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Research Article
Soybean (*Glycine max* L. Merill) Productivity under Phospho-Potassium Fertilization in Burkina Faso

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Abstract

Background and Objective: The low availability of phosphorus and potassium in the soil, combined with the use of NPK formulas that are not specific to soybean cultivation, partly explain the low yield of this crop. In this context, an agronomic experiment was conducted in the field during the rainy seasons, with the aim of determining the effect of phosphorus-potassium combinations on the growth and yield of two soybean varieties. **Materials and Methods:** The experimental design used was a split plot with three replicates. Nine combinations formulated from three doses of P_2O_5 (30, 45 and 60 kg/ha) and three doses of K_2O (30, 60 and 90 kg/ha) were applied to the plots. Unfertilized plots served as controls. Height, collar diameter, number of nodes and branches, foliage and seed yields and harvest index were evaluated. Data were analyzed using Excel 2016 and RStudio (v4.3.2) with two-way and one-way ANOVA, LSD test ($p<0.05$), PCA and DFA to assess treatment effects and variable contributions. **Results:** The results showed a significant effect of the phosphorus-potassium combinations and a significant interaction between these combinations and the variety on the parameters evaluated. The best seed yield was obtained with 30 kg/ha of P_2O_5+30 kg/ha of K_2O (1.83 t/ha) for G 196 and with 30 kg/ha of P_2O_5+30 kg/ha of K_2O (3.42 t/ha) and 45 kg/ha of P_2O_5+90 kg/ha of K_2O (3.30 t/ha) for G 197. **Conclusion:** Thus, the combination (30 kg/ha of P_2O_5+30 kg/ha of K_2O) phosphorus-potassium combination could be recommended for soybean production in the Sudano-Sahelian zone of Burkina Faso on soils similar to those used in this experiment.

Key words: Soybean, phosphorus, potassium, growth, yield

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Agriculture is a crucial sector for the economic development of many African countries. In Sub-Saharan Africa, it is major contributor to gross domestic product (GDP)[1] and is based mainly on cereal crops, tubers and cash crops. In Burkina Faso, agricultural production is dominated by cereals intended mainly for domestic consumption[2]. In addition to these cereal crops, legumes occupy an important and strategic place in the diet and economy. Among the main legumes produced in Burkina Faso is soybeans[3]. Produced mainly for its seeds, soybeans are used for human and animal consumption and are exported as a raw material for processing[4]. Indeed, with the introduction of soybeans in Burkina Faso in recent decades, new food products have appeared and been adopted by the population[5]. These include infant formula, milk, oil, meat skewers, doughnuts and soumbala made from soybeans[6]. In addition, oilseed meal from the processing of seeds or roasted soybean meal is used in animal feed. Furthermore, from an economic perspective, soybean production is an important source of revenue for both producers and the country. It presents growing economic opportunities due to increasing demand for agri-food processing and on external markets. Thus[7], soybeans are classified as a high-performance commercial product that can benefit from efforts to increase productivity. The soybean sector is expanding in Burkina Faso, with an increase in production areas. However, soybean yields remain low, averaging around 1,000 kg/ha[8]. This low yield is partly due to irregular rainfall and soil poor in minerals, particularly phosphorus and potassium[9,10]. However, several studies[11], and[12], have shown the positive effects of phosphorus and potassium on soybean production. In Burkina Faso, the soybean technical data sheet recommends the application of NPK fertilizer at a rate of 150 kg/ha. However, the NPK formula required for soybean cultivation has not been specified. In addition, the proportions of phosphorus and potassium indicated by existing formulas would not adequately cover the nutritional needs of this crop. Also, little scientific data is defining the phosphorus and potassium requirements of soybeans on the soils of Burkina Faso. It would therefore be necessary to define optimal doses of phosphorus and potassium to improve the agronomic performance of soybeans in Burkina Faso. The objective of this study is to determine the effect of phosphorus-potassium combinations on the growth and yield of two soybean varieties.

MATERIALS AND METHODS

Experimental site: The experiment was conducted in 2023 and 2024 at the Rural Development Institute in Gampéla, located about 20 km East of the city of Ouagadougou at coordinates 12°22 West longitude and 12°25 North latitude. The climate in the area is Sudano-Sahelian, with average annual rainfall between 600 and 900 mm[13]. The average rainfall was 759 mm with an average annual temperature of 27.6°C and 982 mm with an average annual temperature of 29.8°C during the rainy season of 2023 and 2024, respectively (Fig. 1). The soils of the experimental plots were silt-loamy in texture. In addition, these soils were acidic with low levels of organic matter, nitrogen, assimilable phosphorus and available potassium (Table 1).

Plant material: The plant material used consisted of seeds of soybean varieties G 196 and G 197. According to Ouédraogo *et al.*[14], among the five soybean varieties listed in Burkina Faso's national catalogue of species and varieties, varieties G 196 and G 197 are the most produced in Burkina Faso. They have a cycle from sowing to maturity that lasts an average of 100 days with a potential yield of between 2 and 2.5 t/ha.

Experimental setup: The experimental setup was a split plot. Two factors were studied, namely fertilizer and variety. The fertilizing factor consisted of ten levels, including nine phospho-potassium combinations and one absolute control (Table 2). Variety was the secondary factor to two variants, G 196 and G 197. The experimental setup was structured of three (03) repetitions spaced 1.5 m apart. Each replicate was composed of 10 main plots of 7.2 m^2 each and spaced 1 m apart. Each main plot had 10 lines 2 m long. All 5 consecutive lines of a primary parcel corresponded to a secondary parcel. The spacing between the lines was 0.4 m and the spacing between the pockets was 0.2 m.

