THE EFFECT OF DIRECT PHOSPHORUS AND POTASSIUM FERTILIZATION ON SOYBEAN (*GLYCINE MAX* L.) YIELD AND QUALITY

by

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DECLARATION

This thesis has been composed by myself and has not been accepted in any previous application for a degree. It is a record of the work that has been done by me and all sources of information have been acknowledged by means of references.

Signed: ……………………. Date: …………………………

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LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	Analysis of Variance
CEC	Cation Exchange Capacity
CRBD	Completely Randomized Block Design
DAFF	Department of Agriculture, Forestry & Fisheries
K	Potassium
KCl	Potassium chloride
LA	Leaf Area
LAI	Leaf Area Index
LSD	Least Significant Difference
OPT (P)	Optimum soil P
P	Phosphorus
PRF	Phosphorus Requirement Factor
WAP	Weeks After Planting

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ABSTRACT

Soybean is a vital cash, oil and protein crop. To achieve good yields and quality, adequate amounts of essential nutrients are required. Therefore, application of P and K plus inoculation with *Bradyrhizobium* bacteria should be included in the general production of soybean. However, the practice in South Africa is to apply no P and K when producing soybean since the farmers rely on residual P and K from the previous cropping season. The objective of this study was to determine that direct P and K application to a soybean crop may have positive results in terms of production and quality. The research was conducted at the Hatfield Experimental Farm of the University of Pretoria under green-house and open field conditions during the 2010/2011 season. The field trial treatments consisted of combinations of 3 levels of P (0, 20 and 40 kg P ha^{-1}) and 3 levels of K (0, 50 and 100 kg K ha^{-1})applied in factorial combination for a Completely Randomized Block design, replicated four times. The pot trial was also a factorial experiment using a Completely Randomized Design with the two factors each at five levels of application (P at 0, 10, 20, 30 and 40 kg P ha^{-1} and K at 0, 50, 100, 150 and 200 kg K ha^{-1}). Each treatment combination was replicated four times. Phosphorus and K were applied as Superphosphate (10.5%) and KCl (50%) respectively. The cultivar LS 6161R was planted under rain-fed conditions while LS 6162R was used as test crop in the green-house. Seeds were inoculated at planting with *Bradyrhizobium japonicum*, with no additional N applied during the season. Composite soil samples were collected from each plot and pot before and after planting and analyzed for pH (H_2O) and plant-available nutrients.

During the growing season,the field trial plants were sampled for LAI while canopy closure and plant height were measured for plants in the middle rows of each plot. Harvesting commenced after leaves senesced and pods had turned brown. The data recorded was on the number of pods per plant, number of seeds per pod, number of nodes per plant, fresh and dry root, stem and pod mass, 100-seed mass, total seed yield as well as protein and oil content. The results for the field trial showed that K significantly improved plant height, canopy closure and 100-seed mass as compared to the control. The application of P and K revealed no significant impact on leaf area index. Although not significantly, pod number per plant was reduced by applying P, resulting in the control having the highest number of pods. A significant improvement in grain yield was observed through application of K. The highest grain yield (2.60 t ha^{-1}) was observed at the highest K level (100 kg K ha^{-1}). The lowest grain yield was observed where no K fertilizer was applied. Although grain yield was not significantly affected by P nor the P*K interaction, there was a trend of increased yield with increased levels of P and P*K.Phosphorus, irrespective of the application rate, increased protein content but decreased oil content, while increased K application rates resulted in increased oil content while it decreased the protein content as compared to the control.

The green-house data showed that plant height was significantly and positively affected by P, K as well as the P*K interaction. Maximum mean plant height were recorded with low application of P and no K (10 kg P + 0 kg K ha^{-1}) as well as medium application of K and no P(0kg P + 100 kg K ha^{-1}) which were significantly higher than the measurements recorded at 20, 30 and 40 kg P

ha^{-1} regardless of K applied. In general, the range in number of nodes per plant was very narrow (19 to 21) and node number was not affected by P and K application. The lower levels of P fertilizer (10 and 20 kg P ha^{-1}) gave the greatest number of pods. P*K interaction effects were not significant. With two exceptions, plants receiving 40 kg P ha^{-1} regardless of K tended to have the highest number of nodules. Although there was no statistical significance recorded between the treatments, 30 kg P + 150 kg K ha^{-1} produced the highest root fresh mass which is higher than that of the control plants but on par with plants receiving 10kg P + 100 kg K ha^{-1}. The data on dry root mass of soybean had shown that various rates of P had a negative effect on it. There was a gradual decrease in pod mass with increased application of P from 10 to 40 kg P ha^{-1}with the latter having the lowest pod mass than even that of the control. Although K and P*K interaction were not significant, all K application rates resulted in increased fresh and dry stem mass.

From the current study, medium to high levels (± 100-150 kg K ha^{-1}) of K applied directly to the soybean crop can be recommended as it had a positive impact on soybean growth and yield. On the other hand, the plant’s reaction to P was very much dependent on the initial soil P level, resulting in varying reactions. Therefore the farmer’s practice of using residual P from the previous season could not be proven completely wrong.

CHAPTER 1

INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important leguminous crops grown for its high nutritive value. Soybeans are believed to have originated in East Asia and the site of domestication can be traced back to Northern China where it was one of the main crops in the 11th century B.C. It was then distributed to the USA and tested by the Scientific Agricultural School and then worldwide by missionaries. It was introduced in Africa from China late in the 19th century and is now widespread across the continent (Lance & Benson, 2005). In South Africa, soybean was firstly believed to be grown in the Cedara Memoirs of 1903 and research station at Potchefstroom in the early 1950s from where the cultivar Geduld was developed and released (DAFF, 2010). This was the most important cultivar up to the early 1980s. Initially, soybean production was limited to Bapsfontein and the northern Lowveld areas and it became important in rotation with wheat in irrigation areas (DAFF, 2010).

A research report by Rodney (2012) shows that soybean production in South Africa is currently 655700 tons per annum with an average yield of 1.39 t ha^{-1} under dry-land condition. According to DAFF (2010), Mpumalanga province produces the largest quantities of soybeans (about 42%). The Free State produces 22% of the total harvest, while KwaZulu-Natal produces 15%, Limpopo 8%, the North West 5% and Gauteng 2%.

This crop is grown as a cash crop by both small scale and commercial farmers. According to Lance and Benson (2005), soybean is one of the larger crops in terms of cash sales and the number one export crop as whole soybean, soybean meal and soybean oil in the United States of America, while South Africa is net importers of soybean oil cake. Dugjie *et al.* (2009) indicated that soybean seeds contain about 18-20% oil on a dry matter basis, and this is 85% unsaturated and cholesterol-free. It is mainly used as a protein supplement, beneficial as building blocks in the bodies of both humans and animals (Merrit & Jenks, 2004). Miniello and Moro (2003) and Giampietro *et al.* (2004) indicated that soybean can be used as protein substitute in various baby formulas in cases where infants are allergic to pasteurized cow milk which affects their growth and development. Not only is soybean a food source for humans, but is also used as a fodder crop for animals. Lance & Benson (2005) clearly stated that soybeans are often used as forage crop rather than harvested for seed which is rich in Omega-6 and important in animal health.

This crop is fast growing and high yielding if grown in soil with a good supply of essential nutrients, hence good soil fertility management. Soil fertility, according to Rooyani and Badamchian (1986) is the ability of the soil to supply essential nutrients in appropriate forms, quantities and proportions for optimum plant growth. The nutritional requirements of soybean are moderately high in comparison with other grains and the crop does best in soils of medium to high fertility and with a favourable soil pH of around 6.5 (Franzen, 1999) while making good use of applied fertilizers (Gregoire, 2005). Therefore, even when the best soybean varieties and cultural practices are used, it could result in the crop not reaching full potential unless soil fertility is properly managed (Alan *et al*., 2005). In addition, soybean plants require a loose, well-drained loamy soil that allows for good aeration and good water-holding capacity (Edamame, 2005). A study by George (2001) also showed that the soybean plant has a strong tap-root system and is able to use nutrients in the subsoil very effectively.

However, research on soil testing reported that about 25% of the soil samples for soybean cultivation, tested low to very low in available P and K (George, 2001). Gregoire (2005) also reported that, approximately 60% of P and 50% of K taken up by a soybean plant is removed from the field when the seeds are harvested. As such, if P availability is low, a band application of 4.5to 14 kg P ha^{-1} is beneficial and if the soil is low in K, 2.5 kg K ha^{-1} is required to raise the soil K test by 1mg kg^{-1} with the recommended fertilizer source being potassium sulphate (Gregoire, 2005). Some researchers have shown that a response to P fertilization should not be expected if the soil test for P is higher than 20-25 mg kg^{-1} (measured by Bray-1 procedure). As like phosphate use, the response to potash fertilization should not be expected if the soil test for K is higher than 120 mg kg^{-1}(George, 2001).

Phosphorus and Potassium play an important role in the growth and development of soybean. They increase frost and disease tolerance, palatability, storage quality as well as yield (Manitoba Soil Fertility Guide, 2004). Phosphorus specifically, enhances photosynthesis rates, enzymatic activity, root development, uptake and transfer of other nutrients and seed germination (Snyder, 2000). Phosphorus deficiency is reported to reduce nodule formation and growth while an adequate supply leads to good development of nodules (Wall *et al*., 2000). However, very high soil phosphate values may depress seed protein and oil content while yield will be low if available Phosphorus is less than 30 kg P ha^{-1} (DAFF, 2010).Similarly, K regulates several plant processes including; water and nutrient transport across cell walls, and regulation of water vapour and carbon dioxide (CO_2) exchange through stomata. Potassium deficiency is reported to cause stunted growth and chlorosis (George & Michael, 2002).

Since soybeans are very efficient in deriving most of their nitrogen needs through N-fixation, no additional N fertilizer application is required (George, 2001). For this reason, the application of other essential nutrient elements like P and K for soybean is often overlooked with the myth being that soybeans don't need fertilizer or soybeans don't need fertilizer management at all. This culture of ignoring soybean P and K fertilizer application is a problem amongst farmers in South Africa resulting in; (1) incorrect P and K application rates used and (2) a lack of knowledge on how soil properties like soil pH, soil structure and/or drainage affect the availability of these nutrients.

Research has indicated that very low pH_{water} (< 5.0) or very high pH_{water} (> 8.0) affects the cycling and overall availability of N, P and K in the soil (Rooyani & Badamchian, 1986). They indicated that the micro-organisms that fix N survive well in a neutral soil pH (7.0), while a low pH causes them to be inactive hence N-fixation is inhibited. Similarly, nutrient elements like P and K under low pH conditions can combine with acid cations (Fe, Cu and Zn) resulting in plant inaccessible compounds (Murata, 2003).

Therefore, soil amendments like application of lime to correct pH should not be neglected when applying P and K fertilizers (Adam, 1980). The fact is that if one wants to manage soybean for higher yields, a good long term fertility plan needs to be in place. Thus, to obtain high yield levels, soil fertility status and plant nutrient concentration must be monitored and adjusted to ensure adequate nutrient availability (Venter, 2003). Thus, the study is aimed to detect the potential effect of direct applied P and K on the overall productivity and yield of soybeans.

HYPOTHESIS

- In season application of Phosphorus and Potassium have a positive effect on growth and yield of soybean and should therefore be included in the general production practices of soybean.
- In season application of Phosphorus and Potassium have a positive effect on soybean oil and protein content.

OBJECTIVES

GENERAL OBJECTIVE

The practice in South Africa is not to apply P and K directly to a soybean crop but to rely on residual soil P and K from the previous cropping season. Therefore, the main objective of this study is to prove that P and K applied directly to a soybean crop can have a positive result in terms of production and quality.

SUB-OBJECTIVES (Specific objectives)

- To evaluate the effect of P and K on the growth of soybeans in terms of plant height, canopy closure and LAI.
- To record the yield and yield components of soybean in response to applied P and K.
- To record the oil and protein content of soybean in response to P and K.

CHAPTER 2

LITERATURE REVIEW

SOIL, PHOSPHORUS (P) AND POTASSIUM (K) RECOMMENDATIONS FOR SOYBEAN

2.1: RECOMMENDED LEVELS

All fertilizers applied should be provided as easily plant-available forms. In the case of P and K, plants can take it up in ionic forms namely $H_2PO_4^-$ (Dihydrogen phosphate) or HPO_4^{2-} (Monohydrogen phosphate) and K^+ respectively (Rooyani & Badamchian, 1986). Soybeans usually prefer their rooting zone bathed in nutrients, rather than concentrated in a small area of the root-zone (Franzen, 1999). Phosphorus is greatly demanded just before the pods begin to form and continues until 10 days before seeds are fully developed (Vitosh *et al.,* 2004), while K uptake is highest during rapid vegetative growth and slows as seed formation begin. The recommended rates for P and K are given based on the following equations (Havenga, 1997):

*Recommended P (kg ha^{-1}) = (OPT. P Value – soil P) x PRF

Where;

OPT (P) = Optimum soil P test value for soybeans (It varies with soil texture and sample density is used as an indicator for soil texture).

PRF = Phosphorus Requirement Factor. It is an amount of applied P ($kgha^{-1}$) required to raise the soil test value by 1 mg L^{-1}.

*Recommended K (kg ha^{-1}) = (Optimum K - soil K) x 2.5

Where applied K is mixed into the soil, it is assumed that 2.5kg K ha^{-1} is required to raise soil K by 1 mg L^{-1} (it is constant).

According to Havenga (1997) the minimum level of P recommended for soybean is 20kg P ha^{-1} and if the soil test value is greater than or equal to 50 mg L^{-1}, then no additional P is recommended while that for K is 120 mg L^{-1}. For soil build up and increased soybean yields, P and K application rates of 13 – 26 and 42 – 149 kg ha^{-1} for P and K respectively are recommended (Table 2.1).

Table 2.1: Phosphorus and Potassium fertilizer recommendations for soybeans (adopted from Johnson, 1989; Havenga, 1997)

Soil test level	**Nutrient recommendations**		
	P (kg ha^{-1})	**K (kg ha^{-1})**	
		Low or medium clay content	**High clay content**
Low	18 –26	83 – 125	100 – 149
Medium	13–18	42 – 83	58 – 83
Adequate	0 – 13	0 – 42	0 – 58
High	0	0	0

However, the rate of P and K to apply depends on quantity of nutrients available within the soil as measured by a soil test, soil type and P and K removal by harvested crop (Vitosh *et al*, 2004). Therefore, to accurately estimate P and K supply of the soil, a soil test based on a representative soil sample collected from the upper root zone at about 0 to 15 cm depth should be conducted. For instant, 60% of soybean rates occur in the top 0 – 15 cm of the soil. According to Snyder (2000), if the crop nutrient removal is greater than the rate of application and soil test results are low, P and K application is recommended to raise the soil content levels over time. The recommendation rates should be followed annually for four years, after which soil should be tested again and rates be adjusted accordingly (Richard *et al.,* 2003). Mike and Darryl (2010) also indicated that the crop response to fertilization is correlated with exchangeable P and K in the soil based on fertilizer recommendation scheme. An example of P and K fertilizer recommendation scheme is shown in Figure 2.1.

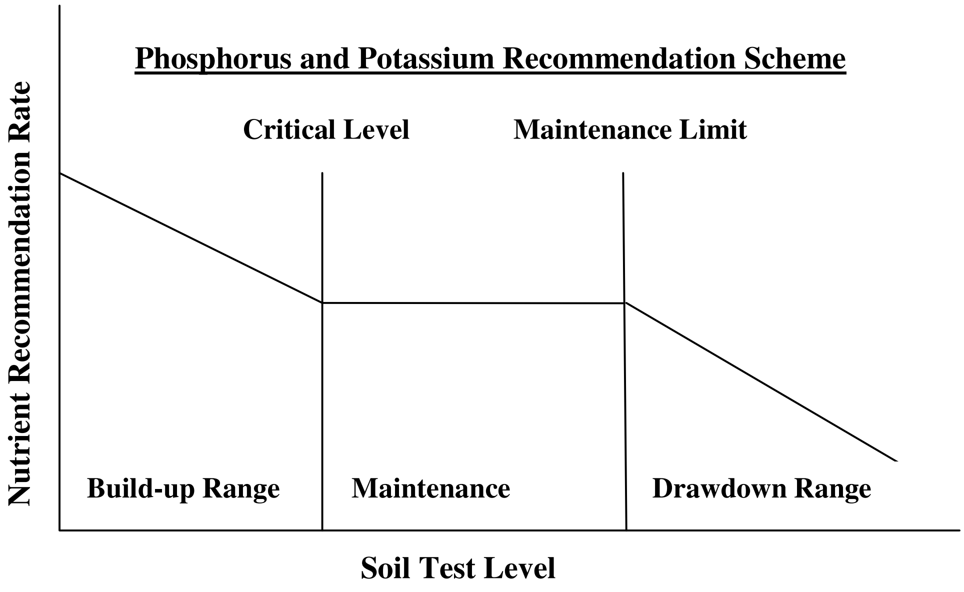


Figure 2.1: Fertilizer (P_2O_5 and K_2O) recommendation scheme (adopted from Mike & Darryl, 2010)

If the soil levels are higher than the critical level (Figure 2.1), the soil should be capable of supplying the nutrients required by soybeans and no fertilization would be expected. This means, in the build-up range, the likelihood and magnitude of response to nutrient application increases as the soil test drops farther below the critical level. According to Mike & Darryl (2010), once the soil test level has reached the critical level for either P or K, enough of that nutrient will be available to produce 95 to 97% of a soil's maximum yield potential. The critical level for Pfor soybeans is15 mg kg^{-1} (Mike & Darryl, 2010) while that of K is calculated by the following formula;

Critical level = 75 + (2.5 x CEC)

CEC = Cation exchange capacity.

The recommendation used in the maintenance region is a safe-guard against sampling or analytical variation, and nutrient recommendation is equal to crop removal rate (Vitosh *et al.,* 2004). Since the purpose of fertilizer application in the maintenance range is to maintain fertility, response to fertilizer in the year of application could be expected. Mike and Darryl (2010) indicated that in the drawdown range, nutrient availability is more than what the crop is removing with soybeans removing 8-9 kg P and 25-40 kg K per ton seed produced per ha.

2.2: RECOMMENDED SOILS

Soybean is more likely to exhibit P and K deficiencies in sandy and silt loam soils (Snyder, 2000). Clay soils tend to have higher native soil P and exchangeable K levels than coarse textured soils. However, with an increase in clay content, P availability may become low because of immobility and fixation on colloidal soil particles. Franzen (1999) showed that soybeans are excellent scavengers of P at medium to higher soil P levels, therefore it is better to load the soil with P-fertilizer at this range of soil test levels. The reason being that, P and K uptake by soybeans occur through a diffusion process (movement of nutrients are from high concentration to low concentration) and if P and K are not maintained at medium to high soil test range levels, diffusion would be impaired, nutrient uptake would be limited and yield would decline (Snyder, 2000). Research reports (Snyder, 2000) indicated that nutrient shortages during the most rapid uptake period can result in significant yield losses.

2.3: ROLE OF PHOSPHORUS AND POTASSIUM IN SOYBEAN

2.3.1(a): Phosphorus' role in the soybean plant and results of a P deficiency

Phosphorus, like N, is essential for growth of soybeans. Phosphorus plays an important role in cell division (Rooyani & Badamchian, 1986) and this helps in growth of the root and consequently the whole structure of the plant including the meristem. Murata (2003) reported that low application rates are a limiting factor in soybean growth. Phosphorus deficiency is reported to cause deep green to blue and later purple coloured leaves. This therefore prevents photosynthesis due to a lack of chlorophyll, and plant growth becomes stunted (Rooyani & Badamchian, 1986). Phosphorus deficiency can also be linked to the reduction of N content in the plant and metabolism activity as well as growth and activity of nodules (Sa & Israel, 1995; Tang *et al*., 2001). This implies that the soybean plant weakens due to a lack of P, as P is responsible in supporting nitrogen fixation. With limiting P, Jnshu and Israel (1994) found a decrease in sucrose content of the soybean nodules while Tsvetkova and Georgiew (2003) found a decrease in the total nodule respiration rate (low root ATP concentration). Therefore there is a need to apply P fertilizers to meet the plants growth requirements since P deficiency can lead to a low energy status in the soybean nodules and therefore poor N fixation and availability to the plant itself.

2.3.1(b): Processes that lead to P unavailability

Phosphorus content in the soil can be low due to sorption and precipitation. Phosphorus fixation is an important factor that needs to be considered when P fertilizer is to be applied. Phosphorus can be fixed and bound to Fe and Al under acid conditions and therefore become unavailable to plants (this is P-adsorption) (Marschner, 1995a; Iyamuremye & Dick, 1996; Murata, 2003). Calcium content in the soil decreases the cation exchange capacity and thereby causes the soil to be even more alkaline. Under high pH (>8), P can combine with Ca making it unavailable to plants (Figure 2.2). Therefore, in order to improve the growth of soybeans, P fertilizer needs to be applied to meet soluble-P requirements. Furthermore, small portion of the total soil P is dissolved in the soil solution in the orthophosphate form which is then readily available to plants (Rooyani & Badamchian, 1986). As the plant depletes orthophosphate in the soil solution, dissolved P is replenished from P in a soil pool (sometimes referred to as labile P) in which P is held by a variety of relatively weak bonds to mineral particles and organic matter (Tisdale *et al*, 2005). The majority of soil P is in a stable pool (sometimes referred to as non-labile P) in which it is strongly held to mineral particles or is combined in mineral compounds of low solubility. The degree and strength to which P is bound in soils are largely determined by the amount and types of Al, Ca, and Fe compounds present and by other soil properties such as pH, organic matter, clay mineralogy, and the amount of P currently present in the soil. Furthermore, some studies have indicated that if P is applied together with organic manure, it can be released and become available hence improving its use by plants (Iyamuremye *et al*., 1996).

