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Responses of Some Soybean Genotypes to Different Soil pH Regimes in two Planting Seasons

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ABSTRACT

Seven genotypes of soybean (*Glycine max* (L.) Merrill) were screened in 2004 and 2005 planting seasons at the experimental research farm of the University of Nigeria, Nsukka to identify the acid tolerant genotypes using some agronomic and yield traits. These genotypes were screened under varying soil pH conditions. The results revealed that the genotypes varied considerably in the agronomic and yield traits at the different pH values. The soil pH, genotype and their interactions had significant effects on most of the traits evaluated in both planting seasons. The traits were greatly reduced at soil pH < 5.5 and, it increased progresively with increase in the soil pH up to 6.0. The principal component analysis (PCA) indicated that the first three principal components contributed 71.12 and 69.28% of the total variability among the genotypes in the 2004 and 2005 plantings, respectively. Thus, under soil acid conditions traits such as root length, fresh root weight and number of nodules are discriminating and can serve as selection criteria to distinguish between acid tolerant and acid-sensitive genotypes. In the 2004 planting, **'**Digil', 'Garikida' and 'Sunkani' were identified as tolerant; 'Kyado' and 'Sebore' as moderately tolerant; 'Gembu' is moderately susceptible while 'TGX1448-2E' is suceptible to soil acidity. In 2005, 'Sebore' and 'Digil' were identified as acid-tolerant; 'Gembu' and 'Sunkani' as moderately tolerant; 'Garikida' and 'TGX1448-2E' as moderately susceptible and 'Kyado' as suceptible to low soil pH. The tolerant genotypes had normal root growth and higher seed yield at pH < 5.5 in both planting seasons indicating their tolerance to low soil pH. The results suggest that 'Kyado', 'Sebore' and 'Digil' can therefore be included in breeding programs to develop new genotypes that can withstand low soil pH conditions in the derived savanna region of south eastern Nigeria.

Keywords: acid tolerance, aluminium toxicity, *Glycine max* (L.), high yield, nodulation, root growth, soil acidity
Abbreviations: PCA, principal component analysis; **DAP**, days after planting; **FC**, field capacity; **$Ca(OH)_2$**, calcium hydroxide; **HCL**, hydrochloric acid; **CEC**, cation exchange capacity; **PC**, principal component

INTRODUCTION

Soybean, *Glycine max* (L.) Merrill, is one of the most important oil crops in the world. It is the world's leading source of oil and protein. It has the highest protein content (40%) of all food crops and is second only to groundnut in terms of oil content (20%) among food legumes (Gurmu *et al*. 2009). In Nigeria, soybean has gained popularity, outranking cowpea (*Vigna unguiculata* (L) Walp), because of its potential to (i) supply high quality protein (Akande *et al*. 2007), and (ii) sustain the world's increasing demand for food and forage (Alghamdi 2004). However, a major constraint to production of the crop is aluminum (A1) toxicity particularly in many humid tropical regions (Minella and Sorelli 1992). It tends to increase soil acidity which in turn increases solubility of iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and aluminum (Al) with Al and Mn reaching levels that are phytotoxic. It also interferes with ion uptake processes especially phosphorus (P). von Uexkull and Mutert (1995) reported that about 30% of the world's total land area consists of acid soils, and as much as 50% of the world's potentially arable lands are acidic. Acid soils are one of the most important limitations to agricultural production worldwide (von Uexküll and Mutert 1995; Kochian *et al.* 2004). Ezeh *et al.* (2007) reported that in acid soils, high concentrations of A1 in tropical soils often inhibit crop performance. This inhibition in plants is often clearly identified as through morphological and physiological disorders. Therefore, to meet the demand of soybean in Nigeria and in sub-saharan Africa, emphasis should be made on increasing crops yield through use of genotypes that can tolerate acid stressed soil conditions.

Although mineral toxicities in acid soils can be ameliorated by the use of lime, the extra cost will further limit the preference of the poor resource farmers. Akinrinde *et al.* (2004) and Ezeh *et al.* (2007) noted that combining sound management practices with genetic tolerance to low pH could ameliorate negative impact of acid soil stress on crop performance. Tolerance levels have, however been reported to be influenced by crop genetic background (Bona, 1994). Since acid-soil involves both nutrient deficiencies and toxicities, the tolerance of plants to soil acidity could take the form of efficient uptake and utilization of those nutrients that are deficient under acid soil conditions or outright tolerance to Al and Mn toxicities. It is therefore important to select acid tolerant soybean genotypes with the intention of reducing the dependence of small farmers on lime and fertilizer inputs. Rao (2001) reported that the improvement of the genetic Al resistance is a less costly complementary approach, especially for low-fertility agricultural systems. Thus, selection of genotypes with high adaptability to the acid soils is a promising alternative (Foy 1988). Such adaptation broadly includes tolerance to high levels of Al and Mn and capacity to grow normally under poor nutrient soil conditions. There exist wide genetic variability among and within the species for tolerance of acid stress conditions (Duncan and Baligar 1990; Dvorak *et al*. 1992; Foy *et al.* 1993). It is therefore very advantageous to breed for acid tolerance through selection of acid tolerant soybean genotypes.

Crop performance across environments is a useful indicator of genotypic performance only in the absence of

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genotype × environment (GE) interaction. Acid tolarance in plants is often clearly identifiable through morphological and physiological symptoms (Rout *et al*. 2001). However, the combination of crop performance and principal component analysis (PCA) are effective in the identification and characterization of genotypes for differential genotypic response across diverse environments. The screening of commonly grown soybean genotypes for low pH tolerance would provide a better understanding of the crops adaptation and the management requirements under low soil pH conditions. Also, differential tolerance of plant genotypes to acid stress is a more promising approach to increase our understanding of acid tolerance in plants. The crop performance and PCA analysis have been widely adopted for screening and characterizing genotypes for tolerance to external pressures (*i.e*., high temperature) in cotton, *Gossypium hirsutum* (Kakani *et al*. 2005; Zhi *et al*. 2006), pepper, *Capsicum* species (Reddy and Kakani 2007) and groundnut, *Arachis hypogaea* L. (Kakani *et al*. 2002). Thus, it is essential to identify soybean cultivars with soil acidity tolerance and also, understand the relationships between responses of soybean to low soil pH. This would help in achieving quick genetic gain through screening of genotypes for high adaptation and stability under low pH conditions prior to their release as cultivars. Therefore, the objectives of this study were to (a) assess the genotypic response of seven soybean genotypes across diverse soil pH environments, and (b) identify high yielding genotypes in low acid soils which would be recommended to farmers in the humid tropics where excessive precipitation has caused low soil pH.