Conduct of the experiment: The experiment was conducted during the rainy season from July to November in 2023 and 2024. The experimental plot was prepared by deep ploughing (20 cm) followed by levelling. Four seeds were sown per pocket. Each variety was sown in five (05) consecutive rows in each main plot. After emergence, two plants were pruned two weeks after sowing while keeping two plants per pocket. In the main plots, mineral fertilization was applied in pockets two weeks after sowing. Indeed, phosphorus was added in the form of triple superphosphate (TSP) and potassium in the form of) Potassium Chloride (KCl). The plots were weeded and

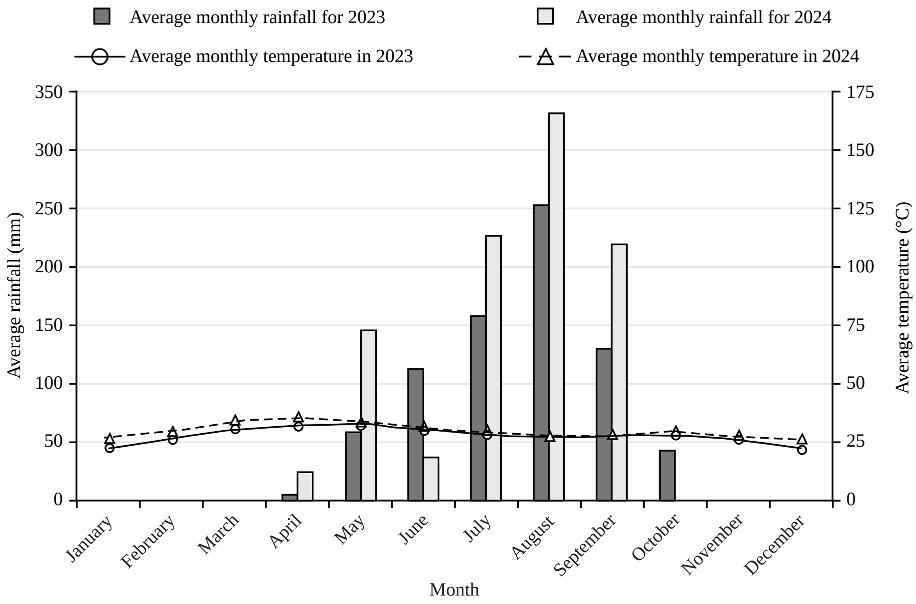

Fig. 1: Evolution of rainfall and temperature during the rainy seasons of 2023 and 2024 in the experimental area

Table 1: Physicochemical properties of the soil of the experimental plot

Physicochemical properties		Plot 2023	Plot 2024
Texture		Sandy silt	Sandy silt
Particle size	Clay (%)	5.88	9.80
	Total silts (%)	19.61	17.65
	Total sands (%)	74.51	72.55
Carbon and organic matter	Organic matter (%)	1.129	1.110
	Total carbon (%)	0.655	0.644
	Total nitrogen (%)	0.053	0.064
	C/N	12	10
Phosphorus	Phosphorus total (ppm)	838	535.21
	Phosphorus assimilable (ppm)	3.98	7.48
Potassium	Potassium total (ppm)	875	1014.59
	Available Potassium (ppm)	39.05	117.52
Tradable bases	Sum of bases	11.22	4.20
Soil response	CEC	11.82	6.62
	pH-H2O	5.45	5.88

C/N: Carbon-to-nitrogen mass ratio, CEC: Cation exchange capacity and pH-H_2O: Hydrogen potential of water

Table 2: Different phospho-potassium combinations

		Fertilizing units (kg/ha)	
Number	Phospho-potassium combinations	P_2O_5	K_2O
1	F0	0	0
2	PK11	30	30
3	PK12	30	60
4	PK13	30	90
5	PK21	45	30
6	PK22	45	60
7	PK23	45	90
8	PK31	60	30
9	PK32	60	60
10	PK33	60	90

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+ 90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23: 45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O and PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O

weeded twice during the experiment. Ridging was also carried out at flowering after a dose of urea at a dose of 50 kg/ha in order to avoid the loss of nitrogen by evaporation and to stimulate root development.

Data collection: Data collection concerned growth and production parameters. For growth monitoring, three plants were previously marked in each secondary plot. Growth parameters were measured weekly for eight weeks and concerned:

- The height of the plant that has been measured from the ground to the apex using a ruler
- The diameter at the collar of the plant that was measured with a calliper
- The number of nodes and branches that have been determined by counting

The production parameters evaluated were:

- The number of pods per plant, determined by counting three plants
- The weight of pods per plant, determined by weighing using a precision electronic scale 0.01 g
- The foliage yield calculated by multiplying the weight of the foliage on the useful plot by the area of one hectare (10,000 m^2) and then dividing the result by the area of the useful plot (1.44 m^2). The following formula was used for the calculation[15]:

$$\text{Foliage yield (t/ha)} = \frac{\text{Foliage weight (kg)}}{\text{Useful plot area (m}^2\text{)}} \times 10$$

- The seed yield was calculated by multiplying the weight of the seeds of the useful plot by the area of one hectare (10,000 m^2) and then dividing the result by the area of the useful plot (1.44 m^2). The following formula was used for the calculation[15]:

$$\text{Seed yield (t/ha)} = \frac{\text{Seed weight (kg)}}{\text{Useful plot area (m}^2\text{)}} \times 10$$

- The harvest index was calculated by comparing the weight of the seeds of the useful plot to the weight of the total dry matter of the useful plot. The following formula was used for the calculation[16]:

$$\text{Harvest index} = \frac{\text{Seed weight (kg)}}{\text{Weight of total dry matter (kg)}}$$

Data treatment and analysis: The data collected was captured and treated using the Excel spreadsheet version 2016. This spreadsheet was also used to calculate averages and to produce graphs. To determine the effect of fertilizer, variety and their interaction on the evaluated parameters, a Two-factor Analysis of Variance (ANOVA) was performed using RStudio software version 4.3.2. In addition, a one-factor ANOVA was performed per variety, followed by the Least Significant Difference (LSD) test with a significance level of 0.05% in order to compare the means. The R software was also used for principal component analysis (PCA) and discriminant factor analysis (DFA) to determine the parameter contributions to total variation and the structuring of soybean plants under the effect of phospho-potassium fertilization, respectively.

RESULTS AND DISCUSSION

Plant height: Plant height varied with fertilizer from 31.25 to 56.11 cm for variety G 196 and from 37.75 cm to 65.86 cm for variety G 197. For variety G 196, plants in plots Fertilized with PK12 recorded the best height (50.80±1.58 cm), while those in plots Fertilized with PK13 were shorter, with an average height of 36.00±2.74 cm (Fig. 2). For variety G 197, plants from plots Fertilized with PK12 recorded the best height at 57.79±4.22 cm (Fig. 2). Furthermore, the average height of plants of the G 197 variety (51.58±5.21 cm) was greater than that of plants of the G 196 variety (43.60±4.93 cm). The results of the two-factor analysis of variance revealed a significant effect of fertilizer ($p<0.001$), variety ($p<0.001$) and a significant interaction between fertilizer and variety ($p<0.001$).