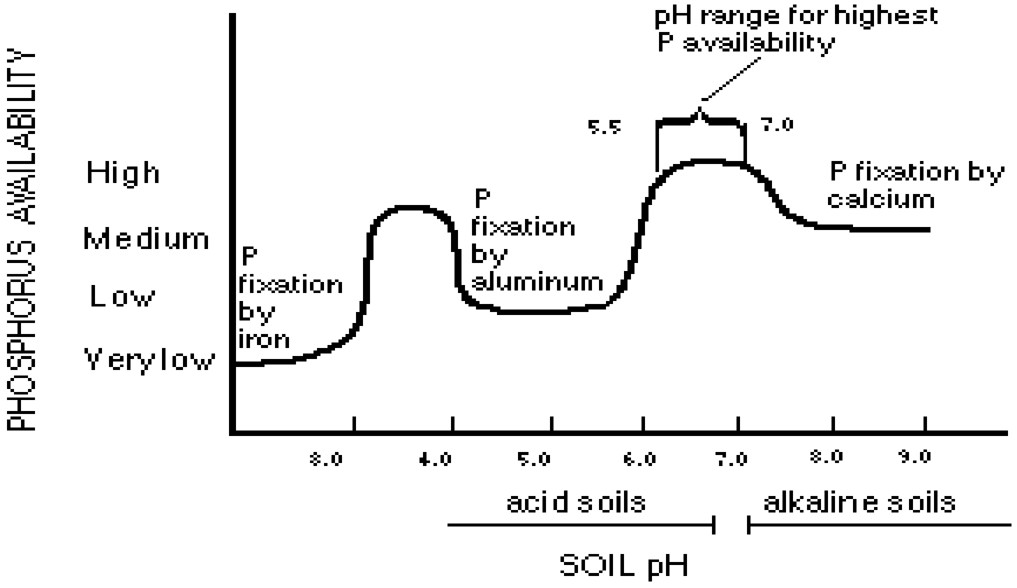


Figure 2.2: Availability of Phosphorus as affected by soil pH (after Tisdale *et al.*, 2005).

However, Figure 2.3 shows that excessive P applications can result in increased P delivery to water resources as eroded from the land and as dissolved P in surface runoff or subsurface drainage. It can also move into groundwater as dissolved P. Only a small portion of the total P is readily available to plants (Rooyani & Badamchian, 1986).

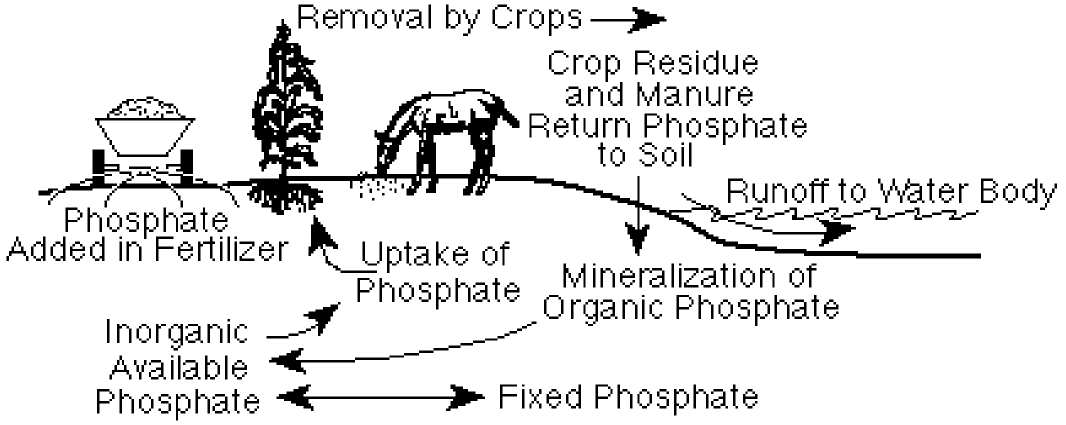


Figure 2.3: Phosphorus cycle (after Rooyani & Badamchian, 1986).

2.3.1(c): Soybean growth and yield parameters in response to Phosphorus

Since P is important in legumes for grain formation and root establishment, it needs to be applied in adequate quantities. Malik *et al.* (2006) argued that soybean requires no N fertilizer (if inoculated) but more P as it plays a vital role in getting higher yield with better grain quality. They studied different aspects of soybean growth and yield applying different Phosphorus treatments namely; control (T_1), 0 kg P ha^{-1} (T_2), 30(T_3), 60(T_4), 90(T_5) and 120 kg P ha^{-1} (T_6). All the P treatments (T2 – T6) were inoculated with *Rhizobium*. For the control, N in the form of urea was used, but no P was applied.

In terms of the number of plants per m^2, none of the treatments significantly affected survival (Table 2.2) although T_5 (90 kg P ha^{-1}) seemed to have had a slightly more positive effect as compared to the other treatments. There was, however, a significant increase in plant height for the treated plants as compared to the control (Table 2.2), with the control plants being the shortest while those receiving 120 kg P ha^{-1} plus *Rhizobium* (T_6) were the tallest. The leaf area index similarly increases with an increase in the rate of P-fertilizer (T_3-T_6) and also responded well to the *Rhizobium* treatment (T_2) (Table 2.2).

By increasing P-fertilizer rates (T_3-T_6), the number of pods per plant increased as did the seed number within each pod (Table 2.2). The number of pods increased from 30.67 (control) to 36.53 (120 kg P ha^{-1} plus *Rhizobium* (T_6)). Inoculation alone (T_2) also had a significantly positive effect on the number of pods per plant, but there was no significant differences between the treatment and the control in terms of number of seeds per pod (Table 2.2). These results agree with the work of Mandal and Sikder (1999) who reported an increase in pod and seed yield as well as the number of seeds per pod with more P being applied.

The seed yield also increased gradually with the combination of inoculation and P-fertilizer application where maximum seed yield obtained was 1955.56 kg ha^{-1} at T_6 and the minimum was 1274.07kgha^{-1}for the control (Table 2.2). Similarly, harvest index was the highest at T6 (40.9%) and the lowest under control conditions (36.6%) (Table 2.2).This study is similar to that of Farani (1988) and Ali *et al.* (2004) who reported an increase in seed yield and harvest index due to increased levels of P.

Table 2.2: Production of soybean as affected by different P levels and seed inoculation (adopted from Malik *et al*., 2006).

Treatment	**Number of plants m^{-2}**	**Plant height (cm)**	**Leaf area index**	**Number of pods plant^{-1}**	**Number of seeds pod^{-1}**	**Seed yield (kg ha^{-1})**	**Harvest index (%)**
T1	38.01	49.37e	3.46e	30.67e	2.30d	1274.07d	36.58b
T2	38.39	51.03d	4.32d	31.97d	2.31d	1540.74c	37.57b
T3	38.51	53.37c	4.81c	33.10c	2.40c	1703.71b	40.06a
T4	38.14	54.47bc	5.65b	33.37c	2.43c	1777.78b	40.53a
T5	38.88	54.87b	5.76ab	34.90b	2.66b	1911.12a	40.69a
T6	38.37	56.20a	5.95a	36.53a	2.73a	1955.56a	40.85a

Any two means in a column not having a letter in common differ significantly at the 5% level of probability.

The results obtained (Table 2.2) also correlates with the findings of Aulakh *et al*. (2002) who indicated that application of Phosphorus fertilizer resulted in better soybean yield especially if applied during humid summers. Aulakh *et al*. (2002) further denoted that humidity minimize the P from moving down by the soil profile. The study was conducted with different levels of P applied to soybean (0, 40, 60, 80 and 100 kg ha^{-1}) and all showed an increased yield over no P being applied (control) up to 80 kg P ha^{-1} (Table 2.3). Higher applications of P-fertilizer (> 80 kg P ha^{-1}) seemed to have reduced the yields. The implication is that as more and more P is applied to the same crop year after year, the yield initially increases till the maximum point where the yield cannot increase any more. The yield at this stage declined due to high concentrations of fertilizer which becomes toxic to the plant.

Table 2.3: Grain yield and Harvest Index of soybean as influenced by different P rates (adopted from Aulakh *et al*., 2002)

Application rate ($kg\ P\ ha^{-1}$)	**Grain yield ($t\ ha^{-1}$)**				**Harvest Index (HI)**
	1993	**1994**	**1995**	**Mean**	
Control	1.52	1.54	1.43	1.50ab	0.39bc
P Applied to soybean					
40	2.17	1.96	2.21	2.11a	0.41b
60	2.36	2.23	2.43	2.34a	0.41b
80	2.53	2.54	2.62	2.56a	0.43b
100	2.51	2.51	2.57	2.53a	0.43b

Means with the same letter are not significantly different from each other at 5% level of confidence

2.3.2 (a): Potassium's role in the soybean plant and results of a K deficiency

Potassium is the most abundant inorganic cation in plants and contributes to about 10% of the dry plant mass (Leigh & Jones, 1984). Potassium is applied in the form of Potassium sulphate or Potassium chloride (water soluble fertilizer).

Many authors have stated the function of K in plants. Tiwani *et al.* (2001) reported K as an important macro-nutrient for metabolic, growth and stress adaptation. In metabolic functioning, Marschner (1995b) stated K as being important in enzyme activation, stabilization of protein synthesis as well as maintenance of cytoplasm pH. Since the role of K is related to cell functioning, it is essential for growth. Pollard (1983) indicated that chloroplasts are responsible for capturing sunlight for the food manufacturing process while the cytoplasm is responsible for growth of the cell, hence the growth of the plant as a whole. Therefore the overall functioning of the plant parts depends on the mobility of K as it is responsible for sustaining the movement of other ions like H^+, sugars and nitrates throughout the whole plant (Marschner, 1995c). Potassium deficiency in the soil is not as common as compared to that of Phosphorus (Fageria *et al*., 2001). Most of the deficiencies are seen in the late stages of soybean growth (flowering to seed filling stages) since its concentration decreases at crop maturity (Aulakh *et al*., 2002).

One of the common K deficiency signs is yellow scorching or firing (chlorosis) along the leaf margins. That is, the margins of upper leaves turn brown and these dead tissues may fall out. In addition, the entire leaf has a light green colour as viewed from a distance (George & Michael, 2002). Furthermore, the presence of Aluminium results in reduced K and thus stunted plants (Sumner *et al*., 1991). According to Armengand *et al.* (2004), K deficiency causes a reduction in growth of the aerial parts as well as lateral roots.

Since K is highly mobile in the plant, there is a need to supply K as an inorganic fertilizer as it gets depleted quickly due to its translocation (Finck, 1982). This measure is made to avoid its deficiency as the growth of the soybean can be retarded in the absence of K. Plants lacking K have reduced photosynthetic rates and impaired regulation of transpiration (Fageria *et al*., 2001). Volenec *et al*. (1996) reported that if soybean photosynthesis is limited, the sugars (food) essential for growth are stopped and the plant cells would not function very well, and as a result plants would die off. This deficiency becomes the limiting factor in high yielding crops.

2.3.2 (b): Processes leading to K unavailability

Like N, K can leach out of the root zone due to heavy rains in poorly structured soils. The other way in which K can be deficient in the soil is due to high plant uptake which results in low residual soil K for the follow up crop. Kolar and Grewal (1994) observed negative K-balance in soybeans due to removal of crop residues by farmers without replacing K. This agrees with the work of Laegreid *et al*. (1999) who suggested that K needs to be applied to plants as its deficiency leads to inefficient use of nitrates which can then leach into ground water. This seems to lower the yield of the soybean as they depend on a steady K supply for their needs.

There are several processes that contribute to the unavailability of Potassium in the soil. Soil solution Potassium is already available in the soil for plant uptake (Figure 2.4), however, the concentration of Potassium is affected by soil weathering, cropping history and fertilizers used. Exchangeable Potassium can reach rapid equilibrium with the soil solution Potassium and it is considered as readily available (Figure 2.4). Fixed and lattice potassium can be grouped together and make up the pool of non-exchangeable inorganic Potassium in the soil (Foth & Ellis, 1997).

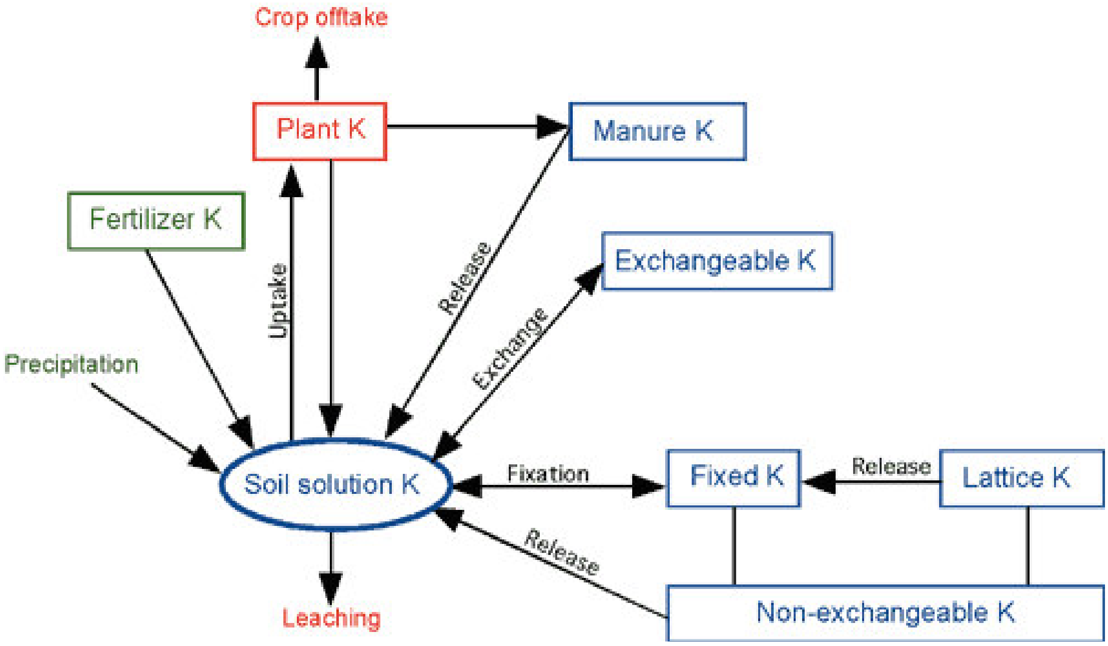


Figure 2.4: Potassium Cycle (adopted from Tisdale *et al.*, 2005).

Factors that lead to unavailability of K therefore include amongst others, soil moisture, soil type, soil air, clay soil type and or cation exchange capacity. High soil moisture means greater availability of K. That is, increased soil moisture increases mobility of K to the soybean plant roots and enhances availability. Brandy and Weil (1999) stated clearly that moisture supply is necessary for diffusion of K to plant roots for uptake. For example, Gene *et al.* (2010) found that increasing soil moisture from 10-28% doubles total soil K transport. Therefore, a soil moisture deficiency can limit K transport, uptake and hence influences K availability.

The soil type is another influential factor in the availability of K. For example, clay soils have high K fixation and can show little response to the applied K fertilizer because available K binds to the clay (Tisdale *et al.*, 2005). On the other hand, sandy soils have a low K supplying power because of low CEC, therefore K availability becomes low in such soils. Ewanek (1989) also showed that calcareous soils tend to have a high concentration of calcium on clay surfaces and on the exchangeable sites and can decrease sorption and increase soluble K. In addition, high concentrations of calcium and magnesium limit K uptake by competing for binding sites on the root surface.

Potassium availability would basically dependent on the clay and organic matter content. Clay and organic matter are negatively charged and therefore have the ability to hold positively charged cations like K (Agsource Cooperative Service, 2006). This ability to hold (not imprisoning) positively charged cations ‘so called soil CEC’ is beneficial because availability of K to soybean plants increases as percentage of exchangeable sites occupied with K increases.

There are basically three soil types that trap K and control its availability (Agsource Cooperative Service, 2006). These include muscovite and mica, illite and montmorillonite or vermiculite. In micaclay types, K is imprisoned between the clay layers and is unavailable to the plants roots. Similarly, Foth and Ellis (1997) showed that illite clay types are a product of weathered muscovite and mica clays and are frayed and wedged open, and can capture K within the walls when repaired. However, vermiculite lacks interior walls that bind clay layers together. Therefore, this allows this clay type to expand and contract during wetting and drying cycles and thereby holding K in a way that makes it readily available for plant roots (Rooyani & Badamchian, 1986). For the roots to function, they require oxygen from the soil. Therefore, compacted soils restrict soybean root penetration and air circulation and therefore K absorption is slow (Tisdale *et al*, 2005).

2.3.2 (c): Potassium uptake and fertilization

Uptake of K by leguminous plants is higher than the uptake of Ca, Mg and P (Venter, 2003). This is also confirmed by Lanyon and Griffith (1998) who indicated that legumes become more nutritious with the application of K. The plants need K in luxury (Reuter & Robinson, 1997). This implies that the K concentration in plants tissue should be in an adequate to high range. According to Ali *et al.* (2004), the uptake of K varies more from week to week than that of Ca, Mg, N or P. Lanyon and Griffith (1998) on the other hand pointed out that omitting K from the fertilizer programme resulted in reduced yield. Therefore, K should be managed through application of adequate quantities of fertilizer to replace K lost through plant uptake and leaching.

Contrary to the above findings, Buchholz and Brown (1993) showed that high levels of soil K could result in pod rot and also interfere with the uptake of other nutrient elements like Ca which is also essential for growth. This implies that plants subjected to high amounts of K are likely to suffer Ca deficiency. Therefore, K should be mixed with soil before planting as to allow for leaching to the root zone. The reasoning behind this is that soybeans are efficient in obtaining K, even under low K levels in the soil (Cox *et al.*, 1982). That is why it is rare to find K deficiencies in soybean (Cox *et al.,* 1982). This is similar to the finding of Weiss (1986) who reported that groundnuts don't require very high K fertilizer application as they rely on residual K in the soil and are able to derive K even in soil with low K availability.

2.3.2 (d): Soybean yield response to Potassium

Potassium is mostly applied as compounds containing potassium chloride. Potassium is reported not only to increase yield but also to increase the uptake of major nutrients like N, P, Mg, Ca and S required for crop growth.

The research reported by Mullins and Burmester (1990) did not only show a soybean yield increase of up to 60% but that application of K at the recommended rate also enhanced uptake of other major nutrients. At the vegetative stage, concentration of K in leaves was higher than that of either N or P. As the crop matures, K uptake is comparatively higher. This is verified by the work of Tiwani *et al.* (2001) who stated that from vegetative growth, K moves largely to the grain hence the reason why uptake at the ripening stage is greater than during vegetative growth (Figure 2.5). An increase in seed yield, oil, and protein content was also recognized by Magen (1997) with the application of 20 kg K ha^{-1}. This rate was also recommended to suppress insect attacks.

Although soybean yield response to K is still unclear, research done in Iowa (U.S.A.) revealed that a significant yield increase in soybean was achieved with the application rate of 40 to 68 kg K ha^{-1}. Marschner (1995b) also obtained increased yields of up to 56% when 20 kg K ha^{-1}was applied. This study agrees with the study of Grewal *et al.* (1994) who observed seed yield increases on loamy sandy soils following the application of 25 kg K ha^{-1}. The application rate of K therefore depends on the soil type and the fertility status of the soil. If the fertility of the soil is low in K, more K is needed than when K is moderate to high in the soil. For example, Annadurai *et al.* (1994) applied 40 kg K ha^{-1} while Grewal *et al.* (1994) applied 25 kg K ha^{-1}while both reported a similar increase in yield.

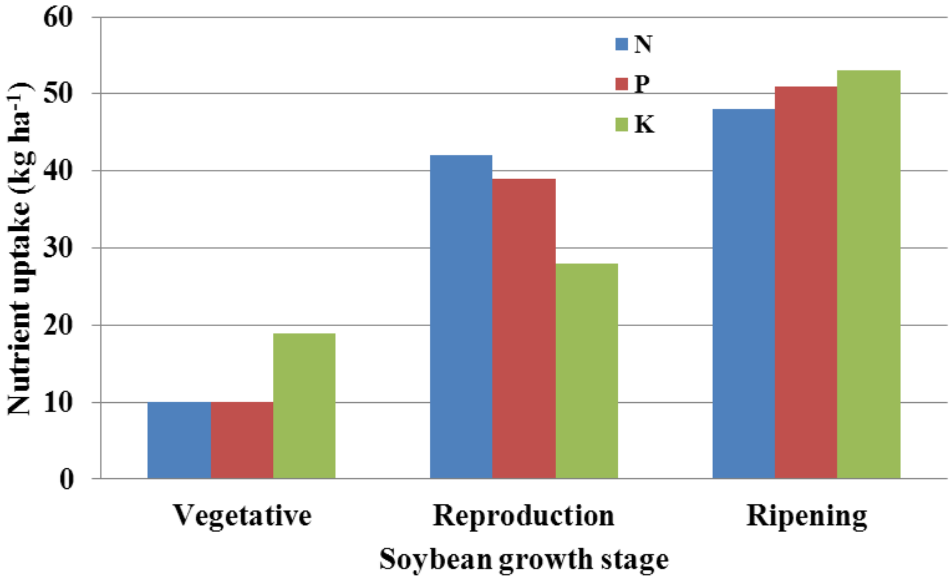


Figure 2.5: Uptake of nutrients by soybean at different growth stages (Tiwani, 2001)

2.4: RECOMMENDED SOIL pH FOR SOYBEAN

Soil pH affects the availability of nutrients to plants. Availability of essential nutrients is influenced by soil pH through its effect on Aluminium saturation percentage and on nutrient fixation and release mechanisms (Johnson, 1989). The pH is defined as a negative logarithm of the activity of H^+ in a soil solution. It ranges from 0 (most acidic) to 14 (most alkaline), with 7 being neutral (Omafra, 2010). Highest soybean yields are usually produced when pH ranges from 6.2 to 7.0.This is also the range at which P and K become available and can be used by soybean. However, soybeans grown on naturally acid oxisols and ultisols will generally produce their potential in slightly acid soils and can tolerate a wide range of pH of 6.0 to 6.5 (Table 2.4). (Franzen, 1999; Johnson, 1989). According to George (2001), economic yield reduction due to soil acidity generally occurs in sandy and silt loam soils at a pH of 5.5 or less.