MATERIALS AND METHODS

Field studies were conducted in the 2004 and 2005 cropping seasons (April to August) at the Department of Crop Science Teaching and Research Farm, Univerity of Nigeria, Nsukka ((Lat 06° 52′ N; Long 07° 24′ E, 447.2 m a.s.l.). The monthly temperature, number of rainy days and rainfall distribution of the location during the crop growing periods are presented in **Table 1**. The material used comprised one improved soybean genotype, 'TCX1448-2E' obtained from the National Cereal Research Institute (NCRI), sub-station at Yadev, Benue State and six local soybean genotypes. The local soybean genotypes include; 'Digil', 'Garkida' and 'Sebore' from Adamawa State, 'Kyado' from Benue State and 'Gembu' and 'Sunkani' from Taraba State. The genotypes were sown in polytene bags during the wet season of 2004 and 2005. 189 polythene bags measuring 40 cm in height and 19 cm in diameter were used for potting the soybean plants. The polythene bags were filled with 4 kg of soil collected from 0-20 cm depth in a 2-year fallow. The bagged soils were moistened to 60% field capacity (FC) and ammended to pH levels of 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0 using different 1.0 N HCl and ($Ca(OH)_2$) concentrations (**Table 2**). The soil sample were collected using a soil auger. The quantity of 1.0 N HCL required to reduce the pH to 3.0, 3.5, 4.0 and 4.5 and the amount of $Ca(OH)_2$ required to raised the pH to 5.5, 6.0, 6.5 and 7.0 were determined after the laboratory soil analysis.

The initial pH of the soil was taken at the beginning of the experiment and the pH of the potted soils was repeatedly determined at 2-weekly intervals for twelve weeks. Mechanical analysis of the soil was carried out by the Bouycous hydrometer method as described by Gee and Bauder (1986). Soil pH was measured using McLean (1982) method and organic carbon contents were determined using weight combustion method as prescribed by Nelson and Sommers (1982). Cation exchange capacity (CEC) of the soil was determined by ammonium acetate method as described by Thomas (1982). Total nitrogen was determined using the micro Kjedahl method as described by Bremmer and Mulvaney (1982) and available phosphorus was obtained by Olsen and Sommers (1982) method. The experiment was done in a factorial design on completely randomized design (CRD) with three replications. The following data were collected: days to emerrgence (DTE), days to flowering (DTF), days to podding (DTP), plant height (PH), number of leaves per plant (NLP), number of nodules per plant (NNP), number of pods per plant (NPP), pod weight per plant (PWP) (g), root length (RL) (cm), fresh root weight (FRW) (g), dry root weight (DRW) (g) and seed weight per plant (SWP) (g) were measured. The NPP and SWP were recorded at harvest. Data for the two years were pooled and analysed using Genstat 5.32 statistical package and significant means were separated by the Least Significant Difference (LSD) at the 5% probability level.

The PCA of some parameters of soil acicity tolerance was used to identify the parameters that best describe soybean tolerance to acidity stress and, to classify the genotypes into acid tolerant and sensitive genotypes. The classification of the soybean genotypes for acid tolerance was performed as according to Kakani *et al*. (2002, 2005) and Zhi *et al*. (2006). The values of the RL, FRW, NNP and SWP at different soil pH levels of 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0 were included in the PCA analysis. The NNP and SWP at pH 3.5 and 4.0 were not included in the PCA analysis because they did not alter the classification of the soybean genotypes. Eigenvectors generated by the PCA were used to identify parameters that best differentiated the genotypes for low soil pH tolerance. The first two PC scores, PC1 and PC2 that accounted for maximum variability of the parameters tested, were used to group the genotypes. Genotypes that had +PC1 and +PC2 scores were classified as tolerant, those with +PC1 and –PC2 scores were classified as moderately tolerant, those with –PC1 and +PC2 were classified as moderately susceptible and finally, those with –PC1 and –PC2 were classified as susceptible. Based on the values of the PC1 and PC2 scores, biplots using PC 1 as horizontal axis and PC 2 as vertical axis were constructed.

Table 1 Mean temperature (°C), rainfall (mm) and the number of rain days during the experimental period.

Month	Temp (°C) (± SEM)**		Rainy days	Rainfall (mm) (± SEM)**
	Min.	Max.		
2004 planting				
January	21.03 ± 0.42	32.58 ± 0.23	1	0.05 ± 0.05
February	22.49 ± 0.33	34.38 ± 0.26	0	-
March	23.52 ± 0.28	34.00 ± 0.44	3	1.19 ± 0.22
April	22.80 ± 0.25	31.90 ± 0.32	6	1.90 ± 1.25
May	23.55 ± 0.33	29.90 ± 0.33	20	8.30 ± 2.44
June	21.76 ± 0.25	28.88 ± 0.23	13	9.37 ± 3.32
July	20.84 ± 0.13	27.65 ± 0.26	18	5.37 ± 1.80
August	20.84 ± 0.13	27.65 ± 0.26	23	5.44 ± 1.46
September	20.47 ± 0.20	28.13 ± 0.22	21	11.31 ± 2.73
October	20.84 ± 0.21	29.23 ± 0.28	14	4.81 ± 1.27
November	21.67 ± 0.32	30.00 ± 0.22	5	2.63 ± 1.60
December	19.74 ± 0.56	31.94 ± 0.23	1	0.05 ± 0.05
2005 planting				
January	20.23 ± 0.35	31.68 ± 0.36	0	-
February	22.86 ± 0.27	34.93 ± 0.20	2	2.522 ± 1.897
March	23.32 ± 0.20	34.48 ± 0.27	2	0.484 ± 0.459
April	23.17 ± 0.25	33.63 ± 0.40	10	4.936 ± 2.651
May	22.26 ± 0.25	30.68 ± 0.35	11	4.597 ± 1.519
June	21.83 ± 0.29	29.47 ± 0.30	18	10.79 ± 3.30
July	20.97 ± 0.28	28.32 ± 0.33	20	8.267 ± 2.602
August	20.39 ± 0.20	27.39 ± 0.306	17	4.048 ± 1.765
September	21.50 ± 0.24	28.73 ± 0.20	19	6.935 ± 2.307
October	21.16 ± 0.24	30.10 ± 0.23	16	17.71 ± 9.87
November	21.37 ± 0.49	32.43 ± 0.19	1	0.3387 ± 0.3387
December	20.71 ± 0.30	32.42 ± 0.21	1	0.0410 ± 0.0410

Table 2 Amount of lime and hydrochloric acid that were added to the soil samples at the beginning of the experiments.

pH	Amount of lime ($Ca(OH)_2$) or hydrochloric acid (HCl) added per 4 kg to amend soil pH
7.0	4.4 g $Ca(OH)_2$
6.5	3.2 g $Ca(OH)_2$
6.0	2.3 g $Ca(OH)_2$
5.5	1.2 g $Ca(OH)_2$
5.0	No ammendment
4.5	12 cm^3 HCl
4.0	36 cm^3 HCl
3.5	64 cm^3 HCl