Plant collar diameter: The collar diameter of the plants varied with the fertilizer from 7.25 to 14.82 mm for variety G 196 and from 6.75 to 14.55 mm for variety G 197. For variety G 196, plants in plots fertilized with PK11 had the best collar diameter (12.62±1.54 mm) (Fig. 3). However, for variety G 197, plants in plots fertilized with PK21, PK32, PK11 and PK12 recorded the best collar diameters with respective average values of 11.99±1.99, 11.95±1.06, 11.92±1.25 and 11.65±1.37 mm (Fig. 3). Comparison of the averages showed that plants of the G 196 variety had a larger average collar diameter (12.07±1.67 mm) than plants of the G 197 variety (10.90±1.64 mm). The results of the two-factor analysis of variance indicated a significant effect of fertilizer ($p<0.001$) on the collar diameter of the plants. However, the effects of variety ($p = 0.382$) and fertilizer*variety interaction ($p = 0.406$) on the collar diameter of the plants were not significant.

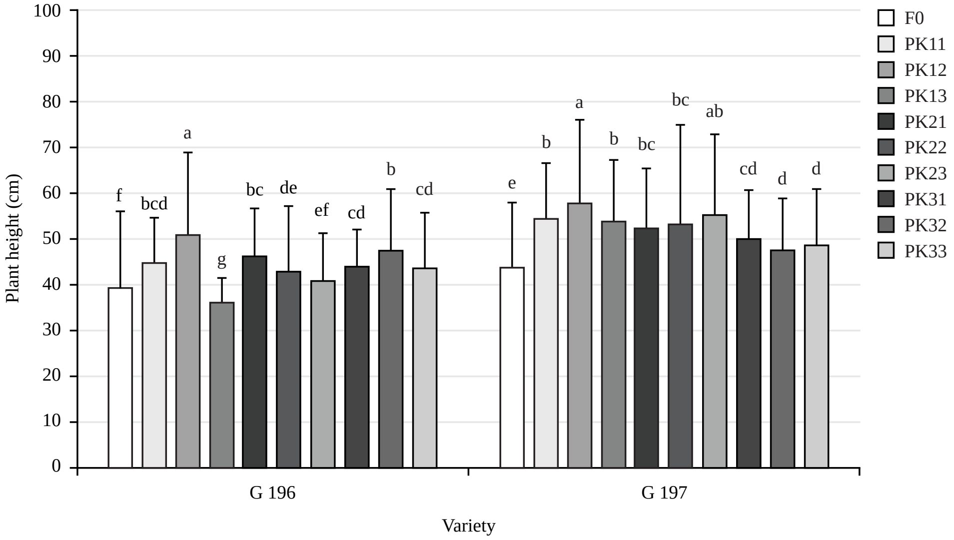

Fig. 2: Effect of phospho-potassium combinations on soybean plant height

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23: 45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O, PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O. For each variety, the averages followed by the same letters are not significantly different at the 5% threshold

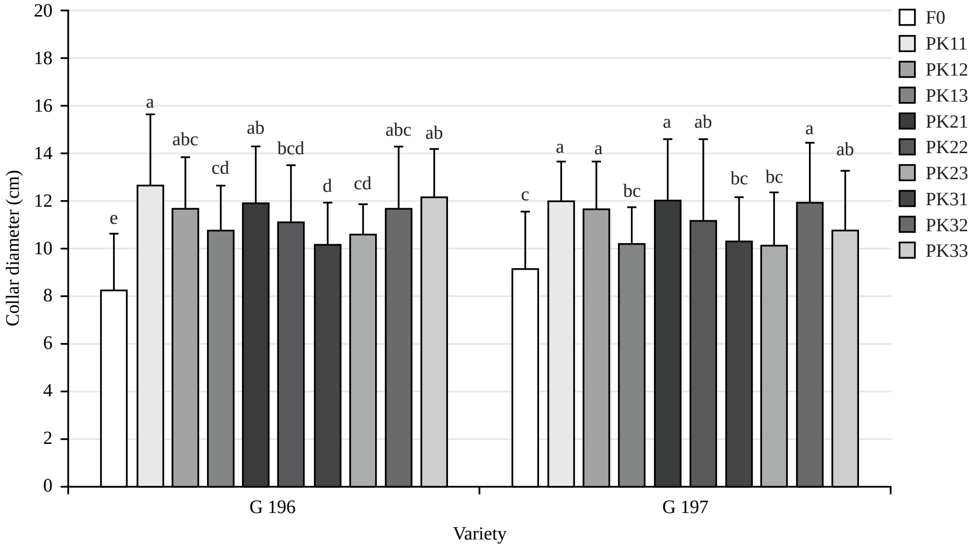

Fig. 3: Effect of phospho-potassium combinations on the collar diameter of plants

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23: 45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O, PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O. For each variety, the averages followed by the same letters are not significantly different at the 5% threshold

Number of nodes per plant: The number of nodes per plant varied with fertilizer from 14 to 18 cm for variety G 196 and from 13 to 20 for variety G 197. For variety G 196, plants in plots fertilized with PK11 recorded the highest number of nodes (17.05±0.63), while the lowest number of nodes (15.61±0.99) was recorded in plants in plots fertilized with PK33 (Fig. 4). For variety G 197, plants from plots Fertilized with PK13 recorded the highest number of nodes (18.16±1.11). In addition, plants of the G 197 variety produced on average more nodes (17.13±1.43) than those of the G 196 variety (16.25±1.01). The results of the two-factor analysis of variance revealed a significant effect of fertilizer ($p<0.001$), variety ($p<0.001$) and their interaction ($p = 0.005$) on the number of nodes.

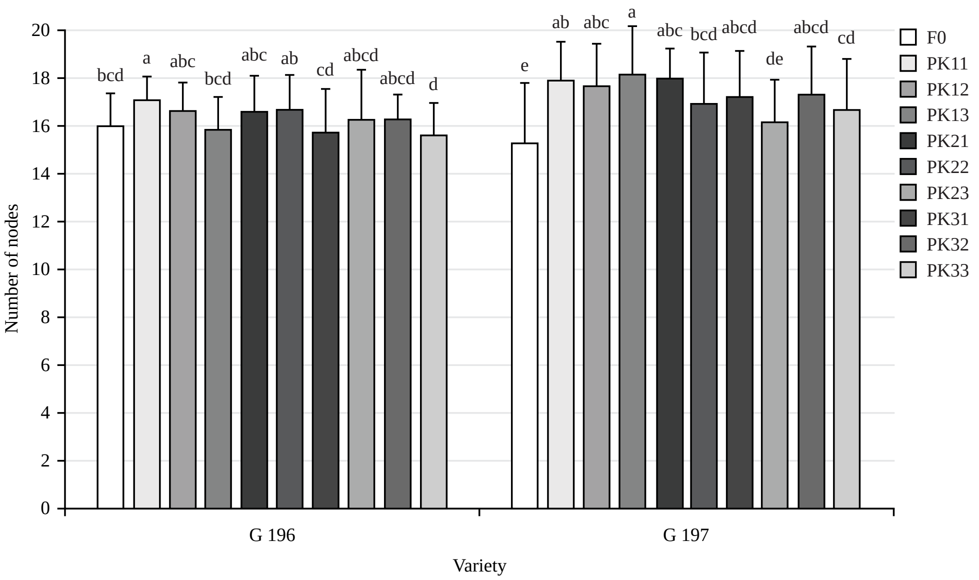

Fig. 4: Effect of phospho-potassium combinations on the number of nodes of plants