Different crops require different soil pH levels for optimum performance and as pH falls below these levels, performance is reduced (Table 2.4). Vitosh *et al.* (2004) reported that top soils in fields with acid sub-soils should be maintained at higher pH than those with neutral or alkaline sub-soils to minimize chances of nutrient deficiencies associated with acid soils. When the pH of organic soils (more than 20 percent organic matter) is maintained at lower levels than the pH in mineral soils (less than 20 percent organic matter) as to minimize micronutrient deficiencies.

Table 2.4: Soil pH recommended for various crops in various soils (after Vitosh *et al.*, 2004)

Crop	**Mineral soils with > pH 6**	**Subsoil pH < pH 6**	**Organic soils**
		pH	
Alfalfa	6.5	6.8	5.3
Forage legumes	6.0	6.8	5.3
Maize	6.0	6.5	5.3
Soybean	6.0	6.5	5.3
Small grains	6.0	6.5	5.3
Other crops	6.0	6.5	5.3

Lowering pH levels is usually not an option because the acidic cations (Al and Fe) would build up in the soil and there would be a need for soil amendments like lime (Franzen, 1999). Under lower pH, P can be fixed and bound with nutrient elements like Fe and Al and become unavailable to plants (Iyamuremye & Dick, 1996; Mutara, 2003). Fixation of P under acidic pH conditions is also reported by Marschner (1995b). Similar to P, Rooyani & Badamchian (1986) indicated that K fixation occurs under dry conditions with soil pH lower than 5.5 when K ions in soil solution are bound within structures of clay minerals. As pH increases above 7.0, Ca and Mg react with P and K and availability again declines. According to Donald (1999), trying to lower pH of calcareous soils to improve P availability is not practical and placement of P near the seeds or seedling is much more feasible. At these pH levels, P availability and soil test levels are reduced.

CHAPTER 3

EFFECT OF P AND K ON SOYBEAN GROWTH AND YIELD UNDER RAIN-FED FIELD CONDITIONS

3.1 INTRODUCTION

Soybean (*Glycine max* L.), a leguminous crop, is an extensively grown crop accounting for 30% of the world's processed vegetable oil, which is also used as a source for producing bio-diesel fuel (Graham & Vance, 2003). Soybean oil-cake, a by-product of soybean oil extraction, is used as a high-protein animal feed in South Africa. Like other grain legumes, soybean plays an important role in biological nitrogen fixation and when included in a cropping system improves soil fertility (Asiegbu & Okpara, 2002). Biological nitrogen fixation play an essential role in soybean crop growth and yield, since no N fertilizer is applied and should therefore fulfil in all the N needs of the plant.

Despite the known ability of legumes to fix atmospheric N in symbiotic association with *Rhizobium*, it has been demonstrated that supplementary N, P and K fertilization can lead to improved performance of crops (McConnell *et al.*, 1995). Lynch (1995) indicated that the availability of P can be an important factor in symbiotic nitrogen fixation by field beans. Zheng *et al.* (2010) reported improved soybean yields through application of P under drought stress conditions.

Potassium, a major plant nutrient, is also critical for soybean yield because of its multiple nutritive effects. The exact function of K in plant growth is to stimulate early growth, increase protein production, improve water use efficiency and improve resistance to diseases, insects and stalk lodging (Rehm & Schmitt, 1997). By ameliorative KCl fertilization, the yield of soybean increases due to the increase in plant nutritional status (Kovacevic & Basic, 1997).

Despite the high potential for rain-fed soybean production, low productivity is often experienced which can be ascribed to environmental and soil factors (Zheng *et al.,* 2010). Many agricultural scientists have provided information to farmers about P and K application since P and K affect soybean growth and yield. Their advice has been that P and K should be included in the presence of *Bradyrhizobium japonicum* during soybean production. However, the culture among the South African soybean producers is to not apply P and K fertilizer since they rely on residual fertilizer application from the previous cropping cycle. So, a field experiment study was undertaken to determine that direct P and K applied to a soybean crop can have positive results in terms of productivity.

3.2 MATERIALS AND METHODS

3.2.1 Study area and soil sampling

The research started on 24 November 2010 and ended 21 weeks later. The experiment was conducted at the Hatfield Experimental Farm of the University of Pretoria (UP) in Pretoria on a red Hutton soil. The area is located at 23° 45’ S and, 28° 16’ E, at 1372 m above sea level with a long term average rainfall of 674 mm per annum. The average temperatures and rainfall data for the period of October to April of 2010/2011 are presented in Table 3.1. From this, it is clear that the average rainfall was about 100 mm more than the long term average. Good rainfall was also experienced during critical phases of growth and flowering as well as pod growth. Furthermore, the minimum and maximum temperatures did not go too high or too low to have had a negative impact on the soybean crop.

Table 3.1: Average temperature and rainfall for the Hatfield Experimental Farm (Supplied by the weather station of the UP Experimental Farm)

	2010			2011			
	October	November	December	January	February	March	April
Min. Temperature (^{o}C)	12.91	15.35	15.94	16.93	16.16	15.85	12.42
Max. Temperature (^{o}C)	29.49	28.95	28.17	27.72	28.59	29.24	23.84
Rainfall (mm)	16.30	107.40	147.70	135.8	41.2	292.4	46.3

At the research site, soil sampling was conducted for both top (0-20 cm) and sub-soil (30-50 cm) before cultivation. Seventy-two (72) samples (36 for top-soil and 36 for sub-soil) were taken at random from different sampling points to produce composite soil samples. These samples were air-dried and taken to the Soil Science Laboratory at UP for pre-experimental analysis.

The pre-experiment soil analysis tested pH (lime requirement), P and K levels of the soil (Table 3.2). The results obtained were used as a guide for rates of P and K to be used in the experiment. The complete soil analysis can be found in the Appendix B. This was the fourth year the P and K fertilizer trial was conducted. This explains the high levels of P in the top-soil where P has been applied, however, the K levels are still relatively low in both the top and sub-soil. The soil pH in both the top and sub-soil is acceptable for soybean production and no lime was applied.

Table 3.2: Initial top and sub-soil chemical composition of the Experimental farm trial site, used for soybean production in the 2010/2011 season.

Treatment		**Top-soil**			**Sub-soil**		
P	**K**	**P (Bray 1)**	**K (Ammonium acetate)**	**pH**	**P (Bray 1)**	**K (Ammonium acetate)**	**pH**
kg ha^{-1}	kg ha^{-1}	mg kg^{-1}	mg kg^{-1}	(H_2O)	mg kg^{-1}	mg kg^{-1}	(H_2O)
0	0	14.1	26.0	6.0	1.4	31.4	5.8
0	50	13.4	39.5	6.1	1.4	33.0	5.7
0	100	13.5	68.8	6.1	1.5	34.5	5.7
20	0	30.3	22.3	6.1	1.4	17.5	5.6
20	50	40.7	47.0	5.9	1.6	29.0	5.6
20	100	30.7	55.3	6.1	1.4	24.3	5.9
40	0	48.1	23.5	5.9	1.1	28.8	5.6
40	50	47.2	37.5	5.8	1.4	26.8	5.4
40	100	60.7	54.0	5.6	1.2	27.3	5.4

3.2.2 Experimental design

The experiment was a factorial arrangement consisting of two main factors (Phosphorus and Potassium) combined into different treatment combinations. The individual treatment combinations have been assigned to the same plots during each cropping season. The nutrients were applied at three levels, with P being applied at 0, 20 and 40 kg P ha^{-1} while K was applied at the rate of 0, 50 and 100 kg K ha^{-1}. Phosphorus fertilizer source used was super-phosphate (10.5%) while KCl (50%) was used as K fertilizer source. These fertilizers were broadcasted evenly over the experimental plots as per treatment combination (Table 3.3) and were incorporated into the soil seven days before sowing. Control plots, receiving zero P and K, were also included in the experiment. Seeds of all treatments were inoculated with *Bradyrhizobium japonicum* based inoculant and plots received no additional N during the growing season.

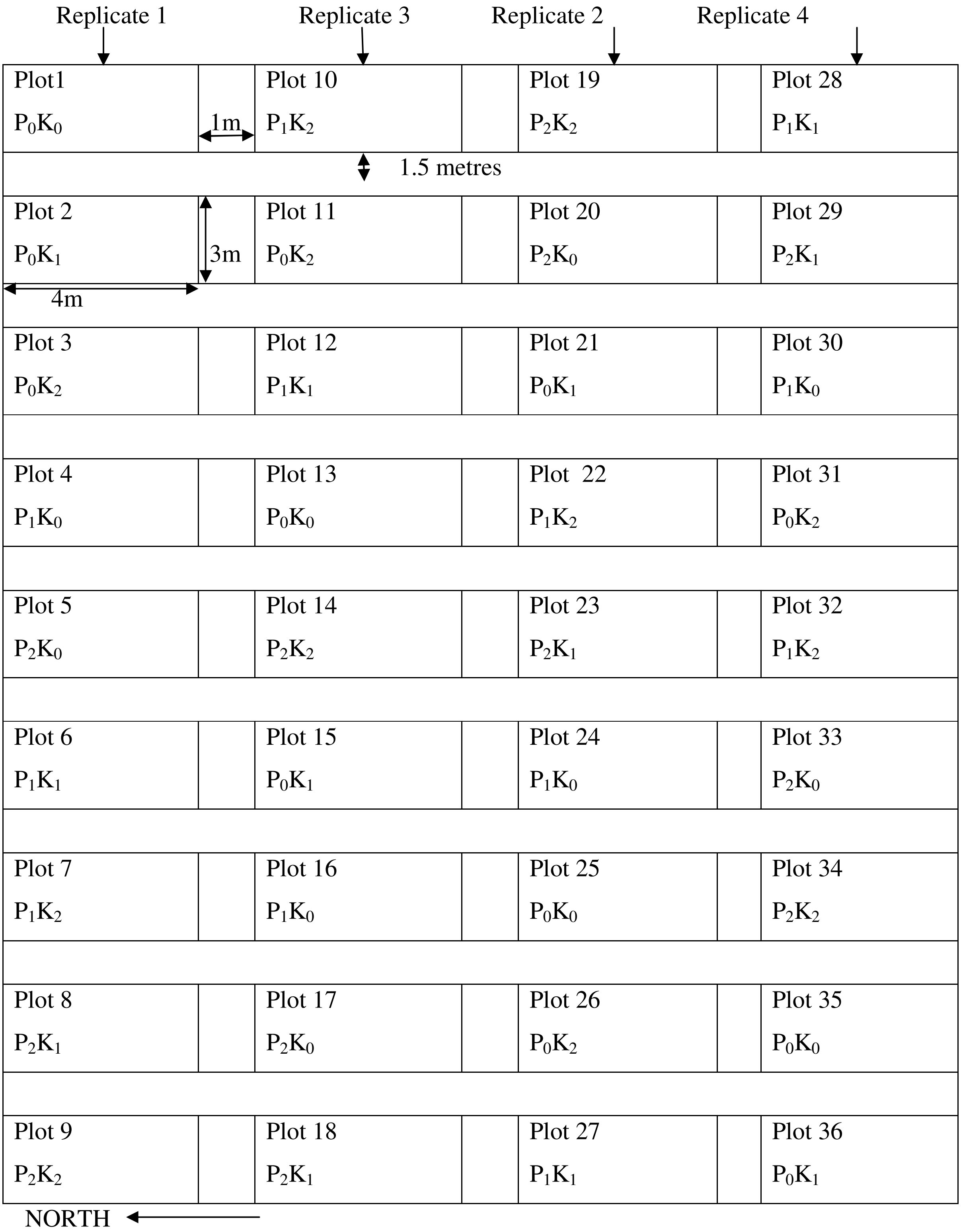
The soybean variety LS 6161R was used as test crop.In South Africa cultivars with a maturity group ranging between 4 and 7 are used. Maturity group 4 is for short season varieties that flowers early in the season and are recommended in the cooler production areas (Southern Kwazulu-Natal, Eastern Free State, Eastern Mpumalanga) while the varieties in group 7 flower late in the season (long season varieties) and therefore are recommended for use in warm areas (North West and Limpopo Province and Northern Kwazulu-Natal).The seed companies producing soybean seed group the cultivars into maturity groups by assigning them numbers, e.g. Link Seeds: LS 6161; the first number indicates which crop it is, in this case, it is 6 for soybean, the first 1 indicates whether the growth habit of the soybeans are determined or undetermined. An even number means determined and an uneven number means undetermined. The second 6 indicates the maturity group while the second 1 indicates whether the soybeans have broad or narrow leaves. An uneven number means a narrow leaf and an even number means a broad leaf. Therefore the LS 6161R planted in this experiment was an undetermined narrow leafed variety belonging to maturity group 6.

The required amounts of soybean seeds were sown by hand with a spacing of ±3 cm between seeds and 75 cm between rows. They were sown at the rate of 40 seeds m^{2} resulting in a plant density of 400 000 plants ha^{-1}. The size of each treatment plot was 12 m^{2} (Figure 3.1 and 3.2). Each treatment was replicated four times, bringing the total number of treatment units to 36. The trial was laid out using a completely randomized block design (CRBD) (Figure 3.2).

Table 3.3: Treatment combinations and P and K levels applied to the soybean crop in the 2010/2011 season

P and K treatment	P – K level (kg ha^{-1})
P_0K_0 (Control)	0 – 0
P_0K_1	0 – 50
P_0K_2	0 – 100
P_1K_0	20 – 0
P_1K_1	20 – 50
P_1K_2	20 – 100
P_2K_0	40 – 0
P_2K_1	40 – 50
P_2K_2	40 – 100

Figure 3.1: General view of the soybean experimental plots at the Hatfield Field Trial Section taken a month after planting (photo by T Mokoena, 2011).



Replicate 1	Replicate 3	Replicate 2	Replicate 4
Plot1 P_0K_0	Plot 10 P_1K_2	Plot 19 P_2K_2	Plot 28 P_1K_1
Plot 2 P_0K_1	Plot 11 P_0K_2	Plot 20 P_2K_0	Plot 29 P_2K_1
Plot 3 P_0K_2	Plot 12 P_1K_1	Plot 21 P_0K_1	Plot 30 P_1K_0
Plot 4 P_1K_0	Plot 13 P_0K_0	Plot 22 P_1K_2	Plot 31 P_0K_2
Plot 5 P_2K_0	Plot 14 P_2K_2	Plot 23 P_2K_1	Plot 32 P_1K_2
Plot 6 P_1K_1	Plot 15 P_0K_1	Plot 24 P_1K_0	Plot 33 P_2K_0
Plot 7 P_1K_2	Plot 16 P_1K_0	Plot 25 P_0K_0	Plot 34 P_2K_2
Plot 8 P_2K_1	Plot 17 P_2K_0	Plot 26 P_0K_2	Plot 35 P_0K_0
Plot 9 P_2K_2	Plot 18 P_2K_1	Plot 27 P_1K_1	Plot 36 P_0K_1

Figure 3.2: Diagram of the experimental plot layout used for the P and K soybean field trial in the 2010/2011 season.

3.2.3 Cultural practices

Since this experiment was a dry land experiment, irrigation was applied once at planting for good crop establishment. For the rest of the season, due to the good rainfall, no additional irrigation was applied. Plots were kept weed-free throughout the growing seasons by either hand pulling or using a digging fork, while no problems with diseases were experienced.

As a precautionary measurement against defoliating insects, the crop was sprayed with cypermethrin (active ingredient) at the rate of 15 ml per 16 liter of water 75 days after sowing. All pesticide solutions were applied with backpack hand sprayer in the early morning (8 – 10 am). The nozzle size was adjusted to deliver the appropriate rate and to ensure uniform distribution.

3.2.4 Data collection and analysis

<u>During the growing season:</u>

The days from planting to emergence were recorded and percent emergence was determined by counting number of plants m^{-2}. Plant height of randomly selected and tagged plants in each plot was measured from the base of the plant to the tip of the shoot apex. Data for plant height was taken at 7day intervals starting from emergence.

At 21 days after emergence, the soybean canopy started to close, therefore, canopy closure measurements were taken on a weekly basis (every 7th day) from then onwards. The measurement of canopy closure (distance between plants in adjecent rows) and plant height were done for the same tagged plants.

Twice during the growing season, three adjacent plants were uprooted and number of nodules on the taproot was recorded. The uprooted plants were also used to determine other plant growth parameters like leaf area using a LI-COR 6400 leaf area meter as to determine leaf area index (LAI). The following equation was used to calculate LAI.

Equation 1;

$$\text{LAI} = \frac{\text{Leaf area plant}^{-1}\ (\text{m}^2)}{\text{Land area occupied by the plant}\ (\text{m}^2)}$$

The uprooted plants were further separated into different plant parts (root, stem, leaf and pod) and the fresh mass per plant and per plant part were determined. The material was then oven dried for two days at 75^0C and weighted again to determine the dry mass.

At harvest:

Three adjacent plants per plot were used for data collection on pod number per plant, node number per plant and the number of 1-, 2-, 3- and 4-seeded pods. The crop was harvested treatment-wise at physiological maturity based on visual observation (yellowing of pods and leaves) (Figure 3.3). The plants were cut by hand using secateurs and put into tagged bags for threshing. The harvested plants from each treatment and replication were stored in a cool place for a month to completely dry, where-after it was mechanically threshed for seed yield determination.

After threshing:

The seeds were manually cleaned using a sieve and a fan to completely separate straw from seeds. The seed moisture content was adjusted to12.5%.Seed moisture content for each plot was determined using a moisture metre. Then, weight of grains per plot and 100-seed mass were determined for each treatment combination. The yield for each treatment combination was determined following equation 2. Thus, obtained seed yield per plot was converted to kg ha^{-1}. The seed samples from each plot for the 2009/2010 season were analyzed for protein and oil content. The protein and oil content of the seeds of the soybean were measured by Near Infra-red Reflectance Spectroscopy (NIR) and Near Infra-red Transmittance Spectroscopy (NIT) methods respectively.

Equation 2;

$$\text{Yield} = \frac{(100 - \text{Moisture }\%)}{(100 - 12.5)} \times \text{seed mass}$$

Where: 100 = Constant

12.5 = Adjusted moisture %

Figure 3.3: The general view of the soybean crop ready for harvest, taken at the Hatfield, Field Trial Section in April, 2011(photo by T Mokoena, 2011).

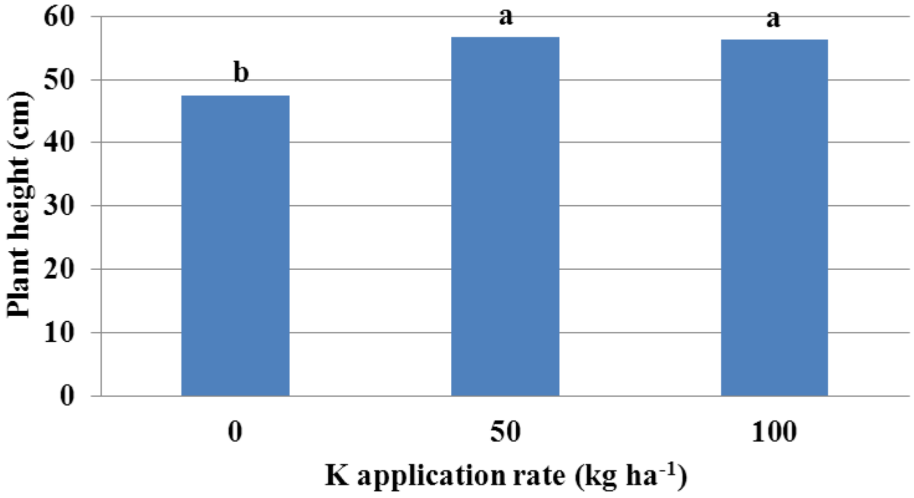
Statistical analysis:

The data was analysed for variation within and between treatments using the linear model procedure of the statistical analysis system (SAS). Where there were significant treatment effects, the means were separated by the Least Significant Test (LSD) of Tukey. ANOVA Tables can be found in Appendix A.

3.3 RESULTS AND DISCUSSION

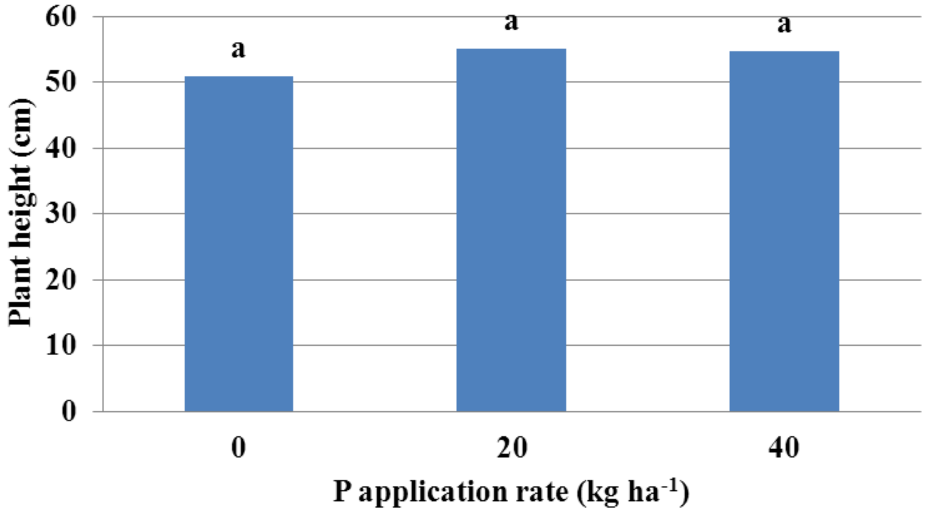
3.3.1 Plant height

Soybean plant height was only significantly impacted by the main effect of K while that of P and the P*K interaction effect were not significant (Appendix A, Table A1). Plant height was significantly increased by applying K (50 or 100 kg K ha^{-1}), as compared to where zero K was applied (Figure 3.4). There was, however, no statistical difference in plant height where 100 rather than 50 kg K ha^{-1} was applied. These results of an increment in plant height due to K fertilizer are in accordance with the results of Babalad (1999) who reported increased plant height due to application of inorganic fertilizers. Where P was applied, the plants tended to be taller than where no P was applied, although there was no significant difference (Figure 3.5).



