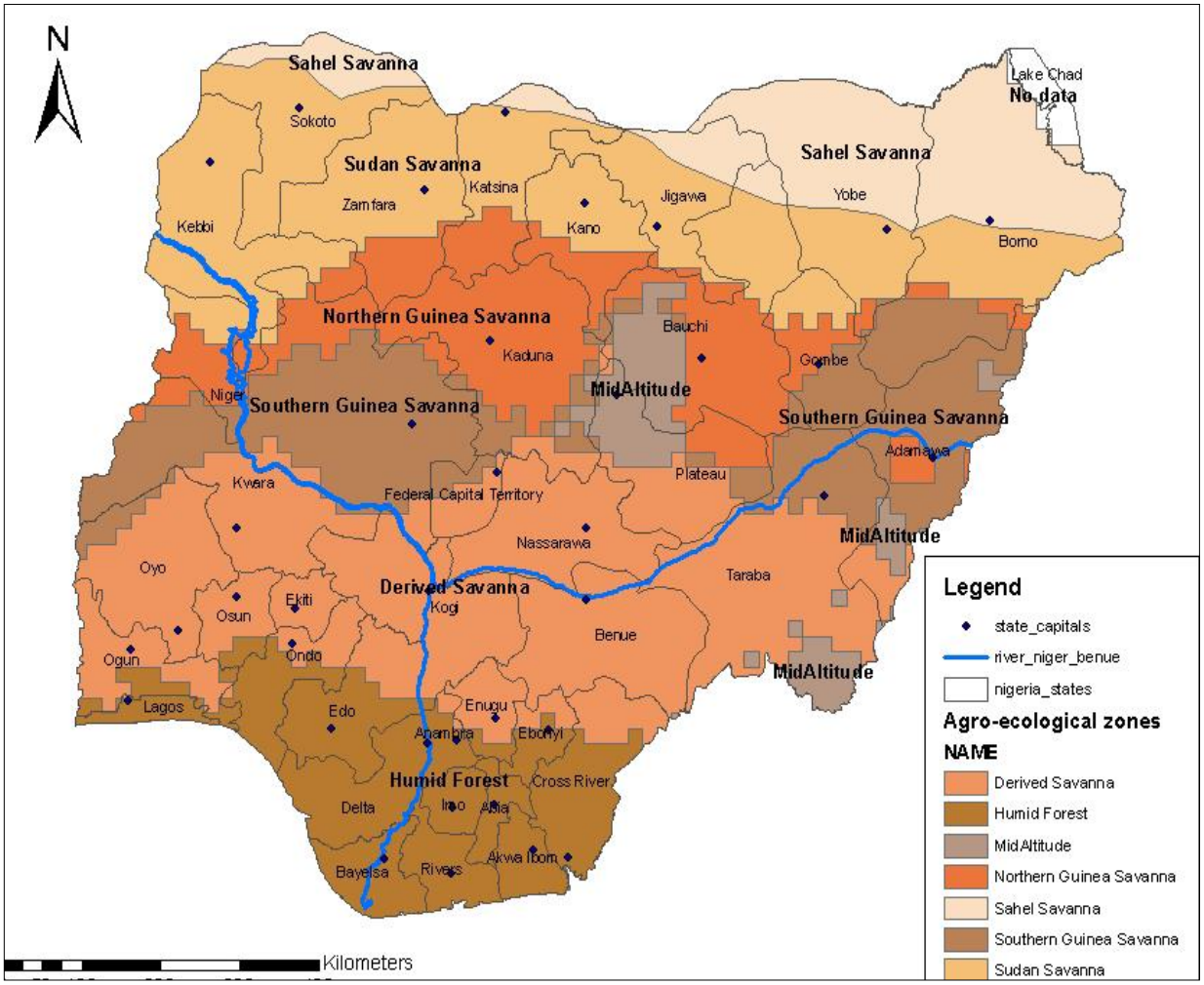
Appendix I: Agro-ecological zones map of Nigeria




Appendix II: Major groundnut-producing countries: area, yield and production of nuts-in-shell in 1991 of countries producing > 500, 000 t per annum. After FAO (2009).

| Country | Area (m $ha^{-1}$) | Yield (t $ha^{-1}$) | Production (m t) |
|---|---|---|---|
| India | 8.26 | 0.85 | 7.00 |
| China | 3.05 | 1.98 | 6.06 |
| USA | 0.81 | 2.76 | 2.24 |
| Nigeria | 1.05 | 1.16 | 1.22 |
| Indonesia | 0.63 | 1.46 | 0.92 |
| Senegal | 0.80 | 0.87 | 0.70 |
| Myanmar | 0.56 | 0.91 | 0.51 |

After: FAO (1992).