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+ 60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23: 45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O, PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O. For each variety, the averages followed by the same letters are not significantly different at the 5% threshold

Number of branches per plant: The number of branches per plant varied with the fertilizer from 6 to 13 for variety G 196 and from 7 to 14 for variety G 197. Comparison of the averages showed that for both varieties, the highest number of branches per plant was recorded for plants in plots fertilized with PK11 (Fig. 5). In fact, the plants in the plots fertilized with PK11 were 12.27±0.97 and 12.44±1.44 for G 196 and G 197, respectively. The comparison of means test also revealed that plants of the G 197 variety had more branches on average than those of the G 196 variety, with average numbers of branches of 11.48±1.46 and 10.85±1.31, respectively. The two-factor analysis of variance revealed a significant effect of fertilizer ($p<0.001$) and variety ($p<0.001$) on the number of branches.

Number of pods per plant: The number of pods per plant varied with fertilizer from 50 to 149 for variety G 196 and from 65 to 278 for variety G 197. Comparison of the averages showed that for variety G 196, the highest number of pods per plant (117.33±23.96) was recorded for plants in plots Fertilized with PK11 (Table 3). However, for variety G 197, plants from plots Fertilized with PK32 recorded the highest number of pods per plant, with an average of 188±36.77 pods (Table 3). Comparison of the averages also showed that plants of the G 197 variety produced significantly more pods than those of the G 196 variety, with average numbers of pods of 113.49±38.17 and 94.71±20.53, respectively. The results of the two-factor analysis of variance showed a significant effect of fertilizer ($p<0.001$) and variety ($p<0.001$) and a significant interaction between fertilizer and variety ($p<0.001$) on the number of pods per plant (Table 3).

Weight of pods per plant: The weight of pods per plant varied with fertilizer from 6.14 to 47.16 g for variety G 196 and from 10.85 to 69.42 g for variety G 197. The comparison of means test showed that plants in plots fertilized with PK21 recorded the highest pod weight per plant (25.37±5.35 g) for the G 196 variety (Table 3). However, for variety G 197, the highest pod weight per plant (36.73±11.80 g) was recorded for plants in plots Fertilized with PK32 (Table 3). Comparison of the means also indicated that plants of the G 197 variety had a higher average pod weight per plant (23.49±10.17 g) than plants of the G 196 variety (16.26±6.38 g). The results of the two-factor analysis of variance showed a significant effect of fertilizer ($p<0.001$), variety ($p<0.001$) and their interaction ($p<0.001$) on pod weight per plant (Table 3).

Foliage yield: The foliage yield varied with the fertilizer from 2.27 to 6.69 t/ha for variety G 196 and from 4.26 to 8.05 t/ha for variety G 197. For variety G 196, plants in plots fertilized with PK33 recorded the highest foliage yield (6.14±0.27 t/ha). For variety G 197, PK23, PK31, PK12 and PK22 fertilizer

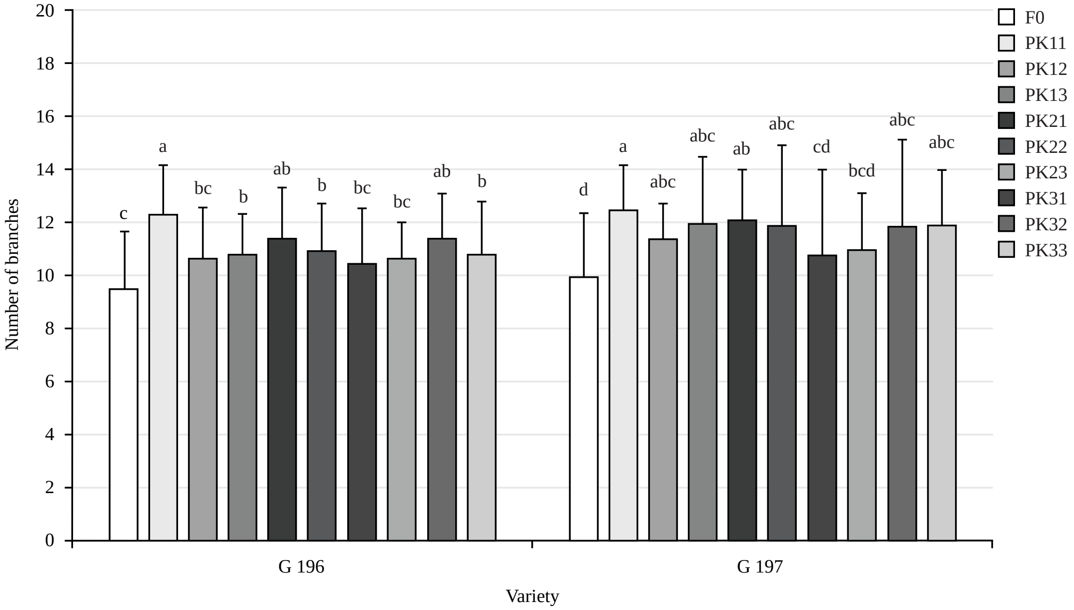

Fig. 5: Effect of phospho-potassium combinations on the number of branches per plant

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+ 60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23: 45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O, PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O. For each variety, the averages followed by the same letters are not significantly different at the 5% threshold