Bars with the same letter are not significantly different at 5% level of confidence.

Figure 3.4: Effect of Potassium application rates on average soybean plant height.



Bars with the same letter are not significantly different at 5% level of confidence.

Figure 3.5: Effect of Phosphorus application rates on average soybean plant height.

Plant height gradually increased over time (Figure 3.6), with plants receiving both P and K being a bit taller at the end of the season than the rest of the treatments. Towards the end of the growing season (25 WAP – data not shown), very little height increase was observed which might be attributed to the plants being mature.

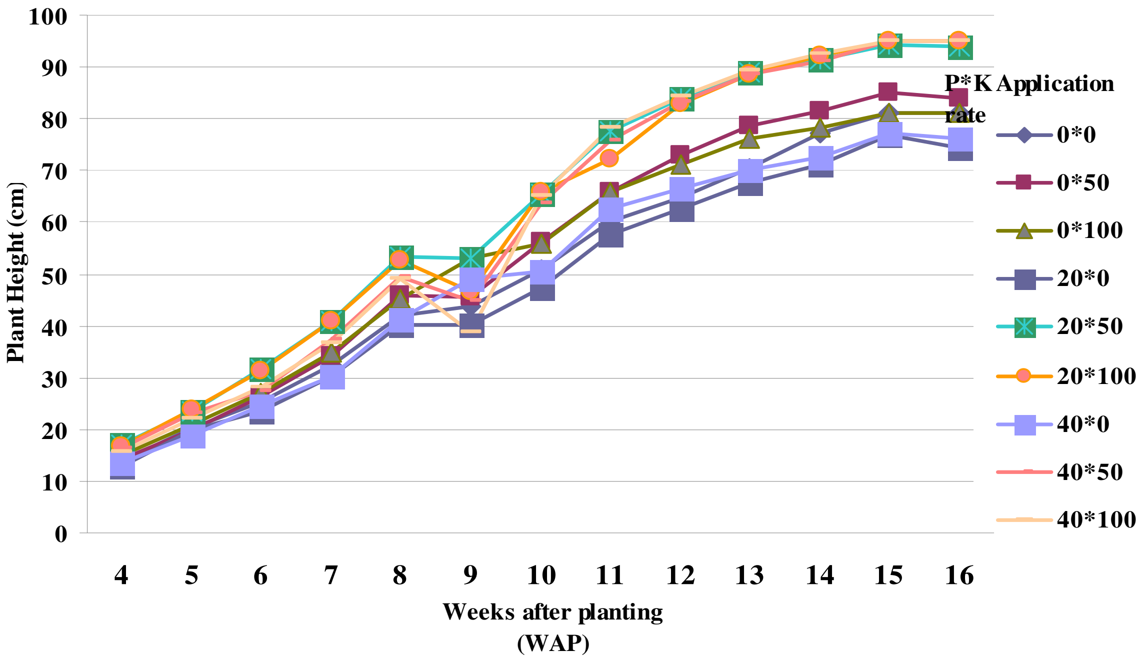
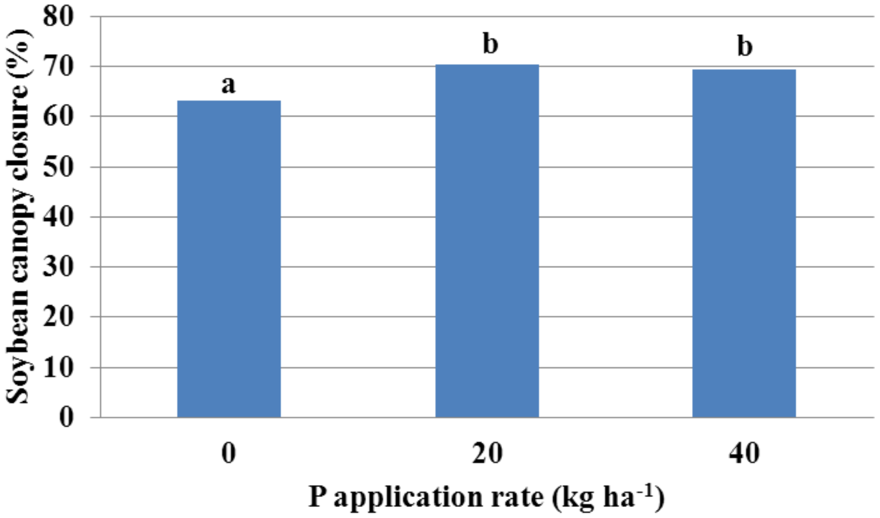


Figure 3.6: The effect of P*K application rates on average soybean plant height over time.

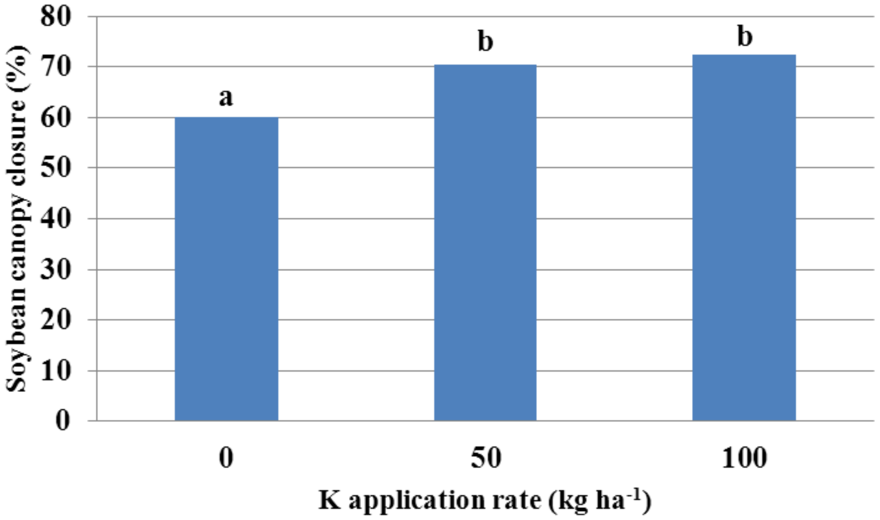
3.3.2 Canopy closure

Plant canopy closure was not significantly impacted by the P*K interaction effect but was significantly influenced by the main effects of P ($P \leq 0.05$) and K ($P \leq 0.01$) (Appendix A, Table A2). Significantly better canopy closure was recorded with application of 20 kg P ha^{-1} which was similar to that of 40 kg P ha^{-1} (Figure 3.7). Similarly to P application, significantly better canopy closure was recorded with 100 kg K ha^{-1} and 50 kg K ha^{-1} as compared to the control receiving 0 kg K ha^{-1}(Figure 3.8).



Bars with the same letter are not significantly different at 5% level of confidence.

Figure 3.7: The effect of Phosphorus application rates on average soybean canopy closure at 16 weeks after planting (WAP).



Bars with the same letter are not significantly different at 1% level of confidence.

Figure 3.8: The effect of Potassium application rates on average soybean canopy closure at 16 weeks after planting (WAP).

Plots receiving both P and K, with exception of 40kg P plus 50kg K ha^{-1} were completely covered at the end of the season (Figure 3.9). The plots receiving only 20kg P ha^{-1} had the most bare soil. The rest of the treatments fell between the two extremes, but could also not cover the soil completely.

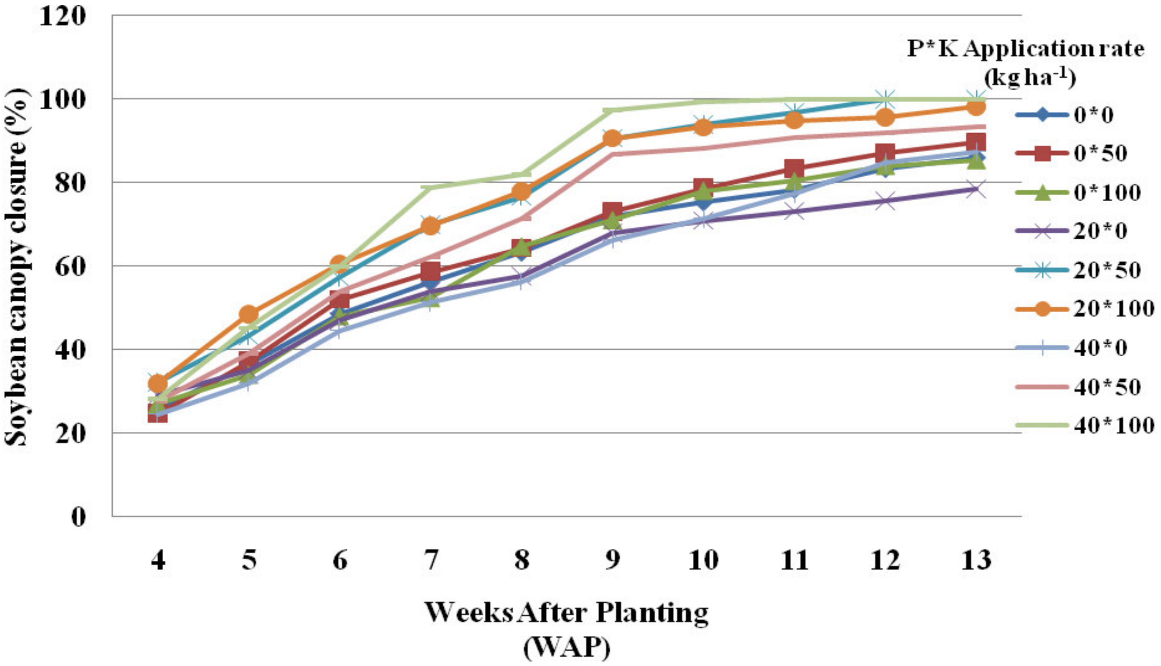
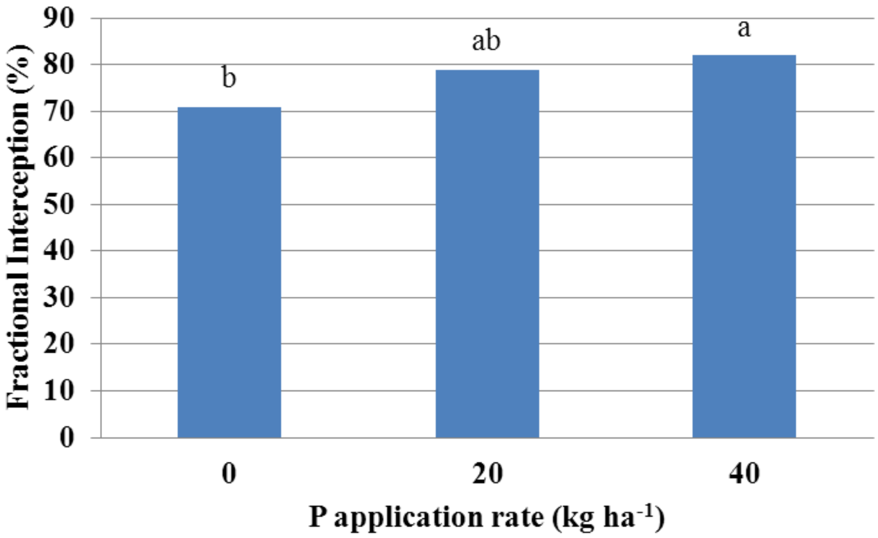


Figure 3.9: The effect of Phosphorus and Potassium on soybean canopy closure.

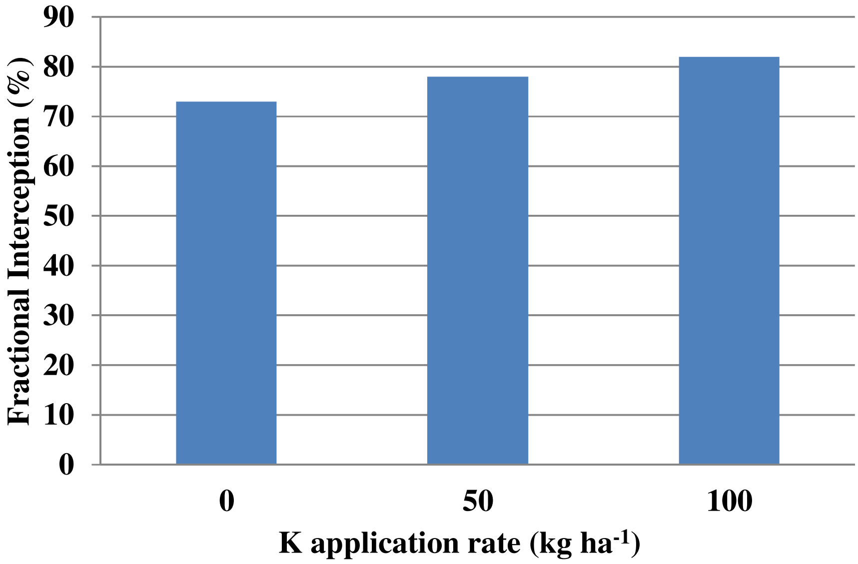
Light interception:

Light intercepted by the soybean canopy was only significantly affected by the main effect of P (Appendix A, Table A2). On average a significant amount of 72% of photosynthetically active radiation (PAR) was intercepted by the control which was statistically different to that intercepted by the plants treated with 20 kg P ha^{-1}(Figure 3.10). The plants receiving the maximum P application rate (40 kg P ha^{-1}) scored the highest value but differed significantly from the control. On the other hand, increased K application rates resulted in more light intercepted (Figure 3.11).



Bars with the same letter are not significantly different at 5% level of confidence.

Figure 3.10: Effect of Phosphorus application rate on light intercepted by the soybean canopy (16 WAP).



Bars with no letters are not significantly different at 5% level of confidence.

Figure 3.11: Effect of Potassium application rates on average light intercepted by the soybean canopy (16 WAP).

3.3.3 Leaf number

The data on the number of leaves per plant at 16WAP as influenced by P and K application rates are presented in Tables3.4 and 3.5 respectively and Appendix A, Table A3. Less leaves per plant were recorded where 20 kg P ha^{-1}was applied as compared to the control and 40 kg P ha^{-1}(Table 3.4), although the differences were not statistically different.

The non-significant impact of K on leaf number may be due to the fact that soybeans were not yet at the flowering stage during which more K is reported to be taken up. It is even confirmed by Karlen *et al*. (1982) that soybeans do not accumulate the majority of its K until flowering. This is also in agreement with the report of Mullins and Burmerster (1990) on cotton (*Gossypiumhirsutum* L.) where cotton takes up the majority of its K during the blooming and boll-filling period. Their study showed a decrease in K concentration in the leaves throughout the growing season while K concentration in the pod fraction increased during seed formation.

Table 3.4: Influence of P application rates on number of soybean leaves at 16 weeks after planting (WAP).

P application rate(kg ha^{-1})	**Number of leaves16 WAP**
0	41a
20	36a
40	41a
LSD	11

Means with the same letter in a column are not significantly different (P≤ 0.05).

Table 3.5: Influence of K application rates on number of soybean leaves at 16 weeks after planting (WAP).

K application rate(kg ha^{-1})	**Number of leaves16 WAP**
0	34a
50	38a
100	45a
LSD	11

Means with the same letter in a column are not significantly different (P ≤ 0.05).

These results showed that irrespective of the rate of P or K applied, the number of leaves remains high, indicating that the soil contained adequate rates of available P for growth of soybean. Similar results were observed by Priyadharsh and Seran (2009) in a cowpea plantation. Their results showed that irrespective of the rate of P and K applied, the content of P and K in a leaf remains comparable, indicating that even in the control treatment, the soil contained an adequate level of P and K for leaf growth.

3.3.4 Leaf area

There were no differences although treatment 20*0 and 20 * 50 kg P*K ha^{-1} tended towards smaller leaf areas than that of the control plants as well as the plants receiving only P or only K (Table 3.6). These differences were, however, not statistically significant. Also the P (Table 3.7) and K (Table 3.8) main effects did not result in statistically significant differences.

Table 3.6: Effect of P*K application rates on soybean leaf area at 16 weeks after planting.

P * K application rate(kg ha^{-1})	**Leaf area (LA) (m^2)**
0*0	0.20a
0*50	0.18a
0*100	0.25a
20*0	0.16a
20*50	0.16a
20*100	0.23a
40*0	0.19a
40*50	0.23a
40*100	0.20a
LSD	0.13

Means with the same letter are not significantly different from each other at 5% level of confidence.

Table 3.7: Effect of P application rates on soybean leaf area at 16 weeks after planting.

P application rate (kg ha^{-1})	**Leaf Area (m^2)**
0	0.21a
20	0.18a
40	0.20a
LSD	0.08

Means with the same letter are not significantly different from each other at 5% level of confidence

Table 3.8: Effect of K applicationrates on soybean leaf area at 16 weeks after planting.

K application rate (kg ha^{-1})	**Leaf Area (m^2)**
0	0.18a
50	0.19a
100	0.22a
LSD	0.08

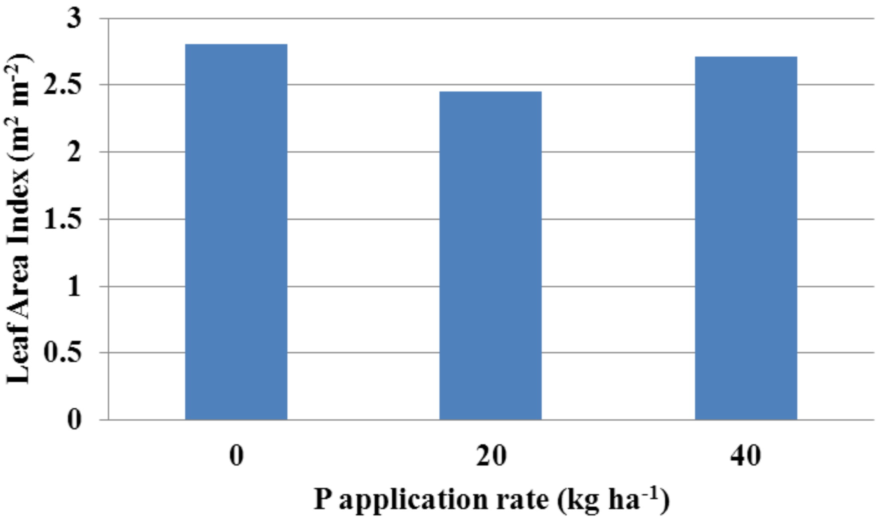
Means with the same letter are not significantly different from each other at 5% level of confidence

3.3.5 Leaf area index

The leaf area index is defined as the leaf area per unit ground surface. This is basically the analysis of growth or light interception, and especially gives information about photosynthesis. The results from this experiment showed that P and K rates did not influence LAI of soybean significantly (Figure 3.12).

The non-significant effect of these nutrient elements (P and K) on LAI might also be due to defoliation which has an influence on soybean yield. Defoliation is a term which is used to describe the removal or loss of leaves. Naturally it starts at the R7 (± 30 days after emergence). Mohan and Rao (1997) observed that seedling defoliation resulted in a soybean seed yield decrease of up to 12%. They believed this to be a result of the failure of the soybean to reach a critical LAI of 3.5 m^2 m^{-2} until well into their reproduction stages, resulting in less light being intercepted (LI) and thus less dry matter being accumulated. In soybeans, it has been reported that LAI levels between 3.5 to 4.0 m^2 m^{-2} are needed at the time of flowering in order to maximize yield potential which is maintained well into the reproductive stage, resulting in more light being intercepted (LI) and thus higher dry matter accumulation.

(a)



(b)

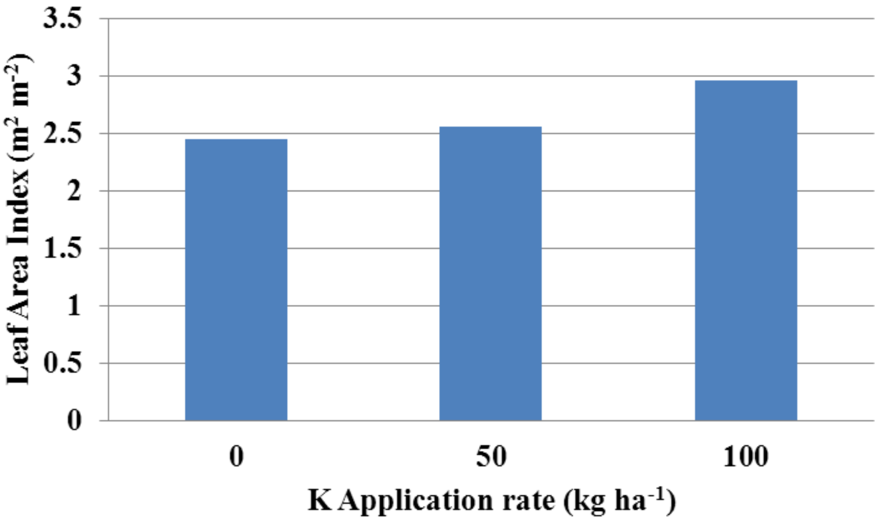


Figure 3.12: Effect of Phosphorus (a) and Potassium (b) application rates on average leaf area index (LAI) of soybean, 16 weeks after planting (WAP).

Board and Harville (1992) on the other hand argued that plant population and row spacing are the main factors that affect LAI and yield. They used growth analysis techniques to study the physiological basis of increased seed yield among narrow rows and varying soybean populations. The seed yield was increased by 31% and 16% by decreasing row width from 75 to 25 cm and 50 to 25cm respectively. They determined that narrow rows (25cm) with higher densities (80seed m^{-2}) produced both higher LAI and more dry matter than narrow rows with lower densities (25 seed m^{-2}). It is therefore assumed that non-significant variation of LAI with P and K fertilization in this study was due to wide rows (75cm) which delayed the timely closure of soybean canopy to maximize light interception and photosynthesis.