Appendix III: Rating for soil fertility classes

| Parameter | Low | Medium | High |
|---|---|---|---|
| Total N (g $kg^{-1}$) | < 1.5 | 1.5 - 2.0 | > 2.0 |
| Bray 1 P (mg $kg^{-1}$) | < 8.0 | 8 - 20 | > 20 |
| Exch. K (cmol $kg^{-1}$) | < 0.2 | 0.2 - 0.4 | > 0.4 |
| Exch. Ca (cmol $kg^{-1}$) | < 5.0 | 5.0 - 10.0 | > 10.0 |
| Exch. Mg (cmol $kg^{-1}$) | < 1.5 | 1.5 - 3.0 | > 3.0 |
| Exch. Na (cmol $kg^{-1}$) | < 0.3 | 0.3 - 0.7 | > 0.2 |
| Org. Matter (g $kg^{-1}$) | < 20 | 20 - 30 | > 30.0 |

Source: FMAWRRD (1989) and FMANR (1990)

Appendix IV: Ratings for soil fertility classes for available DTPA micronutrients

| parameter | Micronutrients Ratings (mg $kg^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Very low | Low | Medium | High | Very high |
| Zn | < 1.0 | 1.0 – 1.5 | 1.6 – 3.0 | 3.1 – 5.0 | > 5.0 |
| Cu | < 1.0 | 1.0 – 2.0 | 2.1 – 4.0 | 4.1 – 6.0 | > 5.0 |
| Fe | - | < 2.5 | 2.5 – 5.0 | > 5.0 | - |
| Mn | < 1.0 | 1.0 – 2.0 | 2.1 – 3.0 | 3.1 – 5.0 | > 5.0 |

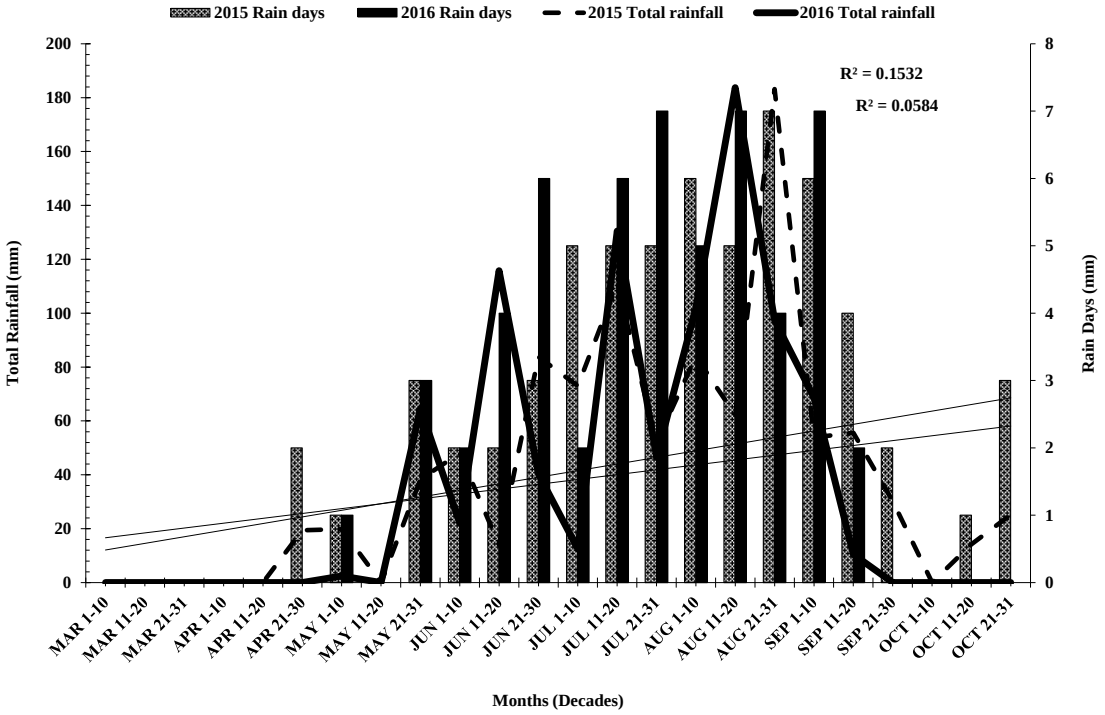
Source: Esu, (1991).