Table 3: Effects of phospho-potassium combinations on yield and its components

Variety	Phospho-potassium combinations	Number of pods per plant	Weight of pods per plant	Foliage yield (t/ha)	Seed yield (t/ha)	Harvest Index
G 196	F0	60.89 ± 8.18^{f}	8.83 ± 1.95^{e}	2.74 ± 0.46^{e}	1.06 ± 0.04^{d}	0.24 ± 0.02^{b}
	PK11	117.33 ± 23.96^{bc}	16.30 ± 2.36^{bcd}	5.37 ± 0.28^{bc}	1.83 ± 0.04^{a}	0.28 ± 0.07^{ab}
	PK12	84.44 ± 18.32^{cd}	12.26 ± 1.84^{de}	5.52 ± 0.30^{ab}	1.48 ± 0.18^{abc}	0.25 ± 0.05^{b}
	PK13	103.06 ± 14.45^{de}	14.86 ± 1.87^{cd}	4.18 ± 0.27^{d}	1.39 ± 0.16^{cd}	0.28 ± 0.03^{ab}
	PK21	97.28 ± 14.01^{cd}	25.38 ± 5.35^{a}	5.91 ± 0.27^{ab}	1.56 ± 0.20^{abc}	0.26 ± 0.00^{ab}
	PK22	109.00 ± 16.02^{bc}	20.11 ± 3.11^{b}	5.66 ± 0.90^{ab}	1.55 ± 0.21^{abc}	0.15 ± 0.03^{c}
	PK23	87.28 ± 9.77^{e}	15.14 ± 3.03^{cd}	4.78 ± 0.28^{cd}	1.74 ± 0.26^{ab}	0.32 ± 0.02^{a}
	PK31	86.67 ± 9.75^{e}	12.60 ± 3.07^{de}	5.26 ± 0.26^{bc}	1.48 ± 0.25^{bc}	0.25 ± 0.05^{b}
	PK32	102.33 ± 11.78^{a}	17.85 ± 12.06^{bc}	5.73 ± 0.27^{ab}	1.57 ± 0.35^{abc}	0.24 ± 0.01^{b}
	PK33	98.83 ± 14.34^{b}	19.28 ± 3.56^{bc}	6.14 ± 0.27^{a}	1.77 ± 0.18^{ab}	0.27 ± 0.05^{ab}
G 197	F0	73.33 ± 6.27^{e}	14.95 ± 3.06^{d}	4.67 ± 0.45^{c}	2.03 ± 0.19^{de}	0.31 ± 0.02^{cd}
	PK11	106.83 ± 10.57^{a}	31.33 ± 5.63^{ab}	6.74 ± 0.35^{ab}	3.42 ± 0.19^{a}	0.42 ± 0.05^{ab}
	PK12	119.17 ± 15.64^{d}	24.98 ± 5.19^{bc}	7.17 ± 0.65^{a}	3.15 ± 0.12^{ab}	0.39 ± 0.03^{abcd}
	PK13	92.11 ± 7.66^{b}	14.90 ± 3.12^{d}	6.16 ± 0.04^{b}	2.00 ± 0.34^{e}	0.33 ± 0.01^{bcd}
	PK21	113.83 ± 6.81^{bcd}	17.29 ± 4.71^{d}	6.27 ± 0.19^{b}	2.83 ± 0.37^{abc}	0.44 ± 0.05^{a}
	PK22	116.39 ± 13.41^{ab}	30.54 ± 14.93^{bc}	7.16 ± 0.56^{a}	3.08 ± 0.78^{ab}	0.38 ± 0.02^{abcd}
	PK23	91.44 ± 9.64^{cd}	19.87 ± 3.77^{cd}	7.41 ± 0.65^{a}	3.30 ± 0.14^{a}	0.42 ± 0.06^{ab}
	PK31	86.72 ± 8.36^{cd}	17.44 ± 4.15^{d}	7.23 ± 0.20^{a}	2.62 ± 0.20^{bcd}	0.37 ± 0.03^{abcd}
	PK32	188.44 ± 36.78^{b}	36.73 ± 11.80^{a}	6.71 ± 0.35^{ab}	2.23 ± 0.28^{cde}	0.30 ± 0.16^{d}
	PK33	146.67 ± 51.79^{bc}	26.90 ± 7.51^{b}	6.94 ± 0.67^{ab}	3.07 ± 0.51^{ab}	0.41 ± 0.06^{abc}
Probability (Fertilizer)		0.001	0.001	0.001	0.001	0.005
Probability (Variety)		0.001	0.001	0.001	0.001	0.001
Probability (Fertilizer*Variety)		0.001	0.001	0.002	0.023	0.118

F0: Control, PK11: 30 kg/ha of P_2O_5+30 kg/ha of K_2O, PK12: 30 kg/ha of P_2O_5+60 kg/ha of K_2O, PK13: 30 kg/ha of P_2O_5+90 kg/ha of K_2O, PK21: 45 kg/ha of P_2O_5+30 kg/ha of K_2O, PK22: 45 kg/ha of P_2O_5+60 kg/ha of K_2O, PK23₌45 kg/ha of P_2O_5+90 kg/ha of K_2O, PK31: 60 kg/ha of P_2O_5+30 kg/ha of K_2O, PK32: 60 kg/ha of P_2O_5+60 kg/ha of K_2O, PK33: 60 kg/ha of P_2O_5+90 kg/ha of K_2O. For each variety, the averages followed by the same letters are not significantly different at the 5% threshold

treatments that produced the best leaf yields, which were 7.41±0.65, 7.23±0.20, 7.17±0.65 and 7.16±0.56, respectively (Table 3). Comparison of the averages showed that the G 197 variety had a higher foliage yield (6.64±0.86 t/ha) compared to the G 196 variety (5.12±1.03 t/ha). Two-factor analysis of variance revealed a significant effect at the 5% threshold of fertilizer ($p<0.001$), variety ($p<0.001$) and their interaction ($p = 0.002$) on foliage yield (Table 3).