3.3.6 Number of pods per plant

At 16 WAP, the main effect of P, K and the P*K interaction did not affect the soybean pod number significantly (Appendix A Table A4). The highest, although not significant, number of pods per plant was found with an application of 0 * 100 kg P*K ha^{-1} followed by 40 * 50 and 40 * 100 kg P*K ha^{-1} (Table 3.9). By only adding P or adding low levels of P (20 kg ha^{-1}) regardless of the K application level, resulted in the lowest number of pods per plant (Table 3.9).

3.3.7 Number of seeds per pod and number of nodes per plant

Data on the amount of 1-, 2-, 3- and 4-seeded pods and number of nodes per plant are presented in Table 3.9 and Appendix A, Table A4. Regardless of the treatment combination, this soybean cultivar mostly tended to produce pods with three seeds (48 – 58%), followed by four seeded pods (15 – 25%), two seeded pods (14 – 22%) and between 4 – 14% pods with only one seed per pot (Table 3.9).

Although there were significant differences in terms of the node number per plant as affected by the P*K interaction, no clear tendency was observed (Table 3.9). There seems to be a positive correlation between the number of nodes and number of pods and 3 seeded pods thus, the more nodes, the more pods and the more 3-seeded pods (Table 3.9).

In this study, 1- and 2-seeded pods were found at the lower nodes. The low number of 1- and 2-seeded pods might have been brought about by the translocation of P and K from the old tissues (lower nodes and pods) to the young developing tissues. This study supports that of Tiwani et al.

(2001) who indicated that K is mobilized from the old tissues to the young developing growth and thereafter the mobilization decreases as the crop matures. It is reported that soybeans respond well to P which continues to be absorbed up to the stage when the beans reach full size (Tiwani, 2001). Aulakh et al. (2002) stated that most of the K deficiencies are seen at the late stage of soybean growth (flowering to seed filling stage) since the soil K concentration decreases at crop maturity.

Table 3.9: Effect of P*K application rates on soybean pod number, number of seeds per pod and node number.

P*K rate (kg ha^{-1})	Pod number*	1-seeded pod*	2-seeded pod*	3-seeded pod*	4-seeded pod*	Node number
0*0	25	1	5	14	5	18.3ab
0*50	23	1	3	11	7	16.4cd
0*100	27	1	4	15	8	18abcd
20*0	21	3	5	11	3	18.8a
20*50	22	1	4	13	5	16.2d
20*100	22	1	4	12	6	16.3cd
40*0	20	2	5	10	4	16.6bcd
40*50	26	2	5	14	6	17.8abcd
40*100	26	2	5	13	6	18.1abc

Means with the same letters are not significantly different from each other at 5% level of confidence; * = Non significant differences

<u>1-seeded pods:</u>

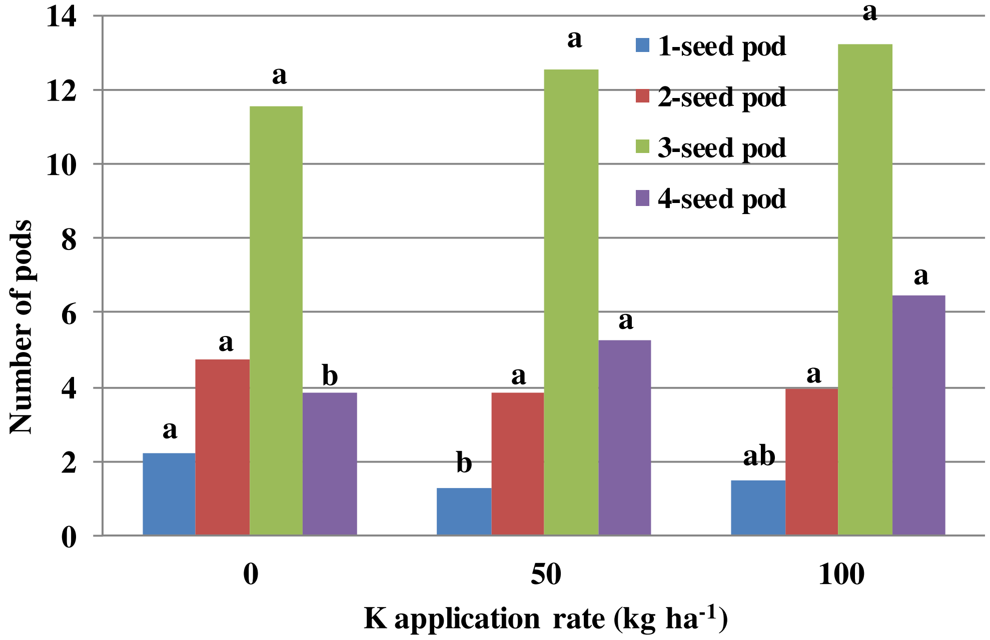
There was a significant variation in 1-seeded pods due the different K application rates (Appendix A, Table A4). The highest number of 1-seeded pods was obtained under control conditions and was statistically different only from those plants receiving 50 kg K ha^{-1} (Figure 3.13). In terms of P, there was neither significant difference nor a clear tendency with the control having a similar number of 1-seeded pods than the plants receiving 40 kg P ha^{-1} (Figure 3.14).

2- and 3-seeded pods:

The main effects of P, K and P*K interaction did not have a significant influence on the number of 2- and 3-seeded pods. The highest number of 2-seeded pods was recorded where 20 and 40 kg P ha^{-1} were applied. In contrary, the control plants (0 kg K ha^{-1}) showed the highest number of 2-seeded pods as compared to plants receiving either 50 or 100 kg K ha^{-1}. The highest number of 3-seeded pods was recorded under control conditions, followed by 40 and then 20 kg P ha^{-1} (Figure 3.14). For K, the highest number of 3-seeded pods was obtained with applying 100 kg K ha^{-1}, followed by 50 and then 0 kg K ha^{-1} (Figure 3.13).

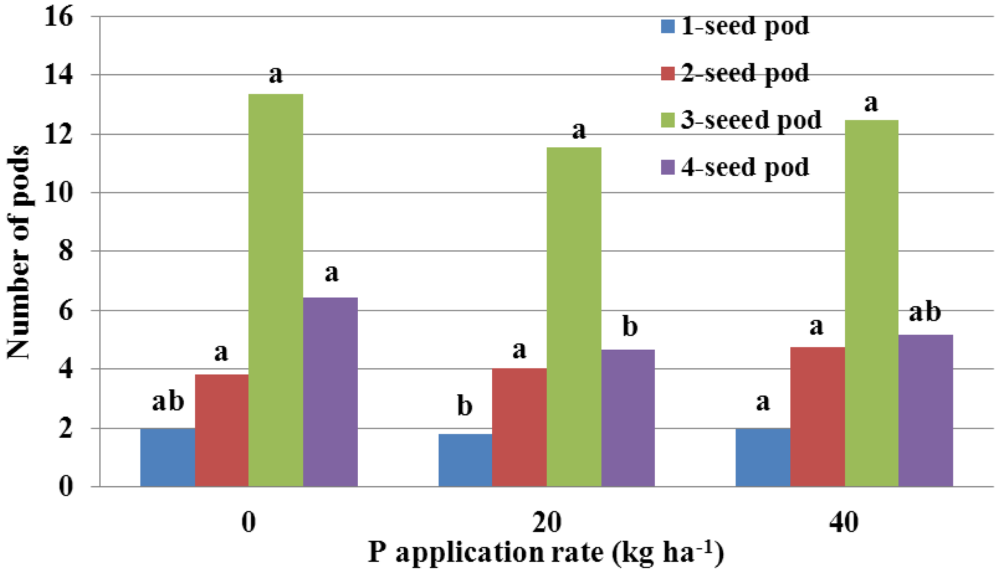
4-seeded pods:

The 4-seeded pods of the soybean crop varied significantly due to the main effect of P ($P \leq 0.05$) and K ($P \leq 0.001$) while the P*K interaction remained non-significant (Appendix A Table A4). The highest number of 4-seeded pods as affected by P, was produced by the control plants (Figure 3.14). In terms of K, however, the highest number of 4-seeded pods was recorded for plants receiving 100 kg K ha^{-1} which was statistically identical to those plants receiving 50 kg K ha^{-1}, while the control plants produced the lowest number of 4-seeded pods (Figure 3.13).



Bars with the same letter and colour are not significantly different at 5% level of confidence.

Figure 3.13: Effect of Potassium application rates on soybean number of pods and seeds per pod.

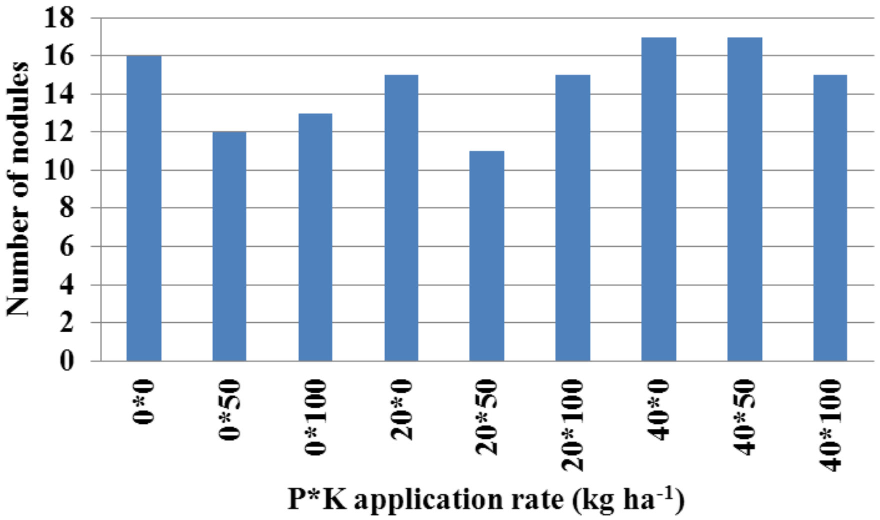


Bars with the same letter and colour are not significantly different at 5% level of confidence.

Figure 3.14: Effect of Phosphorus application rates on soybean number pods and seeds per pod.

3.3.8 Number of nodules per plant

Neither the main nor the interaction resulted in significant different amounts of nodules produced per plant (Appendix A, Table A5). For the P*K interaction, at 16 WAP, plants receiving 40 kg P ha^{-1} regardless of the amount of K, tended to have the highest number of nodules (Figure 3.15) as compared to where only K was applied or where 20 kg P ha^{-1} was combined with lower amounts of K. It was, however, where 100 kg K ha^{-1} was combined with the two levels of P, that the number of nodules was lower than that of the control plots. According to Mengel and Kirkby (1980) K plays a significant role in several physiological and biochemical process in a plant: it activates enzymes; it is essential for photosynthesis and carbohydrate synthesis which provides the energy needed by the nodule bacteria to fix atmospheric N. It also enhances the translocation of carbohydrates to roots and is itself transported to roots where it stimulates new root hair formation as well as nodule development. The positive effect of P application on nodule number was confirmed by Tsvetkova and Georgiew (2003). The data from their experiment showed that nodule number, and nodule fresh and dry weights decreased by almost 50% in P deficient plants.



Bars with no letters above are not significantly different at 5% level of confidence.

Figure 3.15: Effect of P*K application rates on soybean number of nodules per plant, 16 weeks after planting.

3.3.9 Fresh and dry mass

Fresh and dry leaf mass:

The values of both fresh and dry mass of the different parts of a soybean plant are presented in Tables 3.10, 3.11 and Appendix A, Table A6. Different levels of the main P, K and P*K interaction effects had no significant effect on fresh leaf mass at 16 WAP ($P \leq 0.05$). The plot receiving 40 kg ha^{-1} produced higher fresh leaf mass than both control and 20 kg P ha^{-1}(Table 3.10). Although not significant, the control plants recorded higher dry leaf mass than those plants receiving 20 kg P ha^{-1}.

The plants receiving 100 kg K ha^{-1}on the other hand had the highest mean fresh and dry leaf mass as compared to that of the control plants. The application of 50 kg K ha^{-1} resulted in the lowest fresh leaf mass (Table 3.11).

Fresh and dry stem mass:

The application of P and K at different rates did not cause any significant changes in soybean fresh and dry stem mass at 16 WAP. However, there was a strong tendency of the fresh and dry stem mass to decrease where P was applied (Table 3.10). These results are in agreement with Melton and Dufault (1991) who reported that P did not significantly influence any growth parameters of tomato plants such as shoot and root dry mass. Similar trends were observed for the stem as compared to the leaf fresh and dry mass in terms of K. The positive effect (as seen in 100 kg K ha^{-1}) may be due to the role of K in enzyme activity and enhanced translocation of assimilates and photosynthates to the stem (El-Desuki *et al*., 2006). The results are also in line with those of Collin and Duke (1981) who revealed that in legumes, a K deficit may cause inadequate supply of sugars to stems and root nodules which greatly reduce rate of nitrogen fixation and export of bonded nitrogen.

Fresh and dry pod mass:

Pod bearing and pod mass are considered to be the major contributors to seed yield in legumes. The production potential of soybean is determined by the number of pods per plant which is the main yield component.

The different P and K application levels did not impact significantly on the fresh and dry pod mass at 16 WAP. Fresh and dry pod mass was strongly negatively affected by applying P, resulting in the highest fresh pod mass being associated with the control plants (Table 3.10). In terms of K, the fresh and dry pod mass for 100 kg K ha^{-1} and 50 kg K ha^{-1} were higher than that of the control plants (Table 3.10).

In a study by Shivakumar and Sidramappa (2004) they obtained the highest pod weight per soybean plant with an application of 40 kg P ha^{-1}, which contradicts the findings of the current study. El-Habbasha *et al*. (2005) also noticed that increasing P and K levels result in increasing weight of groundnut pods per plant.

Fresh and dry root mass:

The fresh and dry root mass were determined at 16 WAP. There was no significant impact of P and K on fresh and dry root mass. The fresh and dry root mass were higher for the control plants as compared to where P was applied (Table 3.10). In contrary, there was an increase in fresh and dry root mass with an increase in K application rate (Table 3.11).

Table 3.10: Fresh and dry mass of soybean plant as affected by Phosphorus at 16 weeks after planting

P application rate (kg ha^{-1})	Fresh mass(g)				Dry mass(g)			
	Leaf*	Stem*	Pod*	Root*	Leaf*	Stem*	Pod*	Root*
0	7.41	15.95	21.25	2.91	3.13	5.50	6.60	1.99
20	6,70	14.23	18.93	2.44	2.88	4.90	5.98	1.84
40	7.40	14.62	18.53	2.52	3.15	5.09	5.84	1.82
LSD	2.71	6.16	7.34	1.00	1.06	1.92	2.27	0.51

Means with the no letters in a column are not significantly different from each other at 5% level of confidence;
* = Non significant different; LSD = Least Significant Difference

Table 3.11: Fresh and dry mass of soybean plant as affected by Potassium at 16 weeks after planting.

K application rate (kg ha^{-1})	Fresh mass(g)				Dry mass(g)			
	Leaf*	Stem*	Pod*	Root*	Leaf*	Stem*	Pod*	Root*
0	6.95	12.82	15.61	2.29	2.77	4.49	4.92	1.72
50	6.92	14.56	19.76	2.58	2.97	5.06	6.22	1.87
100	7.64	17.41	23.35	3.00	3.42	5.95	7.28	2.06
LSD	2.71	6.16	7.34	1.00	1.06	1.92	2.27	0.51

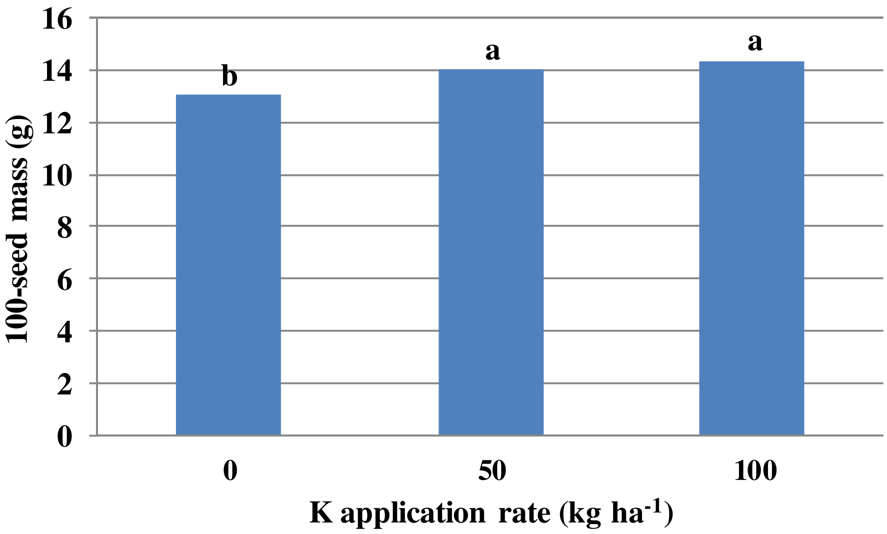
Means with the no letters in a column are not significantly different from each other at 5% level of confidence;

* = Non significant different; LSD = Least Significant Difference

3.3.10 100-seed mass

The P main and P*K interaction effects were not significant in terms of 100-seed weight (Appendix A, Table A7). Rugheim and Abdelgani (2009) also found that chemical fertilizer especially P fertilizer did not affect 100-seed weight in the presence of *Bradyrhizobium japonicum*. In this study, only the main effect of K significantly influenced 100-seed mass (Appendix A, Table A7). The application of 100 kg K ha^{-1} resulted in a 100-seed mass of 14.33 g and was statistically similar to where 50 kg K ha^{-1} was applied (14.07 g) (Figure 3.16). The control obtained the lowest mass (13.07 g).

These results are in close conformity with the findings of Dixit *et al.* (2011) who reported the weight of 100 seeds being significantly affected by an application of 40 kg K ha^{-1}, in comparison to farmers' practice where there was no application of K. The increase in mass of 100-seed by K fertilizer might also have been stimulated by inoculation of seed with *Bradyrhizobium japonicum*. Similar results where an increase in 100-seed weight resulted from *Rhizobium* inoculation with K fertilizer were observed in faba beans (Mohamed 2000).



Bars with the same letter are not significantly different at 5% level of confidence.

Figure 3.16: Potassium application rate effects on soybean 100-seed mass.

3.3.11 Seed yield

A significant variation in grain yield was observed through application of K. The highest grain yield (2.60 t ha^{-1}) was observed at the highest K level (100 kg K ha^{-1}) (Table 3.12). An application of 50 kg K ha^{-1} resulted in statistically similar but relatively lower yield than with 100 kg K ha^{-1}. The lowest grain yield was observed when no K fertilizer was applied. Grain yield was not significantly affected by P (Table 3.13) nor the P*K interaction effect (Appendix A, Table A7). However, yield did tend to increase from the lowest to the highest levels of P and P*K.

This variation in grain yield with K fertilizer application might be due to increased growth with a sufficient K nutrient status which improved the yield components. Similar findings were discussed by Dixit *et al*. (2011) who clearly indicated that K is known as one of the nutrients which are closely involved in metabolic processes and improved yield.

The higher grain yield due to K fertilizer application is also in agreement with Deshmukh *et al*. (1994) who obtained the highest soybean yield and oil content where K was applied. The results from his experiment have clearly illustrated that a response to K application can be obtained with up to a level of 100 kg K ha^{-1}. Grewal *et al*. (1994) on the other hand, observed that soybean seed yield increases following an application of up to 50 kg K ha^{-1} while Annadurai *et al*. (1994) found seed yield increase when 40 kg K ha^{-1} was applied. All these results confirm the complexities when working with different soils and different initial K status levels.

Table 3.12: Effect of Potassium application rates on yield of soybean.

K application rate (kg ha^{-1})	**Yield (t ha^{-1})**
0	1.66b
50	2.45a
100	2.60a
LSD	0.51

Any two means in a column not sharing a letter in common differ significantly at the 1% probability level.

Table 3.13: Effect of Phosphorus application rates on yield of soybean.

P application rate (kg ha^{-1})	**Yield (t ha^{-1})**
0	2.13a
20	2.23a
40	2.35a
LSD	0.51

Any two means in a column not sharing a letter in common differ significantly at the 1% probability level.

3.3.12 Effect of Phosphorus and Potassium on oil content (%)

The data presented in Table 3.14 – 3.15 shows a significant effect among the P and K treatments on soybean oil content (%). It was found that the oil content under control conditions (0 kg P ha^{-1}) was significant higher than where P (20 and 40 kg P ha^{-1}) was applied which are statistically at par (Table 3.14).These results are in contrast with those of Wini *et al.* (2010) who studied the effect of P on seed oil and protein content and P use efficiency in some soybean varieties. They reported an increase in soybean oil content when P was applied up to a rate of 1.0 mM external P-fertilization but decreased soybean protein content with increased P rates.

Table 3.14: Effect of applied Phosphorus on soybean oil content for the 2009/2010 season.

P application rate (kg ha^{-1})	**Oil content (%)**
0	19.39a
20	18.52b
40	18.69b
LSD	0.4889

Means with the same letter in a column are not significantly different at the 5% level of confidence.

The seed oil content (%) increased with increasedrates of K from 0, 50 to 100 kg K ha^{-1}(Table 3.15). The results for the control and 50 kg K ha^{-1} treatment were, however, statistically defferent. These results show the beneficial effect of K fertilization on oil yield. Similar results were presented by Sale and Cambell (1986) showing that seed produced by K deficient plants had a relatively low oil content. They indicated that oil and sugar percentages were significantly higher in seeds from K sufficient plants only at the final harvest. Sawan *et al.* (2006) also studied the protein, oil yield and oil properties of cottonseed as influenced by Potassium fertilization application and foliar application of Zinc and Phosphorus. They mentioned that applied K caused significant increase in seed oil content and oil yield per hectare compared to the untreated control, which confirms the current study's results.

Table 3.15: Effect of applied Potassium on soybean oil content for the 2009/2010 season.

K application rate (kg ha^{-1})	**Oil content (%)**
0	18.45b
50	18.80b
100	19.35a
LSD	0.4889

Means with the same letter in a column are not significantly different at the 5% level of confidence.