RESULTS

The effects of genotype on some agronomic and yield traits of soybean genotypes in 2004 planting are presented in **Table 3**. The Table shows that the genotype, 'Digil' had the longest root (29.40 cm) that differed significantly ($P < 0.05$) from the RL obtained in all but one genotype. RL was found to be lowest (20.30 cm) in 'TGX1448-2E'. FRW was significantly affected by the genotype. The highest FRW of 5.5, 5.4 and 4.6 g were recorded for 'Sebore', 'Garikida' and 'Digil', respectively. Their values were significantly higher than those obtained in the other genotypes. The DRW differed significantly among the genotypes with 'Sebore', 'Garikida' and 'Sunkani' weighing 0.7 g each. The genotypes, 'TGX1448-2E' and 'Gembu' had the lowest root weight of 0.4 g. With respect to DTE, 'Garikida' was the earliest to emerge at 3 DAP but did not differ significantly with Gembu (3.2 DAP). However, DTE was significantly delayed in 'TGX1448-2E' (3.5 DAP), 'Digil' (4.1 DAP), 'Kyado' (4.7 DAP), 'Sebore' (5.3 DAP) and 'Sunkani' (6 DAP). With respect to DTF, the genotype, 'Kyado' was the earliest to flower (40 DAP) followed by 'Digil' (43 DAP) and 'Sebore' (49 DAP) in that order. Flowering was significantly delayed by 25 days in 'TGX1448-2E'. The genotypes differed significantly in DTP with Digil being the earliest (66 DAP) to pod and 'TGX1448-2E' delaying considerably till 95 DAP before podding. The PH varied significantly from 17.7 cm in 'TGX1448-2E' to 25.30 cm in 'Kyado'. The highest NLP was produced in 'Digil' and 'Garikida' with each producing 33 leaves. However, they varied significantly ($P < 0.05$) with 'TGX1448-2E' which produced the lowest NLP (22 leaves). The genotypes differed significantly in nodulation with 'Garikida' producing the highest NNP. The genotype, 'Kyado' produced significantly more NPP (14.20). Moreover, 'Kyado' did not differ with all the other genotypes except for 'Gembu' and 'Garikida' which produced 6.3 and 10.5 NPP, respectively. The PWP varied significantly from 1.85 g in 'Gembu' to 5.84 g in 'Kyado'. The genotype 'Kyado' (4.29 g) and 'Sebore' (3.57 g) produced significantly higher SWP than all other genotypes while 'Gembu' (0.89 g) produced significantly the lowest SWP.

Table 3 also indicates that all the agronomic and yield traits evaluated in 2004 planting season except days to flowering were significantly influenced by the soil pH. The RL, FRW and DRW were found to be significantly highest in soil pH of 6.0 with 33.60 cm, 8.90 g and 1.20 g, respectively. However, the soil pH of 3.5 gave the lowest RL (5.10 cm), FRW (0.10 g) and DRW (0.02 g). With respect to the DTE, the soil ammended to pH of 3.5 was found to be significantly different from the remaining soil pH levels having initiated seed emergence earliest after 3.7 DAP while soil pH of 7.0 delayed seed emergence up to 5 DAP. Although soil pH did not differ in the DTF, flowering was earliest (48.60 DAP) in soil ammendment of pH of 5.5. Flowering was not recorded in the soil ammended to pH of 3.5. With respect to DTP, soil pH of 3.5 and 4.0 did not initiate podding. The earliest podding (77.90 DAP) was observed in the soil pH of 4.5 while the latest (78.80 DAP) was in soil pH of 6.5. pH and NLP varied significantly across the soil pH with the longest plant (28.30 cm) and highest NLP (44.70 leaves) observed in soil pH of 6.0 while the shortest plant and least number of leaves (1.66 cm and 1.00 leaf, respectively) were initiated by the soil pH 3.5. NNP varied from 0.5 in soil pH 4.0 to 14.0 in soil pH of 7.0. Production of nodules was inhibited in soils with pH of 3.5. **Table 3** showed that no pod was produced under pH of 3.5 and 4.0 and thus, PWP and SWP were not recorded. Maximum NPP (17.10), PWP (4.74 g) and SWP (3.22 g) were obtained in soil pH of 6.5 while the minimum values of 6.10, 1.39 g and 0.96 g (NPP, PWP and SWP, respectively) were recorded in pH of 4.5.

The mean values of the agronomic and yield traits of the seven soybean genotypes in 2005 planting seasons are shown in **Table 4**. The table indicates that genotype differed significantly in all the agronomic and yield traits evaluated. The RL varied from 25.20 cm in 'Gembu' to 34.40 cm in 'Sunkani'. The genotypes 'Digil', 'Garikida' and 'TGX1448-2E' produced mean RL of 32.80, 30.50 and 31.10 cm, respectively. These values did not differ statistically with the mean RL produced by 'Sunkani'. Although, the highest FRW was recorded in 'Digil' (7.50 g), it was found to be statistically similar with the remaing genotypes except 'Gembu' and 'Sunkani' which had 3.50 g and 4.50 g FRW, respectively. The DRW was significantly different among the genotypes with the highest value observed in 'Sebore' (1.10 g) and the lowest in 'Gembu' (0.50 g). 'Gembu' and 'Garikida' were the earliest to emerge at 3 DAP and, they varied significantly with the remaining genotypes. 'Kyado' and 'Sebore' were the latest to emerge after 5 DAP. The DTF differ significantly among the genotypes with 'Kyado' and 'Sebore' being the earliest genotypes to flower at 43.60 and 43.90 DAP, respectively. However, 'Digil' was the latest genotype to flower at 48.90 DAP. The DTP varied from 58.60 in 'TGX1448-2E' to 62.70 days in 'Kyado'. The PH varied among genotypes from 13.30 cm in 'Gembu' to 18.30 cm in 'Sunkani'. The highest NLP was produced by 'Sebore' (24.1 leaves) but did not varry statistically with 'Kyado' (20.10 leaves) and 'Garikida' (20.90 leaves). Maximum NNP was produced by 'Garikida' (9.7 nodules), followed by 'Sunkani', 'Kyado', 'TGX1448-2E' and 'Digil', which gave 6.40, 6.00, 5.40 and 5.00

Table 3 Effects of genotype and soil pH on some agronomic and yield traits of soybean in the 2004 planting season

Genotype	RL (cm)	FRW (g)	DRW (g)	DTE	DTF	DTP	PH	NOL	NNP	NPP	PWP	SWP (g)
Kyado	26.40	3.60	0.60	4.70	39.50	73.70	25.30	32.20	6.00	14.20	5.84	4.29
Sebore	25.70	5.50	0.70	5.30	48.70	76.40	20.10	29.20	4.00	11.70	5.80	3.57
Digil	29.40	4.60	0.60	4.10	43.10	65.80	20.90	33.20	5.50	12.70	2.17	1.48
Gembu	23.70	2.00	0.40	3.20	50.10	75.60	24.10	28.30	5.50	6.30	1.85	0.89
Garikida	28.00	5.40	0.70	3.00	49.60	82.70	25.10	33.00	7.40	10.50	2.52	1.87
TGX1448-2E	20.30	2.20	0.40	3.50	65.10	94.90	17.70	21.80	5.80	12.20	3.16	2.58
Sunkani	26.90	4.00	0.70	6.00	54.30	76.20	23.80	25.90	6.50	12.80	2.08	1.74
F-$LSD_{0.05}$	2.49	1.33	0.29	0.17	2.03	1.50	2.47	4.97	3.29	2.72	0.82	0.67
pH												
3.5	5.10	0.10	0.02	3.70	-	-	1.66	1.00	-	-	-	-
4.0	16.10	0.40	0.10	4.30	51.50	-	19.80	18.60	0.50	-	-	-
4.5	24.20	0.90	0.20	4.20	50.40	77.90	23.40	30.80	0.90	6.10	1.39	0.96
5.0	27.00	2.20	0.50	4.20	50.10	79.30	23.20	28.30	1.50	7.00	2.12	1.46
5.5	31.00	4.00	0.50	4.40	48.60	78.00	27.80	36.40	3.50	9.70	3.75	2.64
6.0	33.60	8.90	1.20	4.20	50.10	78.30	28.30	44.70	8.70	12.60	4.08	3.00
6.5	31.30	7.00	1.00	4.50	50.40	78.80	28.20	37.40	11.50	17.10	4.74	3.22
7.0	31.80	7.80	1.00	5.00	49.30	78.10	26.90	35.30	14.00	17.00	3.99	2.80
F-$LSD_{0.05}$	2.66	1.42	0.31	0.18	NS	1.39	2.64	5.31	3.04	2.52	0.762	0.619