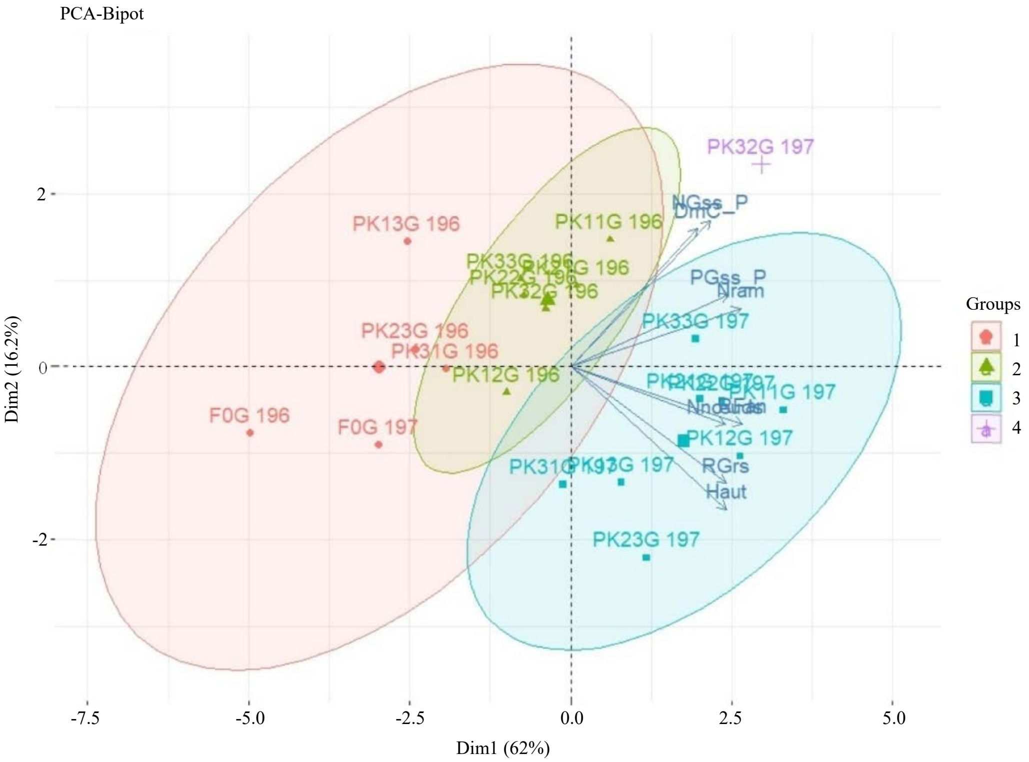

Fig. 6: Biplot of the first two principal components showing the correlation relationships between the parameters and the distribution of plants from fertilized plots with phospho-potassium combinations

Haut: Height of the plants, DmC: Collar diameter, Nnœuds: Number of nodes, Nram: Number of branches, NGss_P: Number of pods per plant, PGss_P: Weight of pods per plant, RFan: Foliage yield, RGrs: Seed yield, IR: Harvest index, F0G196: Unfertilized variety G 196, PK11G196: Variety G 196 fertilized with PK11, PK12G196: Variety G 196 fertilized with PK12, PK13G196: Variety G 196 fertilized with PK13, PK21G196: Variety G 196 fertilized with PK21, PK22G196: Variety G 196 fertilized with PK22, PK23G196: Variety G 196 fertilized with PK23, PK31G196: Variety G 196 fertilized with PK31, PK32G196: Variety G 196 fertilized with PK32, PK33G196: Variety G 196 fertilized with PK33, F0G197: Unfertilized variety G 197, PK11G197: Variety G 197 fertilized with PK11, PK12G197: Variety G 197 fertilized with PK12, PK13G197: Variety G 197 fertilized with PK13, PK21G197: Variety G 197 fertilized with PK21, PK22G197: Variety G 197 fertilized with PK22, PK23G197: Variety G 197 fertilized with PK23, PK31G197: Variety G 197 fertilized with PK31, PK32G197: Variety G 197 fertilized with PK32, PK33G197: Variety G 197 fertilized with PK33

Seed yield: Seed yield varied with fertilizer from 1.02 to 2.02 t/ha for variety G 196 and from 1.66 to 3.62 t/ha for variety G 197. For variety G 196, plants in plots fertilized with PK11 recorded the highest seed yield (1.83±0.04 t/ha). For variety G 197, plants from plots fertilizer with PK11 and PK23 recorded the best seed yields, with average values of 3.42±0.19 t/ha and 3.30±0.14 t/ha, respectively (Table 3). The comparison of means test indicated that variety 197 had a better yield (2.77±0.59 t/ha) than variety G 196 (1.54±0.27 t/ha). The results of the two-factor analysis of variance revealed a significant effect at the 5% threshold of fertilizer ($p<0.001$), variety ($p<0.001$) and their interaction ($p = 0.023$) on seed yield (Table 3).

Harvest index: The harvest index varied with the fertilizer from 0.12 to 0.35 for variety G 196 and from 0.11 to 0.48 for variety G 197. The comparison of means test showed that the best harvest index for variety G 196 was recorded for plants from plots fertilized with PK23. In contrast, for variety G 196, the best harvest index was recorded for plants from plots fertilized with PK21 (Table 3). Furthermore, variety G 197 recorded a better harvest index (0.37±0.07) than variety G 196 (0.25±0.05). In fact, two-factor analysis of variance revealed a significant effect of fertilizer ($p = 0.005$) and variety ($p<0.001$) on the harvest index (Table 3).

Relationship between parameters and distribution of plants subjected to different phospho-potassium combinations: The two main components explained 78.2% of the total variation. Height ($r = 0.81$), number of nodes ($r = 0.78$), number of branches ($r = 0.84$), number of pods per plant ($r = 0.66$), pod weight per plant ($r = 0.77$), leaf yield ($r = 0.88$), seed yield ($r = 0.85$) and harvest index ($r = 0.69$) were strongly and positively correlated with the first principal component