The interaction between P and K shows that the oil content (%) was significantly higher when K was applied in the absence of P, except where P and K were applied at the highest rate (Table 3.16). The maximum oil content was recorded for 0 * 100kg P*K ha^{-1}, which was similar to 40 * 100 kg P*K ha^{-1}.

Table 3.16: Effect of applied P*K on soybean oil content for the 2009/2010 season.

P * K application rate (kg ha^{-1})	**Oil content (%)**
0 * 0	19.25ab
0 * 50	19.28ab
0 * 100	19.65a
20 * 0	18.05d
20 * 50	18.53cd
20 * 100	18.98abc
40 * 0	18.05d
40 * 50	18.60bcd
40 * 100	19.43a
LSD	0.7021

Means with the same letter in a column are not significantly different at the 5% level of confidence.

3.3.13 Effect of Phosphorus and Potassium on soybean seed protein content (%)

The protein content of the plants receiving lower levels of P (20 kg P ha^{-1}) was significantly higher than the zero level (0 kg P ha^{-1}) (Table 3.17). It was also higher than the protein content of plants recieving 40kg P ha^{-1}, but not significantly so. The significantly lowest seeds protein content (41.21%) was obtained under control conditions. Research has shown that very high soil phosphate values may depress seed protein and oil contents, or induce zinc and iron deficiencies (Weiss, 1983).

Table 3.17: Effect of applied Phosphorus on soybean protein content for the 2009/2010 season.

P application rate (kgha^{-1})	**Protein content (%)**
0	41.21b
20	43.08a
40	42.24ab
LSD	1.0384

Means with the same letter in a column are not significantly different at 5% level of confidence.

The protein content of the plants whereno K was applied (0 kg K ha^{-1}) was significantly higher than for plants grown with 50 or 100 kg K ha^{-1} (Table 3.18). The protein content of the plants treated with K (50 or 100 kg K ha^{-}1) did not differ statistically from each other.

Table 3.18: Effect of applied Potassium on soybean protein content for the 2009/2010 season.

K application rate (kgha^{-1})	**Protein content (%)**
0	43.51a
50	41.88b
100	41.13b
LSD	0.4889

Means with the same letter in a column are not significantly different at 5% level of confidence.

The interaction between P and K showed that the protein content (%) was significantly higher where P was applied in the absence of K or at low levels of K (Table 3.19). However, applying K in the absence of P, especially at the higher levels of K, caused a significant decrease in seed protein content as compared to the control. The highest protein content was obtained with 20 * 0 kg P*K ha^{-1} and was statistically at par with 40 * 0 kg P*K ha^{-1}.

The results from this study support those of Shah *et al.* (2001) who indicated that due to the increase in yield and improvement in the nutritive quality of the soybean seeds and shoot, P application is necessary to achieve high protein and oil yields in soybean seeds. Phosphorus has been shown to be an essential element and its application has been shown to be important for growth and yield of soybean (Malik *et al.*, 2006). They noted that P and seed inoculation with *Rhizobium* had significant effects on oil and protein content of soybean.

Table 3.19: Effect of applied P*K on soybean protein content for the 2009/2010 season.

P * K application rate **(kg ha^{-1})**	**Protein content** **(%)**
0 * 0	42.13bc
0 * 50	41.25cd
0 * 100	40.25d
20 * 0	44.45a
20 * 50	42.98ab
20 * 100	41.80bc
40 * 0	43.95a
40 * 50	41.43cd
40 * 100	41.35cd
LSD	1.5276

Means in a column with the same letter(s) are not significantly different at 5% level of confidence.

The increase of protein content due to P application might be attributed to by the N supplied through *Bradyrhizobium japonicum* and soil Mg or Ca which made P available to soybean for increased protein content. Morshed *et al.,* (2008a) conducted research on the effect of N on seed yield, protein content and nutrient uptake of soybean, and discovered that Phosphorus content in seeds was affected by different levels of N applied to soybean. Tufenkci *et al.* (2006) also reported a positive interaction between N application and P content in seeds and that increased rates of N fertilizer application significantly increased the content of Phosphorus in the shoots of soybean. Duraisami and Mani (2001) found that the uptake of P by the soybean was favourably affected by the residual effect of N levels. It is observed that the P uptake by the seeds of the soybean per plant increased significantly with an increase in nitrogen level of up to 26.45 kg N ha^{-1} (Duraisami & Mani, 2001). Jaanpaul and Gananesaraja (1990) reported that soybean oil value varied between 14 and 24% and protein values varied between 23 and 34% in their research in India, as a result of increasing N and P rates and irrigation frequency. In the study performed by Deliboran *et al.* (2011), P and Mg treatments increased the oil and protein contents of the soybean grain, and they estimated that the increase in oil and protein contents to be related to the effect of Mg. They emphazised that Mg increases soil P resolution and facilitates P-uptake by plants. These positive effects of P on oil and protein content suggests that P should be used to maximize protein and oil yield.

3.4 CONCLUSIONS

The goal of this experiment was to provide a framework that can be used to critically assess the effect of P and K on soybean yield. In this experiment, K significantly affected plant height while the canopy closure was significantly greater with application of P and K as compared to the control. No significant effect of K and P*K combination on leaf area were observed, while by applying P it reduced leaf area. The application of both P and K revealed no significant impact in leaf area index.

It was expected that plant nutrition using increased levels of P and K application would increase oil and protein content. However, P application irrespective of the rate decreased the oil content below that of the control. It is believed that soybean relies more heavily on residual P than what was applied during the growing season especially for oil yield since the protein content increased with increasing P rates. The inverse happened with the application of K. Potassium regardless of the rate resulted in increased oil content while it decreased the protein content as compared to the control. From this study, it can be recommended to apply high rates of K (100 kg K ha^{-1}) to increase oil yield while for increased protein content, higher rate of P application (20 or 40 kg P ha^{-1}) is recommended.

In conclusion, the present study indicated that the yield increased with increased rates of K but was not significantly affected by P or the interaction of P*K. The highest yield was obtained from applying 100 kg K ha^{-1}. This suggests that in season application of K can play an important role in increasing soybean yield, while the reaction of the plant to P in this study did not give a clear answer in terms of in season application of P.

CHAPTER 4

EEFECT OF P AND K ON SOYBEAN GROWTH AND YIELD AS TESTED IN A GREEN-HOUSE POT TRIAL

4.1 INTRODUCTION

All factors influencing growth, development and yield of a soybean crop must be integrated at an optimum level if the maximum production potential is to be attained. The contribution by plant nutrients plays a fundamental role in improving plant growth and development. Plants require specific amounts of certain nutrients in a specific form at specific times for their growth and development (Sajid *et al.,* 2008). Since macro nutrients such as P and K are needed in relatively high quantities for adequate soybean growth and yield, their deficiencies induce a great disturbance in different physiological and metabolic processes in the plant.

Studies have shown that deficiency effects of these nutrients, especially P, seriously harm processes associated with energy storage and transfer (Snyder, 2000). Poor seed development, quality and seed size are also reported to be the result of deficiencies in these nutrients. Considerable stunting usually follows from K deficiency, internodes of stems are short, root system development is poor and the production of grain is greatly decreased (George & Michael, 2002).

The decline in soil fertility is the main cause of low productivity of cultivated lands. So far the emphasis has been to supplement the soil with the major nutrients namely N, P and K. According to Ram *et al.* (2011)soil test findings, use of fertilizers, limited recycling of plant residues and the gap between the removal and supplementation of nutrients may result in nutrient deficiencies.

Although the total amount of P in the soil may be high, it is often present in an unavailable form or in forms that are only available beyond the rhizosphere. In many agricultural systems in which the application of P to the soil is necessary to ensure plant productivity, the recovery of applied P by crop plants in the growing season is very slow because in the soil more than 80% of the P becomes immobile and unavailable for plant uptake because of adsorption, precipitation, or conversion to the organic form (Holford, 1997). Soil microbes release immobile forms of P to the soil solution and are also responsible for the immobilization of P. More soluble minerals such as K move through the soil solution via bulk flow and diffusion but P is moved mainly by diffusion. Since the rate of diffusion of P is slow (10^{-12} to 10^{-15} m^2s^{-1}), high plant uptake rates create a depletion zone around the roots (Holford, 1997).

Under conditions where plant-available P and K is low, efficient fertilizer application can be used to increase P and K status of the soybean crop. This can improve P and K use efficiency by allowing the crop roots to access P and K early in the growth of a soybean plant and by slowing the reaction of P with Ca, Mg or with Fe or Al oxides (Sample *et al.*, 1980). In South African soils, there is a negative balance of P and K as their addition through various sources is much lower than the removal. The P and K deficiencies in SA soils need a lot of attention for maintenance of adequate P and K levels in the soil to ensure high yields. Thus this study is aimed at supplementing the information obtained from the field trial in terms of the effect of direct P and K fertilization levels on soybean growth and yield.

4.2 MATERIALS AND METHODS

4.2.1 Site description

A pot experiment was conducted under green-house conditions at the Hatfield Experimental Farm, of the University of Pretoria in Pretoria, during the period of December 2010 to March 2011.The site is located at 23° 45’ S, and 28° 16’ E, at 1372m above sea level.

4.2.2 Soil and *Bradyrhizobium* inoculant

Sandy soil with a pH (H_2O) of 5.9 was placed in 10 L plastic pots. A mesh was placed at the base of each pot before filling it with soil to prevent the soil from being washed out. The pots were filled up to the depth of 25 cm with a headspace of 5cm. Soybean cultivar LS 6162R was used as the test crop in the experiment. The soybean seeds were inoculated with *Bradyrhizobium japonicum* inoculant immediately before sowing. Three seeds were sown per pot during 16 December 2010. Initially, three plants were allowed to grow, but were thinned out to two plants per pot on 28 December 2010.

4.2.3 Cultural practices

Watering was done every 3-4 days with distilled water to ensure enough soil moisture for the young developing plants. Weeding was done whenever necessary by hand pulling to prevent competition. All pots were sprayed once (on 18th February 2011) with amite (an insecticide) to control red spider mite. No diseases were observed.

4.2.4 Experimental treatments and layout

The experiment was a factorial arrangement with two factors (Phosphorus and Potassium) each at five levels using a completely randomized block design (Figure 4.1).Treatments included P (Superphosphate (10.5%)) applied at 0, 10, 20, 30 and 40 kg P ha^{-1} and K (KCl (50%)) applied at 0, 50, 100, 150 and 200 kg K ha^{-1}. Each treatment combination was replicated four times, resulting in 100 units. Fertilizers (first diluted in a container) were applied evenly by hand to each pot before planting the seed.

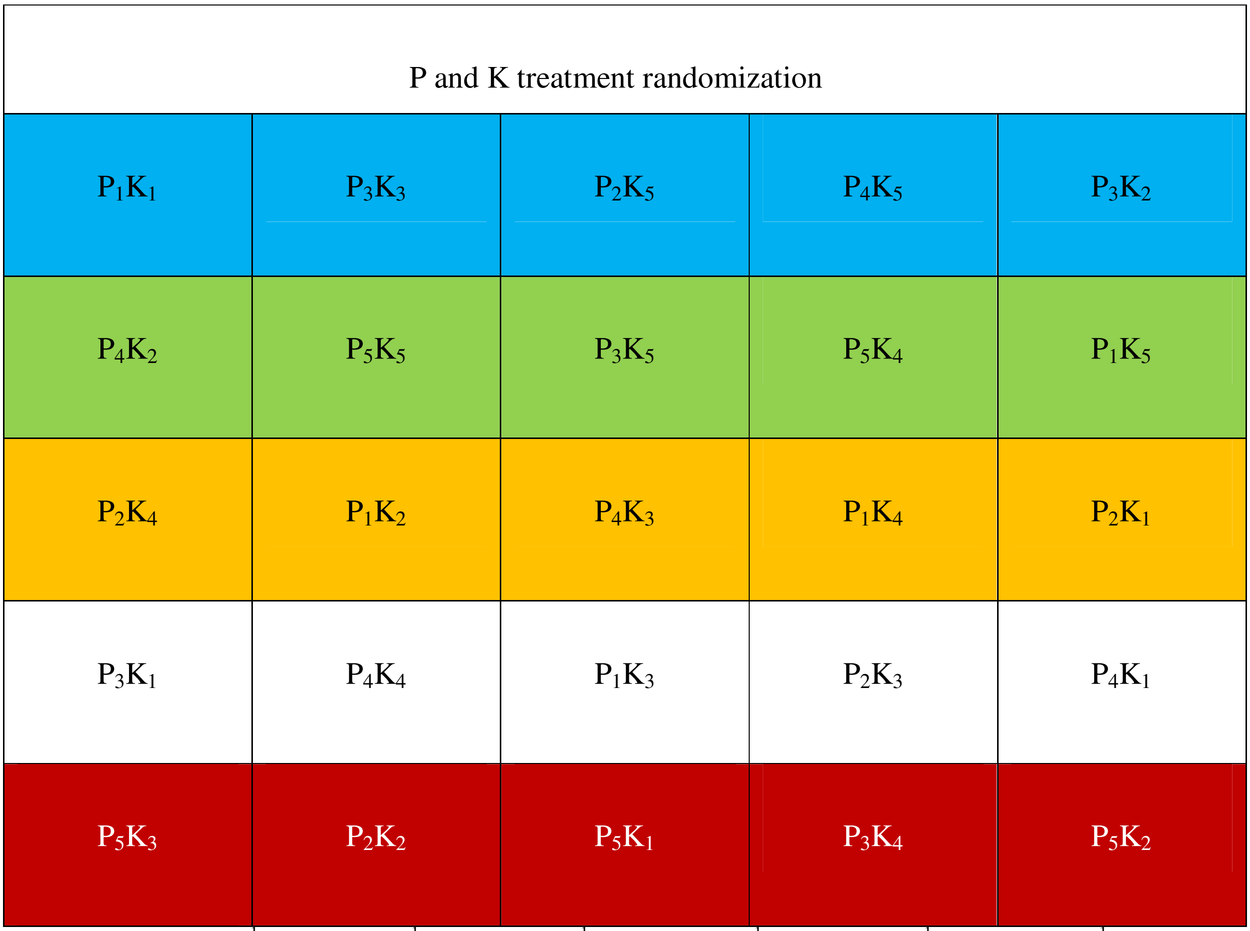
4.2.5 Data collection

Before planting:

Before fertilizers was applied to the test soil, a composite soil sample was collected and analyzed for pH (H_2O) and plant-available nutrients (P, K, Mg, Ca and Na) at the University of Pretoria Soil Science laboratory. Phosphorus content was determined by using Bray-1 while K content was determined by ammonium acetate. The soil analysis data is provided in Table 4.1. The soil analysis revealed a low P level, while that of K was relatively high (Table 4.1). As for the field trial, the soil pH was at an acceptable level for soybean production.

Table 4.1: Soil test results for the soil used in the glass-house pot experiment in 2010 before P and K application and soybean planting.

Year	**pH** (H_2O)	**P - Bray 1** (mg kg^{-1})	**Ammonium Acetate Extractable**			
			K (mg kg^{-1})	**Ca** (mg kg^{-1})	**Mg** (mg kg^{-1})	**Na** (mg kg^{-1})
2010	5.9	4.9	161	321	71	161



P and K treatment randomization

P_1K_1	P_3K_3	P_2K_5	P_4K_5	P_3K_2
P_4K_2	P_5K_5	P_3K_5	P_5K_4	P_1K_5
P_2K_4	P_1K_2	P_4K_3	P_1K_4	P_2K_1
P_3K_1	P_4K_4	P_1K_3	P_2K_3	P_4K_1
P_5K_3	P_2K_2	P_5K_1	P_3K_4	P_5K_2

P_1 = 0 kgha^{-1}; K_1= 0 kgha^{-1}; P_2= 10 kgha^{-1}; K_2= 50 kgha^{-1}; P_3= 20 kgha^{-1}; K_3=100 kgha^{-1};P_4=30 kgha^{-1};K_4=150 kgha^{-1}; P_5=40 kgha^{-1}; K_5=200 kgha^{-1}

Figure 4.1: One replication of the experimental layout of the soybean green-house trial with different P and K levels.

During the growing season:

The days from planting to emergence were recorded. After emergence, data for plant height was taken at 7day intervals starting from two weeks after emergence until maturity (from 29th December 2010 to 23rd February 2011).

At harvest:

At harvest, data was collected on nodule number per plant, pod number per plant, number of nodes per plant, fresh and dry weights for pods, stems and roots per plant per pot.

4.2.6 Statistical analysis

The data was analyzed statistically by analysis of variance (ANOVA) and differences among the treatment means were determined by the least significant difference (LSD) test of Tukey at the 5% level of confidence.

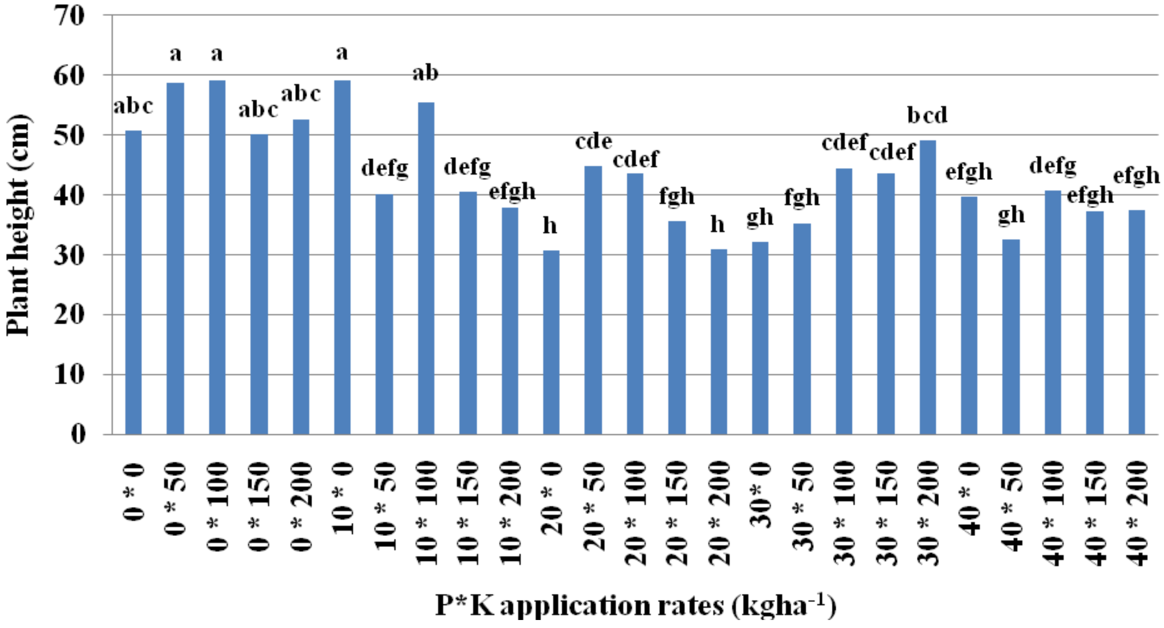
4.3 RESULTS AND DISCUSSION

4.3.1 Plant height

Plant height was significantly affected by P, K as well as the P*K interaction (Appendix C Table C1). Plant height at the first week after fertilization showed no significant difference ($P \leq 0.01$ or $P \leq 0.05$) and was around14.0 cm for all treatments. At the end of the experiment, maximum plant heights of 59.2 cm 58.7 and 59.1cm were recorded with 10 * 0 kg P*K ha^{-1}, 0 * 50 and 0 * 100 kg P*K ha^{-1} which were significantly higher than those recorded at 20, 30 and 40 kg P ha^{-1} regardless of K applied (Figure 4.2). The lowest plant height was recorded at 20 * 0 kg P*K ha^{-1} (30.7 cm) and 20 * 200 kg P*K ha^{-1} (30.9 cm), which were significantly lower than that of the control plants (50.7 cm).The pot experiment thus confirms the results of the field trial where increased levels of K resulted in taller plants. While the field crop were negatively affected by application of P, it was not so for the potted crop. This might be due to the better availability of P since it was applied in a solution and not as dry fertilizer as for the field experiment. It could be due to the confined volume of soil, thus less P available.

Incremental increase in plant height might be due to inoculation and P application. Snyder (2000) indicated that P enhances seed germination, root development, uptake and transfer of nutrients and increases photosynthesis. Tomar *et al.* (2004) showed that increased levels of

Phosphorus had positive effects on plant height while Hernandez and Cuevas (2003) reported that inoculation increased plant height. These findings are similar to those of Qureshi *et al.* (1986) who found a significant increase in plant height due to P application. Increased plant height due to Phosphorus and inoculation were also reported by Menaria *et al.* (2003). These finding are in contradiction to that of the current study, where too high P application rates resulted in shorter plants than under control conditions (Figure 4.2).

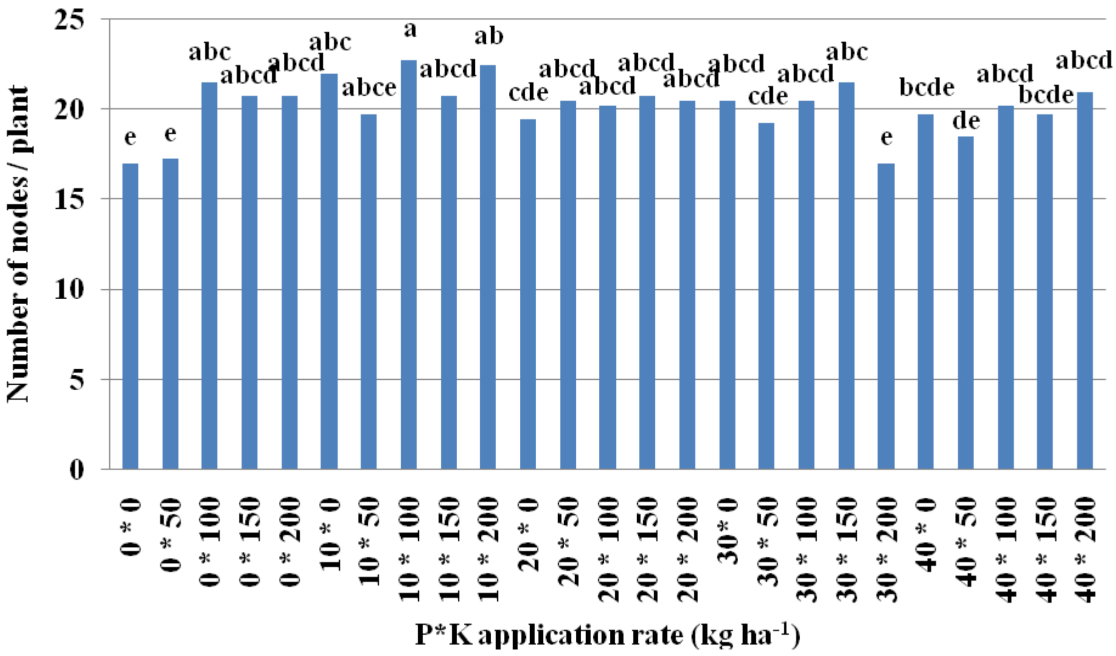


Bar with the same letters are not significantly different to each other at the 5 % level of confidence.