RL: root lenght, FRW: fresh root weight (g), DRW: dry root weight (g), DTE: days to emergence, DTF: days to flowering, DTP: days to podding, PH: plant height, NOL: number of leaves per plant: NNP: number of noddles per plant, NPP: number of pods per plant, PWP: pod weight per plant, SWP: seed weight per plant (g)

Table 4 Effects of genotype and soil pH on some agronomic and yield traits of soybean in the 2005 planting season.

Cutivar	RL (cm)	FRW (g)	DRW (g)	DTE	DTF	DTP	PH	NOL	NNP	NPP	PWP	SWP (g)
Kyado	29.10	4.90	0.80	4.90	43.60	62.70	17.10	20.10	6.00	10.60	3.80	2.45
Sebore	28.70	5.40	1.00	5.00	43.90	60.30	17.90	24.10	4.00	11.30	3.80	1.79
Digil	32.80	7.50	1.10	4.40	48.90	62.10	14.40	15.00	5.00	5.50	2.70	2.04
Gembu	25.20	3.50	0.50	3.20	45.10	59.10	13.30	13.50	4.30	4.00	1.60	0.89
Garikida	30.50	6.40	0.60	3.20	44.70	60.50	15.50	20.90	9.70	6.80	3.20	2.46
TGX1448-2E	31.10	5.60	0.80	3.90	45.80	58.60	15.40	17.60	5.40	9.50	4.80	3.90
Sunkani	34.40	4.50	0.80	4.40	46.80	60.50	18.30	17.50	6.40	7.30	2.80	2.06
F-LSD$_{0.05}$	5.06	2.23	0.34	0.28	0.89	3.00	2.12	4.89	4.70	4.70	0.84	0.69
pH												
3.5	9.30	0.40	0.05	4.80	-	-	1.19	1.00	-	-	-	-
4.0	10.50	0.50	0.20	4.40	49.00	-	21.10	12.70	0.60	-	-	-
4.5	16.40	1.20	0.30	4.10	47.10	60.50	13.60	10.80	1.20	3.50	1.46	0.99
5.0	29.40	2.10	0.60	4.10	45.40	60.20	15.80	16.20	0.90	5.00	2.49	1.42
5.5	37.90	6.90	1.10	4.10	44.00	59.40	20.40	23.00	2.90	6.90	2.82	1.81
6.0	45.20	8.30	1.10	4.10	42.90	61.00	21.00	26.00	7.90	7.60	3.45	2.35
6.5	48.90	11.40	1.40	4.00	43.40	61.50	21.10	26.70	11.50	12.00	4.44	3.46
7.0	44.50	12.40	1.50	4.10	43.10	60.70	22.80	29.20	13.90	12.20	4.72	3.32
F-LSD$_{0.05}$	5.41	2.40	0.37	0.29	0.95	2.78	2.27	5.33	4.35	4.35	0.78	0.64

RL: root lenght, FRW: fresh root weight (g), DRW: dry root weight (g), DTE: days to emergence, DTF: days to flowering, DTP: days to podding, PH: plant height, NOL: number of leaves per plant, NNP: number of noddles per plant, NPP: number of pods per plant, PWP: pod weight per plant, SWP: seed weight per plant (g)

nodules in that order, respectively while Sebore produced the minimum number of nodules (4.00). The genotype, 'Sebore' recorded the highest NPP (11.30), which did not differ statistically with 'kyado' (10.60), 'Garikida' (6.80), 'TGX1448-2E' (9.50) and 'Sunkani' (7.30) but was found to be statistically different from 'Digil' (5.50 pods) and 'Gembu' (4.00 pods). 'TGX1448-2E' produced the maximum PWP (4.80 g) and SWP (3.90 g) while 'Gembu' had the minimum PWP and SWP of 1.60 and 0.89 g, respectively.

The effect of soil pH on the agronomic and yield traits in 2005 planting season is presented in **Table 4**. It indicated that soil pH significantly influenced all the agronomic and yield traits evaluated. The soil pH of 6.5 gave significantly highest RL (48.90 cm) which did not varry significantly with that produced under soil pH of 6.0 (45.20 cm) and 7.0 (44.50). The shortest RL (9.30 cm) was produced in soil ammended to pH of 3.5. The FRW (12.40 g) and DRW (1.20 g) were significantly highest in soil pH of 7.0 while soil pH of 3.5 initiated the lowest FRW and DRW of 0.40 g and 0.05 g, respectively. DTE varied significantly across the soil pH levels with genotypes grown in soil pH 6.5 emerging earliest (4.00 DAP). However, DTE obtained at pH of 6.5 was found to be statistically similar with those obtained for soil pH of 4.5 (4.1 DAP) , 5.0 (4.1 DAP), 5.5 (4.1 DAP), 6.5 (4.1 DAP) and 7.0 (4.1 DAP). It took a delay period of 4.80 and 4.4 DAP for the genotypes to emerge in soil pH of 3.5 and 4.0, respectively. Flowering was earliest in soil pH 6.0 (42.90 DAP) and latest in soil pH 4.0 (49.00 DAP). The genotypes did not flower under soil pH of 3.5. With respect to DTP, pod setting did not take place when the soybean genotypes were grown in ammended soils of pH 3.5 and 4.0. Early (59.40 DAP) and late (60.70) pod setting were recorded in soils of pH 5.5 and 7.0, respectively. The PH and NLP had the maximum values (22.8 cm and 29.2 leaves, respectively) in soil pH 7.0 and, lowest values (1.19 cm and 1.00 leaves, respectively) in soil pH 3.5. Nothwithstanding that the highest NNP (13.90) was recorded in soil pH of 7.0, the value was statistically similar with the value (11.50) obtained when the genotypes were grown at pH of 6.5. However, the soil pH 4.0 gave the lowest NNP while pH 3.5 did not initiate nodule production. The genotype grown in soils of pH 3.5 and 4.0 did not produce pod. The genotypes gave the highest NPP (12.20 pods) and PWP (4.72 g) in pH of 7.0. These values were comparable with the values for NNP (12.00) and PWP (4.40 g) recorded in soil pH of 6.5. The lowest NPP (3.50 pods) and PWP (1.46 g) were observed in soil pH 4.5. The SWP was highest in soil pH 6.5 (3.46 g) followed by pH 7.0 (3.32 g) while lowest (0.99 g) SWP was observed in pH 4.5.