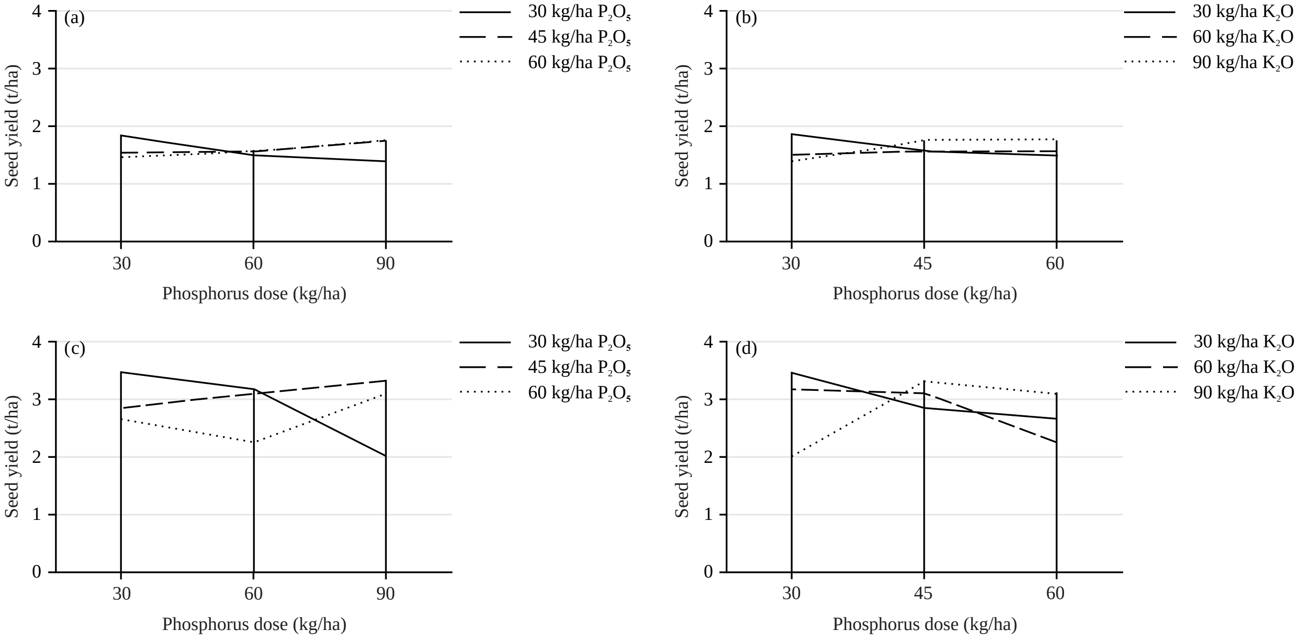

Fig. 7(a-d): Evolution of seed yield for different varieties, (a) Evolution of seed yield in variety G 196 under different potassium doses, (b) Evolution of seed yield in variety G 196 under different phosphorus doses, (c) Evolution of seed yield in variety G 197 under different potassium doses and (d) Evolution of seed yield in variety G 197 under different phosphorus doses

Table 4: Results of analyses of variance and comparison of plant group means

	Plant groups				
Parameter	Group 1	Group 2	Group 3	Group 4	p value
Plant height	40.77^{b}	45.97^{b}	53.06^{a}	47.53^{ab}	0.001
Plant collar diameter	9.75^{ab}	11.84^{a}	10.99^{a}	11.95^{a}	0.06
Number of nodes	15.82^{c}	16.46^{bc}	17.34^{a}	17.27^{ab}	0.001
Number of branches per plant	10.24^{b}	11.20^{a}	11.63^{a}	11.83^{a}	0.001
Number of pods per plant	82.24^{c}	101.53^{bc}	109.14^{b}	188.44^{a}	0.001
Weight of pods per plant	13.27^{c}	18.53^{bc}	22.90^{b}	36.73^{a}	0.001
Foliage yield (t/ha)	4.32^{c}	5.72^{b}	6.88^{a}	6.71^{ab}	0.001
Seed yield (t/ha)	1.53^{b}	1.62^{b}	2.93^{a}	2.22^{ab}	0.001
Harvest Index	0.27^{b}	0.23^{b}	0.39^{a}	0.29^{ab}	0.008

For each parameter, the averages assigned different letters are significantly different

(Fig. 6). The collar diameter was more strongly correlated (r = 0.62) with the second principal component (Fig. 6). Discriminant factor analysis (DFA) identified four (04) groups (Fig. 6). Group 1 consisted of control plants of two varieties, G 196 plants from plots fertilized with PK13, PK23 and PK31. Group 2 consisted of G 196 plants from plots fertilized with PK11, PK12, PK21, PK22, PK32 and PK33. Group 3 consisted of G 197 plants from plots fertilized with PK11, PK12, PK13, PK21, PK22, PK23, PK31 and PK33. Group 4 consisted of G 197 plants from plots fertilized with PK32. The results of the analysis of variance enabled these different groups to be characterised. Plants in group 1 were short in height, with a small collar diameter and low production of pods, leaves and seeds (Table 4). Those in group 2 were characterised by an average collar diameter, average leaf and seed production and a low harvest index (Table 4). Plants in group 3 were characterised by large size, a high number of nodes, high leaf and seed yields and a high harvest index (Table 4). Plants in group 4 were characterised by a large collar diameter, a high number of branches and better pod production (Table 4).

Interaction between phosphorus and potassium doses on seed yield: A significant interaction between phosphorus and potassium doses was observed on the seed yield of both soybean varieties. For variety G 196, at a phosphorus dose maintained at 30 kg/ha, increasing potassium doses led to a decrease in seed yield. However, when phosphorus is applied at 45 or 60 kg/ha, increasing potassium doses lead to an improvement in seed yield (Fig. 7a). Furthermore, at a potassium dose of 30 kg/ha, increasing phosphorus doses led to a decrease in yield. However, at potassium doses of 60 and 90 kg/ha, increasing phosphorus inputs led to an improvement in seed yield (Fig. 7b).

In variety G 197, at a phosphorus dose of 30 kg/ha, increasing potassium inputs leads to a reduction in seed yield. However, at a phosphorus dose of 45 kg/ha, increasing potassium doses lead to an improvement in seed yield (Fig. 7c). At potassium doses of 30 kg/ha and 45 kg/ha, increasing phosphorus inputs led to a decrease in seed yield (Fig. 7d).

DISCUSSION

Phosphorus-potassium combinations had a positive effect on the growth parameters of both varieties, particularly plant height, collar diameter, number of nodes and number of branches. This positive effect can be explained by the essential physiological roles played by the phosphorus and potassium contained in fertilizers. Phosphorus stimulates cell division and promotes increased root development and good height growth. In addition, phosphorus improves nitrogen nutrition in soybeans through its specific role in the initiation, formation and growth of nodules[17]. Furthermore, phosphorus and potassium nutrition stimulates an increase in root mass, which leads to the absorption of a higher concentration of mineral nutrients from the soil[18]. A study by Yao *et al.*[19] pointed out that phosphorus improves the symbiotic nitrogen fixation process by increasing the root system of soybeans, which allows for better absorption of nutrients and water. As for the increase in collar diameter and number of branches in plants in fertilized plots, this is thought to be induced by potassium, which plays an important role in the transfer of assimilates, maintaining the turgor pressure necessary for cell elongation and activating enzymes. Our results are similar to those[20], who showed that the height of *Cajanus cajan* L. Millsp. plants varies according to phosphorus-potassium combinations and range from 275 to 309 cm for the P0K0 control and P80K80 (80 kg/ha of P_2O_5+80 kg/ha of K_2O), respectively. Our results also revealed a significant interaction between phosphorus-potassium combinations and variety for plant height and number of nodes. Indeed, for the G 197 variety, all phosphorus-potassium combinations significantly improved height and number of nodes compared to the control plants. However, for the G 196 variety, plants in plots fertilized with PK13 were smaller than control plants. Furthermore, for the same variety, only PK11 significantly improved the number of nodes. This difference in response between the two varieties to the phosphorus-potassium combinations could be attributed to variations in their nutrient absorption capacities, their sensitivity to mineral imbalances, or specific morphogenetic responses induced by nutritional inputs. These results suggested that the two varieties, G 196 and G 197, have different phosphorus and potassium requirements for growth. Our results also highlighted a significant varietal effect on all growth parameters. Plants of the G 197 variety were on average larger, with a higher number of nodes and branches than those of the G 197 variety. Genetic variability appears to be the determining factor behind the morphological differences observed between the G 196 and G 197 varieties.