Figure 4.2: Effect of Phosphorus and Potassium application rates on average soybean plant height.

4.3.2 Number of nodes per plant

In general, applied nutrients had a significant affected on the number of nodes ($P \leq 0.05$) (Appendix C Table C1). The maximum node number (23) was recorded with10 * 100 kg P*K ha^{-1} (Figure 4.3). The control plants had a low number of nodes (17) and was the same for plants receiving 0 * 50 or 30 * 200 kg P*K ha^{-1}. In general, the range in number of nodes per plant was very narrow (21 to 19). Therefore node number was not severely impacted by P and K application, as was also recorded for the field crop. However, a lack in P and K can have a negative impact on node number. From the field crop it was established that there is a positive correlation between node number, number of pods per plant and number of 3 seeded pots, emphasising the negative impact of a P and/or K deficiency on potential yield.

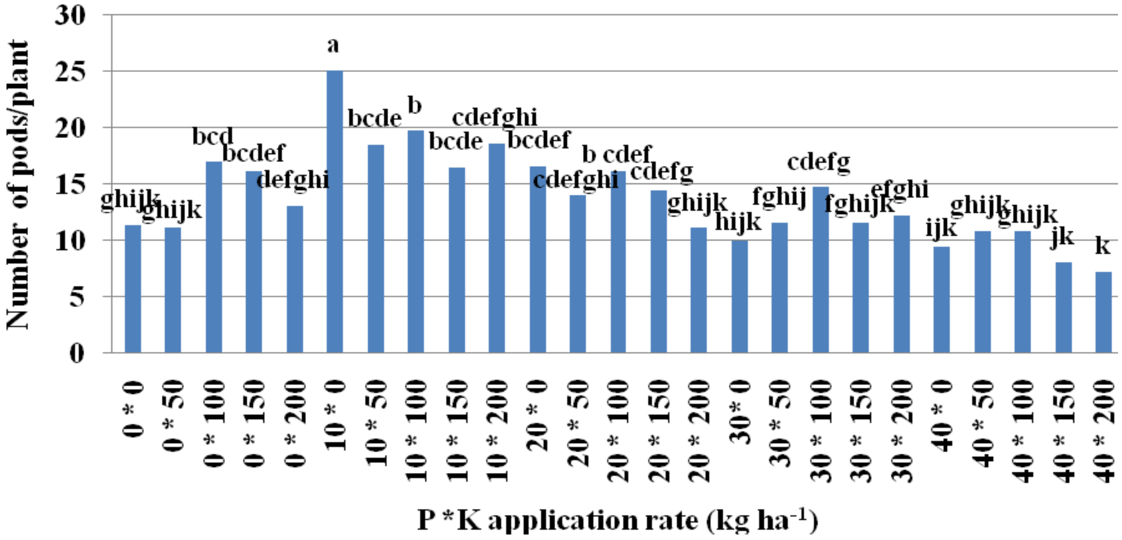


Bars with the same letters are not significantly different from each other at the 5% level of confidence.

Figure 4.3: Number of nodes as affected by Phosphorus and Potassium application rates.

4.3.3 Number of pods per plant

The productive potential of soybean is determined by number of pods per plant which is one of the main yield components (Qasim *et al.*, 2009). The plants where P and K fertilizers were applied were significant impacted on in terms of the number of pods (Appendix C Table C1). Phosphorus fertilizer alone at 10kg P ha^{-1}had a much higher and significant impact on pod number than either K alone or any of the P*K combinations (Figure 4.17). However, too high P application levels (>20 kg P ha^{-1}) resulted in reduced pod number per plant. Too high (>150 kg K ha^{-1}) and too low (< 50 kg K ha^{-1}) K application rates also resulted in lowering of pod number per plant. Mohan and Rao (1997) and Rani (1999), however, reported higher number of pods per plant with higher doses of P and K being applied. Mandal and Sikder (1999) also reported that P and K significantly increased the setting of pods and seeds. Amongst all the treatment combinations (except for 10 * 0 kg P * K ha^{-1}), 10 * 100 kg P*K ha^{-1} showed the highest number of the pods (25) as compared to the rest of the treatment combinations.

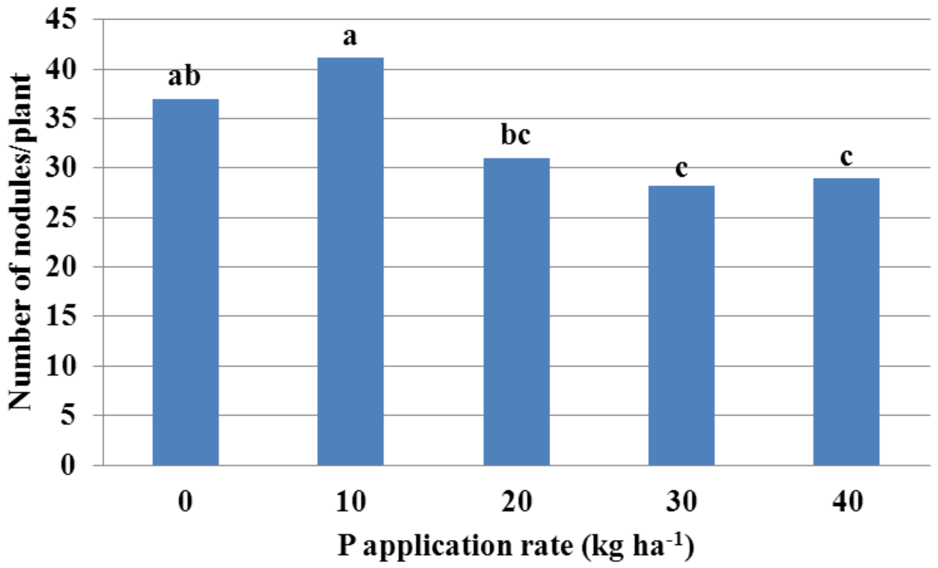


Bars with the same letters are not significantly different to each other at 5% level of confidence.

Figure 4.4: Effect of Phosphorus and Potassium on number of soybean pods per plant.

4.3.4 Number of nodules per plant

The data in Appendix C Table C1 showed that the main effect of K as well as the P*K interactions had no significant effect on the number of nodules. Phosphorus alone, highly affected the number of nodules ($P \leq 0.05$). The results of the study by Rotaru (2010) confirmed that the nodulation process respond significantly to supplementary P nutrition. The maximum number of nodules (41) was recorded with 10 kg P ha^{-1}which was higher than of the control (37) as well as the rest of the P treatments (Figure 4.5). The higher P application rates (30 and 40 kg P ha^{-1}) resulted in the lowest number of nodules (28) as compared to the rest of the P treatments. Dubey and Gupta (1996) reported that a reduction in nodulation with high P application rates is due to imbalance which results in an inadequate release of P to plants from insoluble and fixed forms. Since we did not measure P availability in this experiment, it cannot be said with certainty that this is what happened in the experiment.



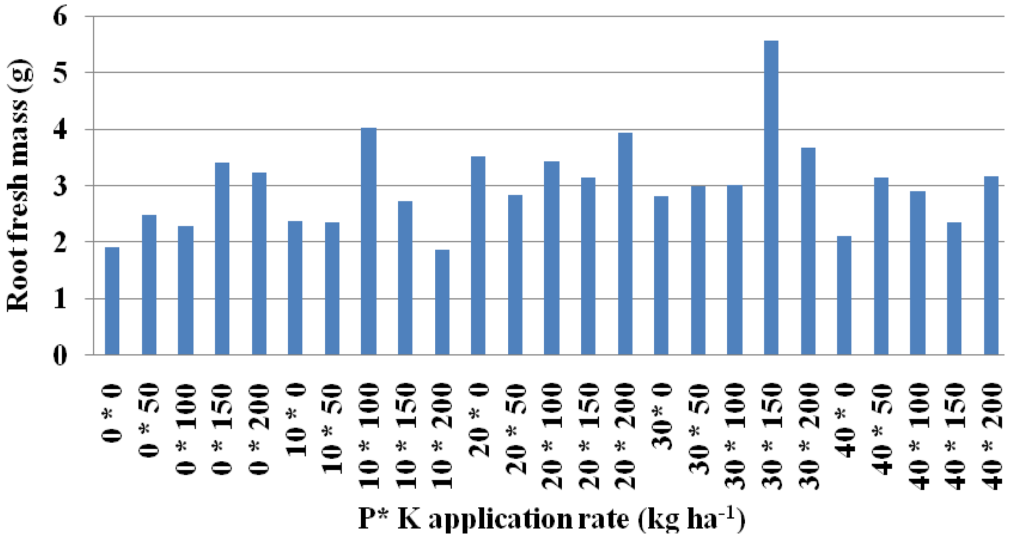
Bars with the same letters are not significantly different to each other at the 5% level of confidence.

Figure 4.5: Number of nodules per soybean plant as affected by Phosphorus.

4.3.5 Fresh and dry root mass

Fresh root mass:

The main effect of P, K and P*K interactions were non-significant in terms of fresh roots mass of soybean. Although there is no statistical significance recorded between the treatments, 30 * 150 kg P*K ha^{-1} produced the highest root fresh mass of 5.56g which is higher than that of the control plants (1.92g). The lowest root fresh mass was obtained with 10 * 200 kg P*K ha^{-1} (1.875 g). In general, too high (> 40 kg P ha^{-1}) or too low (< 10kg P ha^{-1}) P in the absence of K has a negative impact on root growth. In terms of K alone, fresh root mass tended to increase with increased levels of K applied. This confirms the results obtained for the field crop where more K resulted in better root growth.

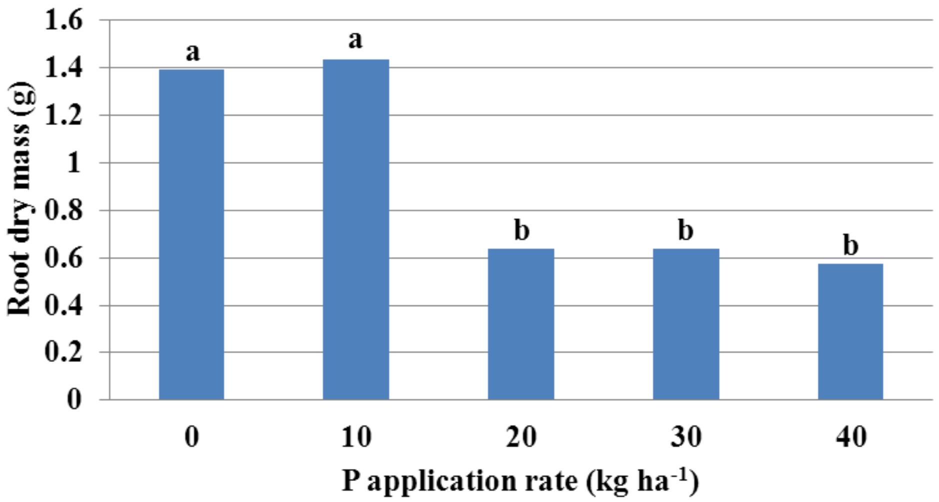


No significant differences

Figure 4.6: Soybean fresh root mass as affected by Phosphorus and Potassium.

<u>Dry root mass:</u>

Various levels of P had a highly significant effect on dry root mass (Figure 4.20). The main effect of K and P*K interaction did not significantly affect the dry root mass. The maximum dry root mass of 1.44g was recorded with10kg P ha^{-1}and was statistically similar to that of the control (1.39g). With increasing levels of P fertilizer, the average dry weight of roots per plant decreased insignificantly. Similar results were noticed by Morshed *et al*. (2008b) who reported insignificant variance of root dry mass from 0.97 to 1.27g due to P treatment variations. Therefore, legume fertilization with P for root growth can only be justified in moderate rates.



Bars with the same letters are not significantly different to each other at the 1% level of confidence.

Figure 4.7: Soybean dry root mass as affected by Phosphorus.

4.3.6 Fresh and dry stem mass

Fresh stem mass:

There was a highly significant main effect of P and K on fresh stem mass while the interaction of P*K was not significant. The highest fresh stem mass (5.46g)was recorded where 10kg P ha^{-1} was applied and varied significantly from all the other P application rates as well as the control (Table 4.2). The stems of the control plants weighed 3.48 g which was statistically similar to all the P rates except for 10kg P ha^{-1}. The highest P rate (40 kg P ha^{-1}) resulted in the lowest fresh stem mass.

However, there was a gradual increase in fresh stem mass from 2.76 g to 5.05 g with increased levels of K, up to 150 kg K ha^{-1}, but adding more K resulted in a decrease in stem mass (Table 4.3). Potassium applied at 150 kg K ha^{-1}resulted in the highest fresh stem mass which significantly differed from all the treatments (except 100 kg K ha^{-1}), with the control plants having the lowest mass.

Dry stem mass:

The dry mass was not significantly affected by the main effect of K and the P*K interactions but was influenced by the P main effect alone (Appendix C Table C1). A significantly higher dry stem mass of 1.93 g was obtained with 10kg P ha^{-1} and was on par with the control (1.97 g). In general, there was a gradual decrease in stem dry mass with increasing levels of P fertilizer (Table 4.2). Although not significant, the dry stem mass tended to increase with increase application rates of K up to 100 kg K ha^{-1}. Overall, the stem dry mass was higher where some K was applied (Table 4.3).

Table 4.2: Effect of Phosphorus application rate on fresh and dry stem mass of soybean.

P application rate (kg ha^{-1})	**Fresh stem mass (g)**	**Dry stem mass (g)**
0	3.48b	1.97a
10	5.46a	1.93a
20	3.48b	1.14b
30	3.89b	1.13b
40	2.85b	0.76b
LSD	1.3995	0.448

Means sharing same letters within a column did not differ significantly at the 1% level of probability.

Table 4.3: Effect of Potassium application rate on fresh and dry stem mass of soybean.

K application rate (kg ha^{-1})	**Stem fresh mass (g)**	**Stem dry mass (g)**
0	2.76c	1.19
50	3.40bc	1.25
100	4.36ab	1.66
150	5.05a	1.56
200	3.60bc	1.27
LSD	1.3995	NS

Means sharing same letters within a column did not differ significantly at the 5% level of probability. NS = Non-significant.

4.3.7 Fresh and dry pod mass

Fresh pod mass:

Soybean yield is governed by different components such as number of pods, pod mass, seeds per plant and number of seeds per pod as influenced by nutrition. According to the findings from this experiment, the main effect of K and P*K interactions did not affect the fresh pod mass significantly (Appendix C Table C1). Application of P, however, has resulted in highly significant differences in fresh pod mass of soybean ($P \leq 0.01$).

Among the P treatments, plants receiving 10kg P ha^{-1} produced the highest fresh pod mass (19.41 g) which differed significantly from the rest of the P treatments (Table 4.4). The fresh pod mass of the control and the rest of the P levels (20, 30 and 40 kg P ha^{-1}) did not differ statistically from each other. There was a gradual decrease in pod mass with increased application of P from 10 to 40 kg P ha^{-1}with the latter having the lowest pod mass than even that of the control.

Although not significant, the fresh pod masses where 100 and 150kg K ha^{-1} were applied were higher than that of the control. By applying low (50 kg K ha^{-1}) or too high (200 kg K ha^{-1}) K levels, gave similar fresh pod masses as where no K was applied.

Dry pod mass:

The main effect of P and K had a highly significant effect on dry pod mass while the P*K interaction showed a non-significant effect. The control plants had higher dry pod masses than those receiving P and K except with the application of 10 kg P ha^{-1}(11.04 g) or100 kg K ha^{-1}(8.56g) (Table 4.4 and 4.5 respectively). The dry pod mass from these treatments differed significantly from the rest of the treatments. The lowest dry pod masses were recorded where 40 kg P ha^{-1} or 200 kg K ha^{-1} was applied. This again confirms that too high P and K application rates can have a devastating effect on yield.

Table 4.4: Effect of Phosphorus application rates on fresh and dry pod mass of soybean.

P application rate(kg ha^{-1})	Fresh pod mass(g)	Dry pod mass (g)
0	9.26b	7.42b
10	19.41a	11.04a
20	10.64b	6.16bc
30	10.41b	4.88cd
40	6.99b	3.15d
LSD	3.6865	2.056

Means sharing same letters within a column did not differ significantly at the 1% probability level of confidence.

Table 4.5: Effect of Potassium application rates on fresh and dry pod mass of soybean.

K application rate (kg ha^{-1})	Fresh pod mass (g)	Dry pod mass (g)
0	10.61	7.15ab
50	10.13	6.65abc
100	13.91	8.56a
150	11.47	5.32bc
200	10.59	4.99c
LSD	NS	2.056

Means sharing same letters within a column did not differ significantly at the 1% level of probability of confidence.

NS = Non-significant.

4.4 CONCLUSIONS

From this research we recommend that attention should be given to applying lower P (10 kg P ha^{-1}) and higher K rates (100 kg K ha^{-1}) if high plant height and number of nodes are to be obtained. The above characteristics suggest that high yielding soybeans should be tall with a high number of nodes. Phosphorus at lower levels (10 kg P ha^{-1}) also had a positive impact on nodulation, illustrating the importance of P for good nodulation. Too high P application levels, however, resulted in reduced nodulation and producers should be cautioned against applying too much P when legumes are inoculated.

Statistically significant differences in number of pods per soybean plant as affected by different P levels (10 and 20 kg P ha^{-1}) were observed but not for K alone and or the P*K combination. The lower levels of P fertilizer (10 and 20 kg P ha^{-1}) gave the greatest number of pods. All the treatments resulted in increased fresh and dry stem weights although the K and P*K were also not significant with regard to dry stem mass.

In conclusion, this study supported that applying P and K is an important way to raise the plant growth and yield of soybean. In the pot experiment the initial soil P level was much lower than that of the soil in the field plots. This might explain why there were some reactions of the plant when P was applied. But still, too high P applications resulted in reduced yields. In terms of K, too low (< 100 kg K ha^{-1}) and too high (>150 kg K ha^{-1}) K application rates may result in poor plant performance. From the pot experiment, it was thus clear that direct application of P and K can have a positive effect on soybean production.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The goal of this experiment was to determine if direct application of P and K can have a positive effect on soybean growth, yield and quality. This research question came about due to the fact that South African soybean producers belief that residual P and K from the previous crop is significant for good soybean production. To answer this question, a pot and field experiment with different levels of P and K were conducted at the Hatfield Experimental farm during the 2010/2011 growing season. In the pot experiment five levels for each P and K were used, while three levels for each was used in the field experiment.

Plant height provided information about the plant dry matter accumulation. The results demonstrated large variations in reaction to P and K application rates and there was a positive association between the plant height and P, K and or P*K fertilizer application in the field trial. Soybean plant height was only significantly impacted by the main effect of K. This might be due to the build-up of P in the top-soil due to continuous P application over a three year period. However, the green-house experiment quantified the effect of both P and K application rates to significantly affect plant height. From these results, it is recommend that attention should be given to applying lower P (10 kg P ha^{-1}) and higher K rates (100 kg K ha^{-1}) if high plant height and number of nodes are to be obtained.

Both the field and pot experiment crops showed a positive reaction to the application of some P and K in terms of the number of nodules produced. In both trials an application of 20 kg P ha^{-1} or more had a negative impact on nodule development, while application of K in the absence of P also suppressed nodulation. When K was combined with P, K applications as high as 100kg K ha^{-1} resulted in a higher number of nodules produced as compared to the control.

Increased P and K application rates resulted in an optimum soybean population level which ensured early canopy development, resulting in good soil coverage and maximum light interception. An application of 40kg P and 100kg K ha^{-1} resulted in the highest amount of light intercepted by the soybean canopy. As a result of this increased light interception during vegetative and early reproductive development stages, yield increased. It should be noted that light interception is always greater for narrow leaf crops due to greater light penetration down into the lower portion of the canopy where the lower leaves can absorb it.

Under both field and pot trial conditions, the node number per plant did not vary much, but P and K did have a slight positive effect on it. There was also a positive correlation between node number, number of pods and 3 seeded pots. Therefore a lack in P and K can have a negative impact on yield.

The number of pods per plant under field conditions did not differ significantly, but by applying 50 or a 100kg K ha^{-1} the number of pods tended to increase. In the pot experiment, both the application of P and K resulted in a significantly higher number of pods as compared to the control. For the specific soil used in the pot trial, too high P (> 30 kg P ha^{-1}) and too high (> 200 kg K ha^{-1}) or too low (<50 kg K ha^{-1}) K applications had a negative impact on pod number.

Under field conditions the fresh and dry root, stem, leaf and pod masses tend to more affected by the application of K than P, but still the differences were not very high as compared to where no K was applied. In the pot experiment, P application did, however, have a significant positive impact on most of the fresh and dry masses. On the other hand the effect of K was not always significant, but the plants reacted positively to the application of higher levels of K. Both P and K had a significant and positive effect on dry pod mass, which differed from the situation under field conditions. Under field conditions P application had a negative impact on pod mass.