Fig. 1 shows the effects of genotype and soil pH interaction on some agronomic and yield traits of soybean genotypes in the 2004 and 2005 planting seasons. The genotype and soil pH interaction had significant effect on all the traits evaluated. Generally, the soil pH 3.5 initiated significantly shortest RL among all the genotypes when compared with the values obtained for RL across the remaining soil pH levels. In 2004 planting (**Fig. 1A**), the RL obtained at soil pH between 3.5 and 5.0 in 'TGX1448-2E' and 'Sunkani' differed significantly from those at the other soil pH. On the other hand, RL at soil pH 5.0 to 7.0 in 'Gembu' varied significantly ($P < 0.05$) from those at pH 3.5 to 4.5. The genotype, 'Digil' recorded the longest RL of 36.70 cm at soil pH 6.0 whereas 'TGX1448-2E' recorded the shortest RL (4.50 cm) at pH 3.5. In 2005 planting season (**Fig. 1B**), the genotype and soil pH interaction had significant effect on RL. In 'Kyado', RL at pH 4.0 and 4.5 were comparable and differ significantly from RL of genotypes grown at pH 6.0 to 7.0. However, in the genotype 'Sebore' grown at soil pH 4.0 to 5.0 did not vary in RL but were found to have varied significantly with those grown at soil pH 5.5 and 6.0. In 'Digil', variations in RL were not dictected at the ammended soil pH of 3.5 to 5.0. But, the RL increased with increase in the soil pH from 5.5 to 7.0. The genotypes, 'Gembu' and 'TGX1448-2E' grown at pH 3.5 and 4.5 were similar in RL but varied statistically from those grown at pH of 5.0 to 7.0. In 'Garkida', plants grown on pH 3.5 to 4.5 had comparable RL and differed significantly from plants grown at pH 5.5 to 7.0 . Similarly, in Sunkani plants grown on pH 3.5 and 4.0 differed significantly in RL from those grown at pH of 4.5. The genotype, 'Sebore' recorded the longest RL (57.70 cm) at pH 6.5 while 'Kyado' had the shortest RL of 6.30 cm at pH 3.5.

The interaction of genotypes and soil pH on the FRW showed that in 2004 planting, genotypes had less FRW at pH < 5.5 and better FRW at pH > 5.5 (**Fig. 2A**). The FRW obtained between 3.5 and 5.5 were statistically different from that obtained from soil pH 6.0 to 7.0 in 'Kyado', 'Garikida' and 'Sunkani'. The FRW of 'Sebore' and 'Digil' at soil pH 3.5 to 5.0 were found to differ statistically from the FRW of the other soil pH levels. The genotype x soil pH interactions had significant effect on FRW in all the genotypes in 2005 planting season (**Fig. 2B**). In 'Kyado', plants grown at pH 3.5 to 5.5 were comparable in FRW and differed significantly ($P < 0.05$) from those grown at pH 6.0 to 7.0. However, in 'Sebore', plants grown at pH 3.5 to 5.0 differed significantly in FRW from those grown at soil pH of 6.5 to 7.0 but plants grown on pH 5.5 had comparable FRW with plants on both pH levels. Generally, plants grown at pH 6.5 performed better with highest FRW (18.10 g) recorded on 'TGX1448-2E' while 'Kyado' recorded the lowest FRW (0.20 g) at pH 3.5.

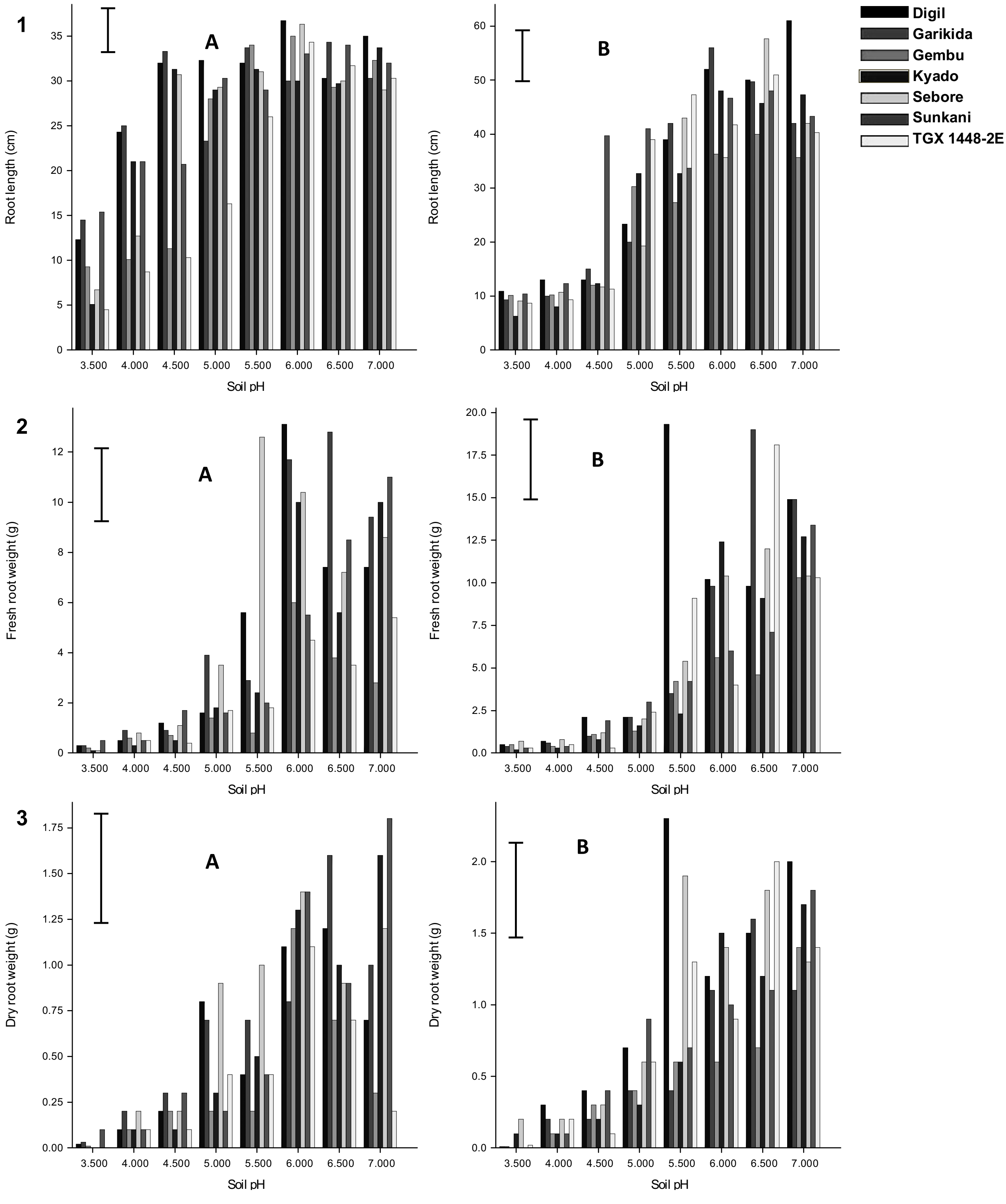


Fig. 1 Effects of genotypes × soil pH on root length (cm) in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.