Appendix V: Meteorological information for the experimental sites during 2015 and 2016 cropping seasons

| **Location** | **Minjibir** | | | | **Samaru** | | | |
|---|---|---|---|---|---|---|---|---|
| Season | 2015 | | 2016 | | 2015 | | 2016 | |
| Month | MM Temp. ($^{O}$C) | MM Rainfall (mm) | MM Temp. ($^{O}$C) | MM Rainfall (mm) | MM Temp. ($^{O}$C) | MM Rainfall (mm) | MM Temp. ($^{O}$C) | MM Rainfall (mm) |
| Mar. | 0 | 0 | 0 | 0 | 36 | 91 | 35 | 25 |
| Apr. | 41 | 19 | 39 | 0 | 36 | 0 | 39 | 2 |
| May | 40 | 58 | 27 | 67 | 37 | 90 | 35 | 81 |
| Jun. | 35 | 146 | 34 | 178 | 33 | 66 | 31 | 133 |
| Jul. | 31 | 236 | 32 | 174 | 31 | 189 | 31 | 218 |
| Aug. | 31 | 329 | 31 | 399 | 30 | 249 | 31 | 269 |
| Sep. | 33 | 140 | 32 | 79 | 32 | 34 | 30 | 229 |
| Oct. | 35 | 39 | 35 | 39 | 33 | 64 | 34 | 0 |
| Total | | 967 | | 936 | | 783 | | 957 |

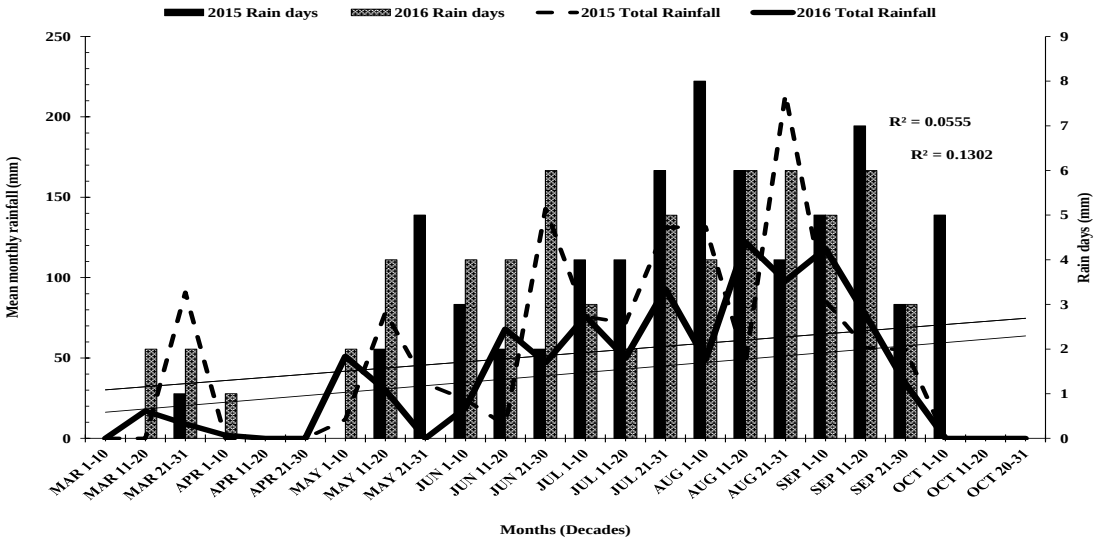
MM = mean monthly; Temp. = temperature.
Source: Meteorology Unit of the Institute for Agricultural Research, Ahmadu Bello University, Zaria

Appendix VI: Total (decadal) rainfall and raindays information for the Sudan savannah agro-ecology (Minjibir) in 2015 and 2016 cropping seasons




Source: Meteorology Unit of the Institute for Agricultural Research, Ahmadu Bello University, Zaria

Appendix VII: Total (decadal) rainfall and rain-days information for the northern Guinea savannah agro-ecology (Samaru) in 2015 and 2016 cropping seasons




Source: Meteorology Unit of the Institute for Agricultural Research, Ahmadu Bello University, Zaria