It was expected that the application of P and K would increase the quality of the soybean seed (oil and protein) especially due to the high fertility needs of the soybean crop. However, this study found that P fertilizer irrespective of the rate decreased the oil content below that of the control while having the opposite effect on the protein content. Potassium applied at any of the rates resulted in increased oil content and decreased protein content compared to that of the control. From this study it therefore seems as if one can manipulate the protein and oil content by varying the P (20 or 40 kg P ha^{-1} for protein) and K (100 kg K ha^{-1} for oil) application rates.

This field study indicated that the yield increased with increased rates of K but was not significantly affected by P or the interaction of P*K. The highest yield was obtained from applying 100kg K ha^{-1}. This suggests that in season application of K can play an important role in increasing soybean yield, while the reaction of the plant to P in this study was much depended on the initial soil P content. In the pot trial the initial soil P level was much lower than that of the soil in the field trial. This might explain why there were some reactions of the plant when P was applied. But still, too high P application rates resulted in reduced yields. In terms of K, too low (< 100kg K ha^{-1}) and too high (>150kg K ha^{-1}) K application rates may result in poor plant performance. From the pot trial, it was clear that direct application of P and K can have a positive effect on soybean production. Thus, the pot trial supported that applying P and K is an important way to raise plant growth and yield of soybean.

The following recommendations can be made:

- Soybean producers should give more attention to P and K fertilizer application and not only rely on residual P and K to improve yields.
- P and K application should be done at the hand of a soil analysis. When the results of the field and pot trial are compared, it is clear that the initial nutritive status of the soil had a huge impact on the soybeans reaction on applied P and K.
- A cost analysis study should be conducted to compare the profit margins of applying P and K to a soybean crop versus residual P and K from the previous crop.

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APPENDIX A: ANOVA Tables for the field trial during the 2010/2011 season.

Table A1: Effect of Phosphorus and Potassium on soybean plant height for the 2010/2011 growing season.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr> F**
Model	8	11131.4384	1391.4298	2.10	0.0347
Error	423	280379.4068	662.8355		
Corrected Total	431	291510.8452			
R-Square	0.038185				
Co-efficient variation	48.08681				
Root MSE	25.74559				
Height Mean	53.53981				
Phosphorus	4	1517.535220	758.767610	1.14	0.3193
Potassium	2	7915.022442	3957.511221	5.97	0.0028
Phosphorus*Potassium	2	1698.880752	424.720188	0.64	0.6337

Table A2: Effect of Phosphorus and Potassium on soybean canopy closure and light interception for the 2010/2011 season.

Variable	**R-Square**	**Co-efficient of Variation**	**Root MSE**	**Mean**	**Source**	**LSD**	**PR > F**
Canopy closure	0.87120	74.08805	17.95704	24.23743	Phosphorus	4.5722 S*	0.0365
					Potassium	4.5722 S**	0.0001
					Phosphorus*Potassium	7.9197 NS	0.0767
LI	0.55202	12.32345	0.09562	0.775898	Phosphorus	0.0806 S*	0.0354
					Potassium	0.0806 NS	0.1265
					Phosphorus*Potassium	0.1395 NS	0.0536

LI = Light interception; Root MSE = Root Mean Squared Error; LSD = Least Significant Difference; S* = Significant at 5% level of confidence; S** = Significant at 1% level of confidence; NS = Non-significant

Table A3: Effect of Phosphorus and Potassium on soybean leaf number and leaf area 16 weeks after planting for the 2010/2011 season.

Variable	R-Square	Co-efficient of Variation	Root MSE	Mean	Source	LSD	PR > F
					Phosphorus	11.006NS	0.4816
Leaf number	0.43756	33.23228	13.06213	39.30556	Potassium	11.006NS	0.1307
(16 WAP)					Phosphorus*Potassium	19.063 NS	0.2790
					Phosphorus	0.0775NS	0.7641
Leaf Area	0.31078	46.20544	0.092030	0.199177	Potassium	0.0775 NS	0.5592
(16 WAP)					Phosphorus*Potassium	0.1343 NS	0.0789

WAP = Weeks After Planting; Root MSE = Root Mean Squared Error; S* = Significant at 5% level of confidence; NS = Non-significant

Table A4: Effect of Phosphorus and Potassium on number of pods per plant, 1-, 2-, 3- and 4-seeded pods and number of nodes per soybean plant during the 2010/2011 season.

Variable	**R-Square**	**Co-efficient of Variance**	**Root MSE**	**Mean**	**Source**	**LSD**	**Pr> F**
Pod number	0.082975	32.71565	7.724529	23.61111	Phosphorus	3.6126 NS	0.2573
					Potassium	3.6126 NS	0.3148
					Phosphorus*Potassium	6.2573 NS	0.4293
1-seeded pods	0.145556	99.98336	1.647874	1.648148	Phosphorus	0.7707 NS	0.1193
					Potassium	0.7707 S*	0.0498
					Phosphorus*Potassium	1.3349 NS	0.1845
2-seeded pods	0.062412	59.10286	2.479037	4.194444	Phosphorus	1.1594 NS	0.2446
					Potassium	1.1594 NS	0.2579
					Phosphorus*Potassium	2.0082 NS	0.9113
3-seeded pods	0.107394	40.22096	5.008999	12.45370	Phosphorus	2.3426 NS	0.3037
					Potassium	2.3426 NS	0.3809
					Phosphorus*Potassium	4.0576 NS	0.1186
4-seeded pods	0.213376	50.80585	2.756688	5.425926	Phosphorus	1.2893 S*	0.0217
					Potassium	1.2893 S**	0.0002
					Phosphorus*Potassium	2.2331 NS	0.9912
Node number	0.171521	12.45908	2.168802	17.40741	Phosphorus	1.0143 NS	0.6536
					Potassium	1.0143 NS	0.1087
					Phosphorus*Potassium	1.7568 S**	0.0067

Root MSE = Root Mean Squared Error; LSD = Least Significant Difference; S* = Significant (Pr< 0.05); S** = Significant (Pr< 0.01); NS = Non-significant

Table A5: Effect of Phosphorus and Potassium on soybean nodule number 16 weeks after planting for the 2010/2011 season.

Variable	**R-Square**	**Co-efficient of Variation**	**Root MSE**	**Mean**	**Source**	**LSD**	**PR > F**
Nodule number	0.162937	40.47472	5.853844	14.46296	Phosphorus	4.9323 (NS)	0.5328
					Potassium	4.9323 (NS)	0.5862
					Phosphorus*Potassium	8.5431 (NS)	0.9129

WAP = Weeks After Planting; Root MSE = Root Mean Squared Error; LSD = Least Significant Difference; level of confidence; NS = Non-significant

Table A6: Effect of Phosphorus and Potassium on soybean fresh and dry mass16 weeks after planting for the 2010/2011 season.

Variable	**R-Square**	**Co-efficient of Variation**	**Root MSE**	**Mean**	**Source**	**LSD**	**PR > F**
Fresh leaf mass	0.193704	44.79879	3.211658	7.169074	Phosphorus	2.7061NS	0.8275
					Potassium	2.7061NS	0.8285
					Phosphorus*Potassium	4.6871NS	0.7350
Fresh stem mass	0.289421	48.94210	7.307373	14.93065	Phosphorus	6.1571NS	0.8340
					Potassium	6.1571NS	0.3166
					Phosphorus*Potassium	10.664NS	0.1372
Fresh pod mass	0.399499	44.51399	8.711429	19.57009	Phosphorus	7.3401NS	0.7136
					Potassium	7.3401NS	0.1151
					Phosphorus*Potassium	12.713NS	0.3267
Fresh root mass	0.504260	45.32058	1.189707	2.625093	Phosphorus	1.0024NS	0.5861
					Potassium	1.0024NS	0.3558
					Phosphorus*Potassium	1.7363NS	0.6842
Dry stem mass	0.340359	44.16466	2.281881	5.166759	Phosphorus	1.9227NS	0.8080
					Potassium	1.9227NS	0.3059
					Phosphorus*Potassium	3.3302NS	0.8659
Dry pod mass	0.410699	43.90619	2.695474	6.139167	Phosphorus	2.2712NS	0.7667
					Potassium	2.2712NS	0.1208
					Phosphorus*Potassium	2.9338NS	0.2873
Dry root mass	0.324814	32.19009	0.606426	1.883889	Phosphorus	0.511NS	0.7465
					Potassium	0.511NS	0.3885
					Phosphorus*Potassium	0.885NS	0.5364
Dry leaf mass	0.303482	41.30010	1.260456	3.015944	Phosphorus	1.062NS	0.8460
					Potassium	1.062NS	0.4478
					Phosphorus*Potassium	1.8395NS	0.7760

WAP = Weeks After Planting; LSD = Least Significant Difference; S* = Significant at 5% level of confidence; NS = Non-significant

Table A7: Effect of Phosphorus and Potassium on soybean moisture content, 100-seed mass, and mean yield for the 2010/2011 season.

Variable	R-Square	Co-efficient of Variation	Root MSE	Mean	Source	LSD	PR > F
Seed moisture	0.151490	5.249126	0.435677	8.300000	Phosphorus	0.3649 NS	0.5235
					Potassium	0.3649 NS	0.2496
					Phosphorus*Potassium	0.6321 NS	0.9647
100-seed mass	0.296903	7.861391	1.086619	13.82222	Phosphorus	0.9102 NS	0.9604
					Potassium	0.9102 S*	0.0201
					Phosphorus*Potassium	1.5765 NS	0.6907
Mean yield	0.410997	27.06298	0.605384	2.236944	Phosphorus	0.5071 NS	0.6781
					Potassium	0.5071 S**	0.0015
					Phosphorus*Potassium	0.8783 NS	0.8580

Root MSE = Root Mean Squared Error; LSD = Least Significant Difference; S* = Significant (Pr< 0.05); S** = Significant (Pr< 0.01); NS = Non-significant.

APPEDIX B: Soil analysis data

Table B1: Top-soil analysis data for the 2009/2010 soybean cropping season.

			P- Bray 1	Ammonium acetate					
P	K		P	K	Ca	Mg	Na	R	pH
kg ha^{-1}	kg ha^{-1}	Rep	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	ohm	(H_2O)
0	0	1	14.5	39	382	138	5.49	4160	6.36
0	0	2	27.4	32	410	150	2.97	3630	6.21
0	0	3	8.6	15	242	98	2.35	4860	5.75
0	0	4	5.7	18	253	97	2.13	4970	5.51
		Average	14.05	26	321.75	120.75	3.235	4405	5.9575
0	50	1	15.8	59	367	131	4.31	3930	6.38
0	50	2	17.5	27	452	158	5.09	3710	6.36
0	50	3	12.7	41	357	126	4.21	4500	6.15
0	50	4	7.7	31	260	95	4.4	4850	5.5
		Average	13.425	39.5	359	127.5	4.5025	4247.5	6.0975
0	100	1	21.4	58	320	111	3.73	4520	6.14
0	100	2	18.1	98	344	114	2.73	3780	6.4
0	100	3	10.9	65	343	119	5.74	4110	5.86
0	100	4	3.7	54	302	113	4.64	4150	5.9
		Average	13.525	68.75	327.25	114.25	4.21	4140	6.075
20	0	1	41.3	27	358	130	3.79	4250	6.24
20	0	2	40.3	15	401	128	8.16	3290	6.24
20	0	3	32.9	17	357	129	3.22	4000	6.03
20	0	4	6.7	30	344	122	2.69	4510	5.84
		Average	30.3	22.25	365	127.25	4.465	4012.5	6.0875
20	50	1	36.3	35	360	118	3.57	3660	6.03
20	50	2	56.7	57	423	131	3.82	4050	6.1
20	50	3	49.4	43	308	88	4.66	3900	5.46
20	50	4	20.3	53	366	124	5.96	4290	5.84
		Average	40.675	47	364.25	115.25	4.5025	3975	5.8575
20	100	1	48.9	46	352	114	2.39	4400	5.85
20	100	2	39.8	69	393	128	1.82	3620	6.35
20	100	3	26.7	60	354	118	5.38	4220	6.16
20	100	4	7.5	46	304	110	4.11	4220	5.93
		Average	30.725	55.25	350.75	117.5	3.425	4115	6.0725
40	0	1	56.2	25	337	112	3.68	3450	5.92
40	0	2	80.5	22	422	121	4.67	3730	6.13
40	0	3	39.5	24	368	113	3.49	3950	5.93
40	0	4	16.3	23	341	119	3.73	3830	5.63

		Average	48.125	23.5	367	116.25	3.8925	3740	5.9025
40	50	1	66.5	40	341	105	9.61	4020	5.67
40	50	2	71.9	38	399	108	5.4	3980	5.8
40	50	3	41.1	27	307	97	2.75	3900	6
40	50	4	9.3	45	324	112	2.72	4050	5.81
		Average	47.2	37.5	342.75	105.5	5.12	3987.5	5.82
40	100	1	85.2	50	291	73	2.99	3780	5.39
40	100	2	69.4	50	375	117	4.98	3540	6.03
40	100	3	63.4	73	300	77	1.66	4010	5.66
40	100	4	24.9	43	279	92	1.94	4200	5.49
		Average	60.725	54	311.25	89.75	2.8925	3882.5	5.6425

Table B2: Top-soil analysis data for the 2010/2011 soybean cropping season.

			P- Bray 1	Ammonium acetate					
P	K		P	K	Ca	Mg	Na	R	pH
kgha^{-1}	kgha^{-1}	Rep	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	ohm	(H$_2$O)
0	0	1	12.8	46	391	140	18.6	2940	6.31
0	0	2	21.5	31	292	100	17.7	3990	6.19
0	0	3	9.1	21	256	90	19.7	3530	5.77
0	0	4	9.9	23	244	89	20.2	3290	5.65
		Average	13.325	30.25	295.75	104.75	19.05	3437.5	5.98
0	50	1	11.5	72	321	110	18.7	3180	6.35
0	50	2	14.2	47	368	122	18.3	4370	6.3
0	50	3	11.9	48	306	104	21.8	3560	6.08
0	50	4	6.9	37	247	92	19.9	3130	5.84
		Average	11.125	51	310.5	107	19.675	3560	6.1425
0	100	1	12.7	82	299	102	14.8	4090	6.29
0	100	2	14.1	115	321	96	18.9	3350	6.26
0	100	3	9.3	83	278	86	19.4	4250	5.88
0	100	4	4.3	69	293	105	22.5	3520	6.12
		Average	10.1	87.25	297.75	97.25	18.9	3802.5	6.1375
20	0	1	21.9	33	386	144	16.2	3280	6.54
20	0	2	30.9	23	347	110	18.2	3330	6.26
20	0	3	17.7	23	308	98	19.6	2770	6.06
20	0	4	7.3	30	346	116	19.8	3710	5.96
		Average	19.45	27.25	346.75	117	18.45	3272.5	6.205
20	50	1	20.1	48	351	110	17.8	3040	6.03
20	50	2	25.1	59	344	106	18.4	2810	6.16
20	50	3	14.8	39	246	75	15.8	4140	5.67
20	50	4	11.8	60	309	100	19.3	3480	5.87
		Average	17.95	51.5	312.5	97.75	17.825	3367.5	5.9325
20	100	1	26.4	67	295	87	16.5	4020	5.94
20	100	2	17.3	65	314	95	16.9	3030	6.2
20	100	3	15.6	86	297	85	18.6	3040	6.06
20	100	4	7.1	76	382	131	19.1	3510	5.98
		Average	16.6	73.5	322	99.5	17.775	3400	6.045
40	0	1	32.6	36	387	119	16.3	2420	6.04
40	0	2	37.7	28	369	111	24.4	3950	6.18
40	0	3	42.9	28	364	107	18.7	2510	6.1
40	0	4	30.2	26	313	99	19.9	3100	5.82
		Average	35.85	29.5	358.25	109	19.825	2995	6.035
40	50	1	37.1	39	280	80	16.3	2870	5.74

40	50	2	30.3	48	282	75	16.8	3560	5.73
40	50	3	22.4	50	362	110	18.5	3350	6.12
40	50	4	10.7	52	308	98	23.1	3280	5.92
		Average	25.125	47.25	308	90.75	18.675	3265	5.8775
40	100	1	26.7	57	272	81	18.7	3730	5.76
40	100	2	39.1	74	343	97	16.9	2770	6.02
40	100	3	33.4	69	317	88	16.6	2920	5.96
40	100	4	14.6	57	270	86	16.2	3670	5.63
		Average	28.45	64.25	300.5	88	17.1	3272.5	5.8425

Table B3: Sub-soil analysis data for the 2009/2010 soybean cropping season.

			P- Bray 1	Ammonium acetate					
P	K		P	K	Ca	Mg	Na	R	pH
kg ha^{-1}	kg ha^{-1}	Rep	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	mgkg^{-1}	ohm	(H$_2$O)
0	0	1	1.9	78	347	129	5.25	2862	5.88
0	0	2	0.98	19	356	108	3.19	3230	5.76
0	0	3	1.8	10	356	116	2.61	3730	5.98
0	0	4	0.92	18	413	132	5.81	3000	5.46
		Average	1.4	31.35	368	121.25	4.215	3205.5	5.77
0	50	1	1.6	82	343	113	2.61	3090	5.97
0	50	2	1.1	17	259	103	2.31	3270	5.5
0	50	3	1.8	17	474	110	3.61	2950	6.04
0	50	4	1.2	16	317	95	5.76	3000	5.44
		Average	1.425	33	348.25	105.25	3.5725	3077.5	5.7375
0	100	1	1.5	71	274	94	1.56	2910	5.41
0	100	2	1.6	21	395	114	4.06	2970	5.76
0	100	3	1.4	17	367	109	3.54	2750	5.72
0	100	4	1.6	29	457	130	6.86	3010	6.07
		Average	1.525	34.5	373.25	111.75	4.005	2910	5.74
20	0	1	1.6	23	269	95	2.11	3920	5.52
20	0	2	0.99	14	251	88	3.67	3060	5.37
20	0	3	1.1	11	309	94	2.68	3120	5.67
20	0	4	1.8	22	435	126	11.15	2560	5.84
		Average	1.3725	17.5	316	100.75	4.9025	3165	5.6
20	50	1	1.1	18	314	104	2.66	3320	5.69
20	50	2	1.7	17	399	111	5.25	3260	5.73
20	50	3	1.6	20	427	122	3.72	2840	5.44
20	50	4	1.8	61	296	97	4.21	2620	5.53
		Average	1.55	29	359	108.5	3.96	3010	5.5975
20	100	1	1.4	24	284	100	1.35	2750	5.48
20	100	2	1.8	16	434	121	3.13	3400	6.1
20	100	3	0.87	28	453	131	4.17	2620	5.63
20	100	4	1.4	29	410	136	6.59	2740	6.18
		Average	1.3675	24.25	395.25	122	3.81	2877.5	5.8475
40	0	1	1.2	26	270	100	1.76	2770	5.6
40	0	2	0.87	17	287	97	4.07	2870	5.21
40	0	3	1.6	58	391	98	3.05	3300	5.76
40	0	4	0.88	14	334	116	4.67	2960	5.84
		Average	1.1375	28.75	320.5	102.75	3.3875	2975	5.6025
40	50	1	1.9	22	280	87	2.53	3280	5.46

40	50	2	1.2	17	274	93	2.95	3020	5.08
40	50	3	0.76	19	380	127	5.19	2500	5.76
40	50	4	1.7	49	336	113	3.72	2730	5.43
		Average	1.39	26.75	317.5	105	3.5975	2882.5	5.4325
40	100	1	1.7	31	318	96	6.02	2700	5.35
40	100	2	0.87	12	249	82	4.44	3270	5.32
40	100	3	1.4	48	364	99	3.39	2330	5.58
40	100	4	0.67	18	327	123	4.28	2450	5.43
		Average	1.16	27.25	314.5	100	4.5325	2687.5	5.42

APPENDIX C: ANOVA tables data for the pot trial during the2010/2011 season.

Table C1: Effect of Phosphorus and Potassium on various soybean parameters for the 2010/2011 pot trial.

Variable	**R-Square**	**Coefficient of Variance**	**Root MSE**	**Mean**	**Source**	**LSD**	**PR > F**
Soybean height (1st WAF)	0.135489	15.66130	2.134635	13.63000	P	1.3447 NS	0.5297
					K	1.3447 NS	0.9372
					P*K	3.0069 NS	0.9473
Soybean height	0.204073	40.83441	17.67313	43.28000	P	4.1476	< 0.0001
					K	4.14769.2742	0.0026
					P*K		< 0.0001
Pod number	0.448405	34.40475	4.768498	13.86000	P	2.1044	< 0.0001
					K	2.1044	0.0272
					P*K	4.7056	0.0377
Nodule number	0.322591	35.56487	11.81821	33.23000	P	7.445	0.0026
					K	7.445 NS	0.8174
					P*K	16.647 NS	0.4567
Node number	0.429987	9.744223	1.966384	20.18000	P	1.2387	0.0110
					K	1.2387	0.0162
					P*K	2.7699	0.0405

Fresh root mass	0.259284	50.38801	1.515067	3.006800	P	0.9544 NS	0.1489
					K	0.9544 NS	0.3631
					P*K	2.1342 NS	0.5399
Fresh stem mass	0.364626	57.98224	2.221647	3.831600	P	1.3995	0.0061
					K	1.3995	0.0178
					P*K	3.1295 NS	0.55885
Fresh pod mass	0.488322	51.59732	5.852013	11.34170	P	3.6865	< 0.0001
					K	3.6865 NS	0.2634
					P*K	8.2433 NS	0.6114
Dry root mass	0.447231	63.82200	0.597693	0.936500	P	0.3765	< 0.0001
					K	0.3765 NS	0.5826
					P*K	0.8419 NS	0.5278
Dry stem mass	0.470601	51.30409	0.710921	1.385700	P	0.4479	< 0.001
					K	0.4479 NS	0.1526
					P*K	1.0014 NS	0.5860
Dry pod mass	0.580390	49.97210	3.263628	6.530900	P	2.0559	< 0.0001
					K	2.0559	0.0060
					P*K	4.5972 NS	0.1935

WAF = Weeks After Fertilization; Root MSE = Root Mean Square Error, LSD = Least Significant Difference, NS = Non significant, P = Phosphorus, K = Potassium