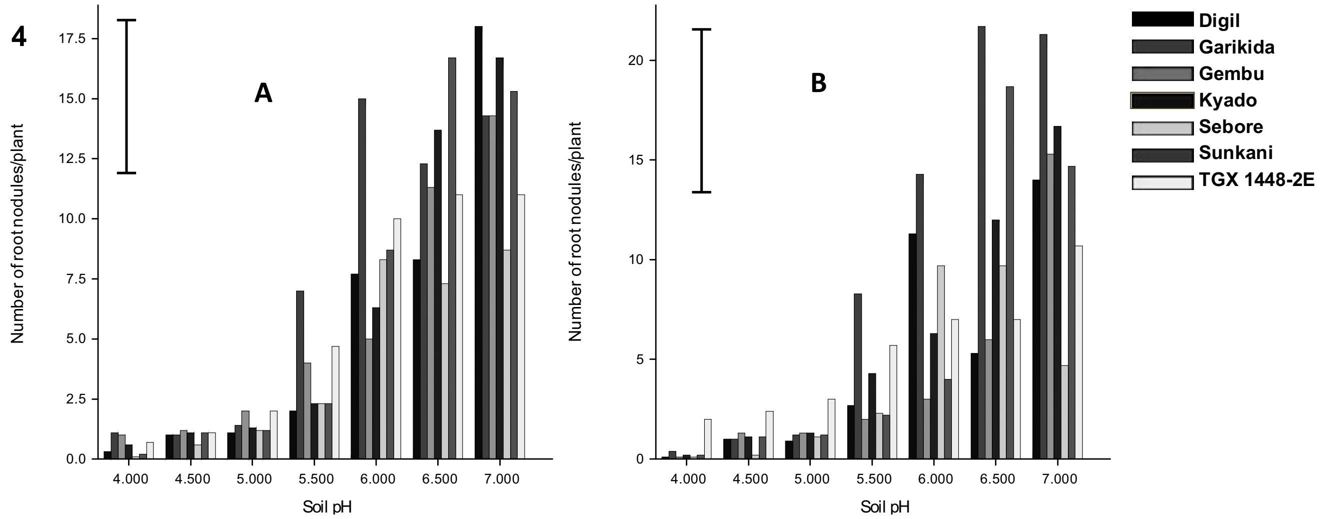
Fig. 2 Effects of genotypes × soil pH on fresh root weight (g) in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.

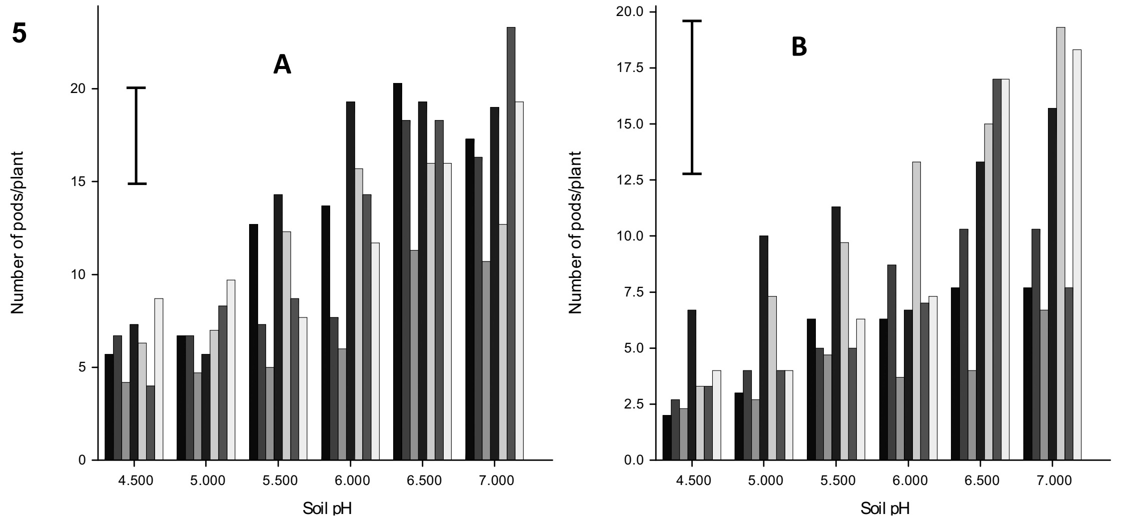
Fig. 3 Effects of genotypes × soil pH on dry root weight (g) in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.

In the 2004 planting season, the interaction of genotype and soil pH on DRW showed that the soil pH of 3.5 and 4.5 were significantly different from the DRW obtained at pH 6.0 and 6.5 in some of the genotypes (**Fig. 3A**). The 2005 plantings indicated that the genotype × soil pH interaction had significant effects on DRW in all the genotypes (**Fig. 3B**). In genotypes, 'Kyado' and 'Garkida' plants grown at pH 3.5 to 5.5 varied significantly in DRW from those grown at pH 3.5 to 7.0. The genotypes, 'TXG1448-2E' and 'Digil' recorded the highest DRW of 2.00g at pH of 6.5 and 7.0, respectively. However, 'Sunkani' gave the lowest DRW (0.001 g) at pH 3.5.

Fig. 4A indicated that genotype and soil pH interaction had no significant effect on nodulation in virtually all the genotypes except in 'Digil' were nodulation at soil pH 7.0 differed significantly from nodulation across the other pH levels (**Fig. 4A**). However, the genotype 'Digil' recorded the highest number of nodules (18) at soil pH 7.0 while the lowest was obtained in Sebore at the soil pH of 4.0.