Our results showed a significant influence of phosphorus-potassium combinations on the number and weight of pods per plant. For both varieties, phosphorus-potassium combinations significantly increased the number and weight of pods per plant compared to control plants. This improvement in pod production is thought to be linked to phosphorus, which promotes fertilization and fruiting in soybean[21]. Our results corroborate those[22], who showed that 175 kg/ha of phosphorus+120 kg/ha of potassium yielded the highest number of filled pods per plant. Our results differ from those[23], who showed in a study that the interaction phosphorus-potassium was not significant for the number of pods per plant, the yield and 100-seed weight. This difference in results may be partly due to the fact that[23] used the mung bean as plant material but also at doses of phosphorus and potassium different from ours. In our study, a variation in response to phosphorus-potassium combinations between the two varieties was observed for both the number of pods per plant and the weight of pods per plant. In fact, for the G 196 variety, the best number and weight of pods per plant were obtained with PK11 (30 kg/ha of P_2O_5+30 kg/ha of K_2O) and PK21 (45 kg/ha of P_2O_5+30 kg/ha of K_2O), respectively. However, for G 197 variety, the highest number and weight of pods per plant were obtained with PK32 (60 kg/ha of P_2O_5+60 kg/ha of K_2O). These results indicate that for better pod production, G 196 variety would require low doses of phosphorus (30 to 45 kg/ha) and potassium (30 kg/ha), unlike G 197 variety, which would require medium doses of phosphorus (60 kg/ha) and potassium (60 kg/ha).

Concerning seed production, phosphorus-potassium combinations improved seed yield in both varieties compared to control plants. This positive impact of fertilizers is attributed to phosphorus and potassium. Phosphorus and potassium supplied to plants play an important role in seed formation and filling. Potassium also plays a role in seed filling by activating photosynthesis and promoting the formation of carbohydrates in the leaf and their accumulation in storage organs[24,25]. Our results are similar to those[26], who have suggested that phosphorus application to previously degraded oxisol improves soybean yield by improving soil cover even at low soil phosphorus levels. Our results are also similar to those[18], who reported that phosphorus-potassium fertilization impacted soybean yields, with the highest yields observed in the combined P120K40 treatment (120 kg/ha of P_2O_5+40 kg/ha of K_2O). In addition, a study by Awuni *et al.*[27] demonstrated that the combination of treatments of 25 kg/ha of phosphorus and 40 kg/ha of potassium significantly increased bean yield. Furthermore, study by Nakagawa and Sarr[28] highlighted a significant interaction between phosphorus and soybean variety on pod weight and seed yield per plant.

The results of the multivariate analyses showed that plants of the G 196 variety from plots fertilized with PK11, PK12, PK21, PK22, PK32 and PK33 constituted a group with average production of leaves, pods and seeds. These results suggest that the G 196 variety has a limited phosphorus and potassium requirement that should not be exceeded to maximize seed production. This could be linked to G 196 variety's low sensitivity to excessive phosphorus and potassium inputs for its physiological reproduction processes. It was also noted that plants of the G 197 variety subjected to phosphorus-potassium combinations (except PK32) constituted a group of large plants with good seed production. These results indicate that G 197 makes efficient use of nutrients and has a greater capacity to adapt to varying levels of phosphorus and potassium. The G 197 variety therefore has a higher phosphorus and potassium requirement than the G 196 variety in order to produce a better seed yield. This difference in phosphorus and potassium requirements is thought to be linked to the different genetic and intrinsic characteristics of the two soybean varieties and their differing abilities to absorb and utilize minerals.

Our results also showed a significant interaction between phosphorus and potassium on seed yield, with different responses depending on the variety (G 196 and G 197). The decrease in yield observed at low phosphorus doses (30 kg/ha) when potassium inputs increase indicates a nutritional imbalance. Thus, a relative excess of potassium in conditions of phosphorus deficiency or low availability can limit the absorption and efficient use of phosphorus by the plant, an element essential for fruit and seed development[29]. However, at doses of 45 and 60 kg/ha of P_2O_5 for variety G 196 and 45 kg/ha of P_2O_5 for variety G 197, the simultaneous increase in potassium improves seed yield. This reflects a synergy between these two elements when their levels are adequate. The variability in the response of varieties to different phosphorus-potassium combinations would reflect genetic differences in root architecture and physiological efficiency[30].

In terms of the results of this study, adapted and differentiated phosphorus and potassium fertilization according to variety would be an effective strategy for improving soybean production in Burkina Faso. However, further trials would be needed to adjust the specific phosphorus and potassium requirements of each variety. Furthermore, it would be appropriate to extend the experiment to the Sudanian zone, taking into account the diversity of soil types present.

CONCLUSION

The study determined the effect of phosphorus-potassium combinations on the growth and yield of two soybean varieties. The phosphorus-potassium combinations applied had a positive effect on the growth and yield of both soybean varieties. The G 196 and G 197 varieties responded differently to combined doses of phosphorus and potassium. The G 196 variety has limited phosphorus and potassium requirements compared to the G 197 variety, which is more responsive to various phosphorus-potassium combinations. The PK11 phosphorus-potassium combination yielded the highest seed yield in both varieties. The PK11 phosphorus-potassium combination (30 kg/ha of P_2O_5+30 kg/ha of K_2O) could be recommended for the production of soybean varieties G 196 and G 197 on sandy-silt soils in the Sudano-Sahelian zone of Burkina Faso, as well as in areas with the same soil and climate characteristics as our experimental area.

SIGNIFICANCE STATEMENT

The study is significant as it identifies optimal phosphorus-potassium fertilizer combinations that enhance soybean growth and yield under nutrient-deficient Sudano-Sahelian soils. The findings provide evidence-based guidance for improving fertilizer use efficiency, supporting sustainable intensification of soybean production and contributing to food security and soil fertility management in Burkina Faso and similar agro-ecological regions.

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