The 2005 planting season indicated that genotype and





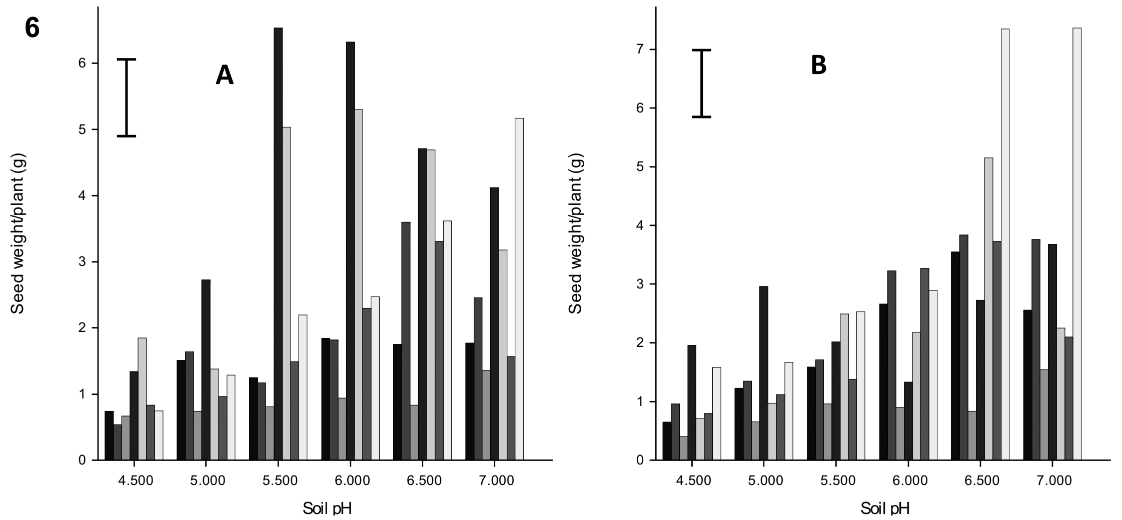


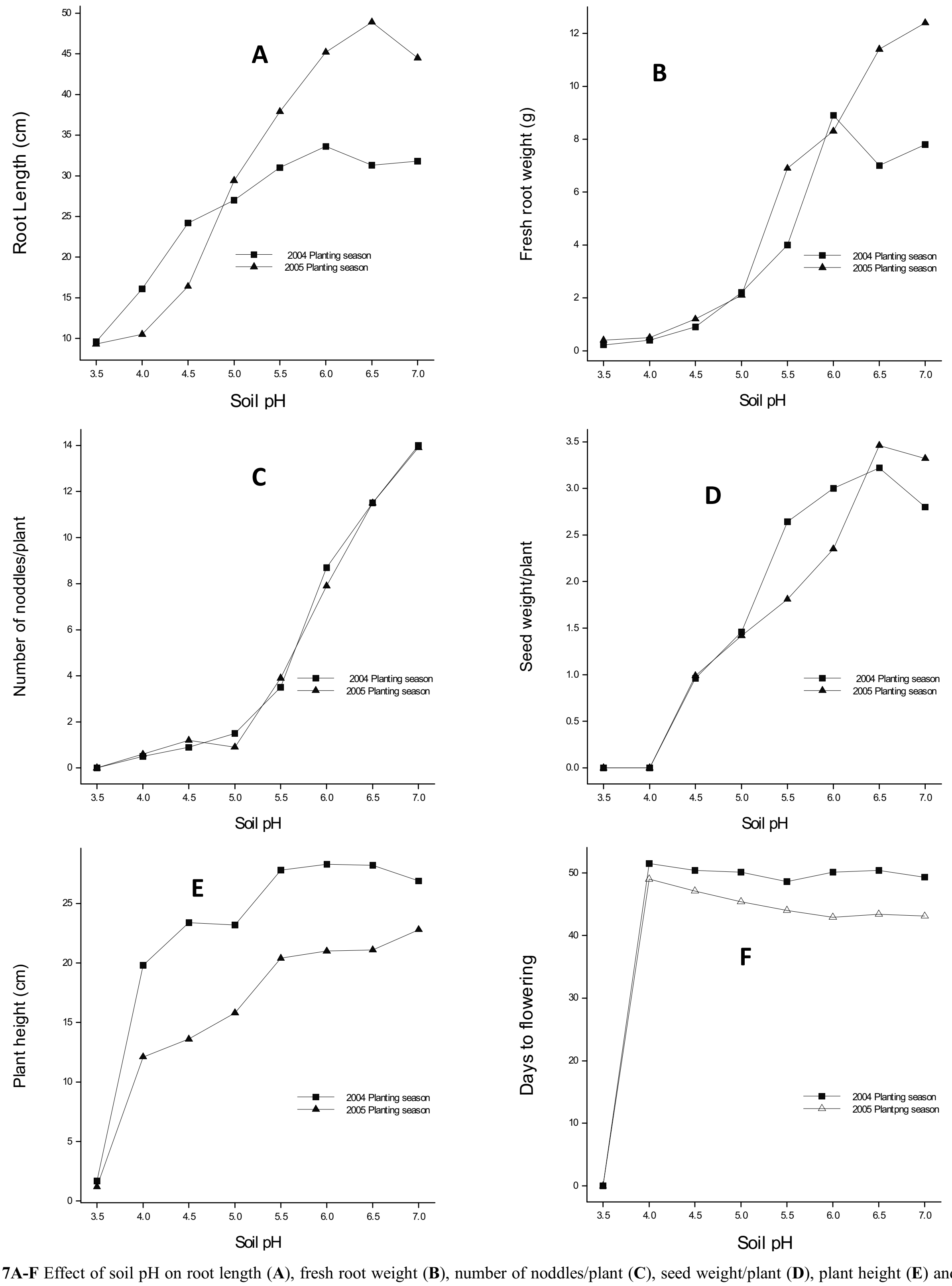
Fig. 4 Effects of genotypes × soil pH on number of root nodules per plant in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.
Fig. 5 Effects of genotypes × soil pH on number of pods per plant in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.
Fig. 6 Effects of genotypes × soil pH on seed weight per plant (g) in 2004 (**A**) and 2005 (**B**). Bars indicate the value of $LSD_{0.05}$.

soil pH interaction had a significant effeccts on nodulation (**Fig. 4B**). The NNP produced by plant grown at pH 4.0 varied significantly from the NNP produced by the plants at pH 6.5 and 7.0. The genotypes recorded higher number of nodules at pH between 6.5 and 7.0. The results indicated that 'Garkida' produced the highest number of nodules at pH of 6.5 (21.7 nodules) and 7.0 (21.3 nodules) whereas the lowest number of noddles was recorded for 'Sebore', 'Digil' and 'Gembu' at pH 4.0.

In the 2004 planting (**Fig. 5A**), the genotype × soil pH interaction had no significant effects on number of pods produced in 'Gembu' but in genotypes such as 'Kyado', 'Sebore' and 'Digil', the number of pods produced at pH 4.5 and 5.0 were comparable and differed significantly from those produced at 5.5 and 7.0. In 'Garikida', the number of pods produced at pH 6.5 and 7.0 were statistically similar but differed from those produced at pH 4.5 to 6.0. On the other hand, the number of pods produced in 'TGX1448-2E' and 'Sunkani' at pH 4.5 and 5.5 were comparable but differed significantly with those produced at pH 6.0 to 7.0. The highest (23.30 pods) and lowest (4.00 pods) NPP were produced by 'Sunkani' at pH of 7.0 and 4.5, respectively.

The 2005 plantings showed that the genotype and soil pH had no significant effect on NPP in genotypes such as ‘Kyado’, ‘Digil’, ‘Gembu’ and ‘Garkida’ (**Fig. 5B**). However, the number of pods produced in ‘Sebore’ and ‘TGX1448-2E’ at pH 6.5 and 7.0 was high and differed significantly from those produced at pH 4.5 and 5.0. Also, the number of pods produced in Sunkani at pH 6.5 was significantly higher than those produced when grown at pH 4.5 and 5.0. The highest number of pods was recorded for ‘Sebore’ (19.30 pods) and ‘TGX1448-2E’ (18.30 pods) at pH 7.0 while the lowest number of pods was recorded in ‘Gembu’ (2.30 pods) at pH 4.5.

The interaction between the genotype and soil pH on seed yield showed no significant effect in ‘Digil’ and ‘Gembu’ in 2004 planting. **Fig. 6A** also indicated that seed yield in ‘Kyado’ and ‘Sebore’ at pH 5.5 to 7.0 were comparable and differ significantly from seed yield at other soil pH levels. Similarly, the seed yield of ‘Garkida’ and ‘Sunkani’ at pH 4.5 were comparable with seed yield at pH 5.0 but were different from the seed yield at pH 5.5 to 7.0. The table (**Fig. 6A**) revealed that the highest yield of 6.53g in ‘Kyado’ was produced at pH 5.5 while the least seed yield (0.54g) was obtained in ‘Garkida’ at soil pH 4.5. In **Fig. 6B**, there was no significant genotype × soil pH interaction



Figs. 7A-F Effect of soil pH on root length (**A**), fresh root weight (**B**), number of noddles/plant (**C**), seed weight/plant (**D**), plant height (**E**) and days to flowering (**F**) of soybean genotypes in 2004 and 2005 planting seasons.

effect on the seed yield of 'Gembu', but in 'Kyado' seed yield produced at pH 4.5 was lower and varied significantly from those produced at pH 7.0. Generally, results indicated that the gentypes performed better in terms of seed yield at pH 6.5 and 7.0 and, lower at pH 4.5. The highest seed weight was recorded for 'TGX1448-2E' at pH 6.5 (7.35 g) and 7.0 (7.36 g) while the lowest seed yield (0.41 g) was observed in 'Gembu' at pH 4.5.

The differential response of some agronomic and yield traits of soybean genotypes were determined at pH levels of 3.5 to 7.0 in both 2004 and 2005 plantings and, the results are shown in **Fig. 7**. The figures indicated that at both planting seasons, most of the traits were greatly inhibited at pH below 4.0 and, were found to increase progresively with the increase in the soil pH up to 6.0. In **Fig. 7A,** the root growth inhibition was more severe in 2004 than in 2005 plantings. The root growth had a gradual increase with the decrease in the soil acidity (*i.e.,* increase in soil pH) in both planting seasons. It increased simultaneously with the increasing soil pH up to pH of 6.5 and, thereafter there were no significant root growth. The DRW followed the same trend as RL (**Fig. 7A**) except that the DRW response to soil pH got to the pick at pH 6.0 and 7.0 for 2004 and 2005, respectively (**Fig. 7B**). In **Fig. 7C**, the NNP increased simultaneously with the increase in soil pH levels. The response of NNP to soil pH levels were found to increass gradually between pH of 3.5 and 5.0 but thereafter, increased greatly with the increase in the soil pH in both planting seasons. At soil pH between 3.5 and 4.0, no response was observed in seed weight per plant (**Fig. 7D**). However, SWP increased greatly from pH 4.5 to 7.0 with the highest SWP response observed at pH 7.0 in both plantings. The PH performed less in 2005 plantings when compared with the 2004 planting as shown in **Fig. 7E**. At both plantings, the PH initial response to pH was rapid from 3.5 to 4.0 but thereafter it showed a gradual increase. DTF followed the same trend as PH at the onset. Initially, DTF increased rapidly from pH 3.5 to 4.0 and thereafter, between pH of 4.0 and 7.0, DTF showed a gradual declined at both plantings (**Fig. 7F**).

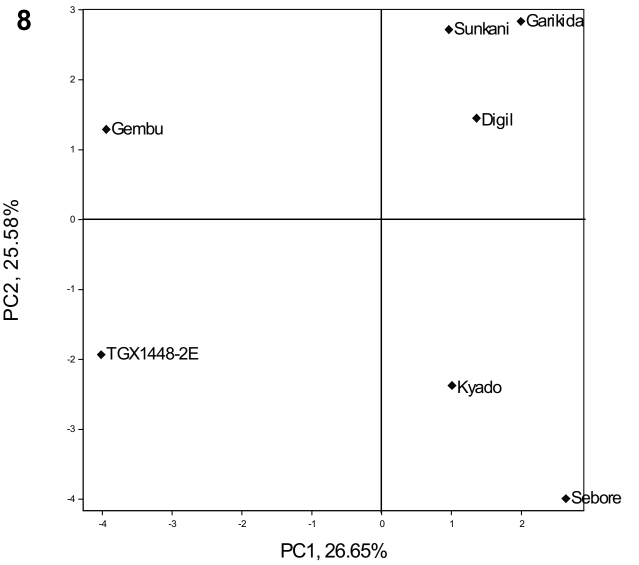
The PCA of some agronomic and yield traits used to differentiate the seven soybean genotypes on the basis of their level of tolerance to soil acidic conditions during the 2004 and 2005 planting seasons is presented in **Table 5**. In the 2004 planting season, the first three principle components vectors (PC1, PC2, and PC3) accounted for 71.12% of the total variation, and the percentage accounted for by

Table 5 Principal component analysis eigenvectors PC1, PC2 and PC3 of seven soybean genotypes for root lenght (RL), fresh root weight (FRW), number of noddles per plant (NNP), seed weight per plant (SWP) and their respective soil pH levels (pH levels; 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5 and 7.0) and the variation accounted for by each eigenvector.

Parameters	Principal component eigenvectors					
	2004 planting season			2005 planting season		
	PC1	PC2	PC3	PC1	PC2	PC3
RL at pH 3.5	0.1377	0.3286	0.0122	0.1981	0.1481	0.1018
RL at pH 4.0	0.2607	0.1932	-0.0562	0.2215	0.2010	0.03901
RL at pH 4.5	0.3348	-0.0111	-0.0054	0.0965	-0.0210	-0.1378
RL at pH 5.0	0.1987	0.0587	-0.3107	-0.1164	-0.2237	-0.0138
RL at pH 5.5	0.1037	0.1333	-0.0320	-0.2180	0.2930	0.0769
RL at pH 6.0	-0.066	-0.0744	-0.1427	-0.0089	0.1458	-0.4011
RL at pH 6.5	0.0882	0.2175	0.2360	-0.0852	0.3181	0.1193
RL at pH 7.0	0.0013	0.1192	-0.3495	0.0900	0.1935	-0.1442
FRW at pH 3.5	0.1333	0.3051	-0.0883	0.1654	0.1809	0.2861
FRW at pH 4.0	0.1052	0.0597	0.3146	0.0551	0.3434	0.1699
FRW at pH 4.5	0.1965	0.1732	-0.1042	0.2832	0.1298	-0.0742
FRW at pH 5.0	0.2134	-0.0434	0.3180	-0.0597	0.1711	-0.0710
FRW at pH 5.5	0.2149	-0.2024	0.0248	0.0515	0.2131	0.0705
FRW at pH 6.0	0.2699	0.0064	-0.0233	0.0814	0.1040	-0.1865
FRW at pH 6.5	0.2670	0.1858	0.1862	-0.2513	0.2208	-0.0650
FRW at pH 7.0	0.2967	0.0190	0.0106	0.0975	0.1689	-0.3717
NNP at pH 4.0	-0.1709	0.1275	0.1998	-0.3307	0.0137	0.0980
NNP at pH 4.5	-0.2262	0.1953	-0.1043	-0.2304	-0.1241	0.0091
NNP at pH 5.0	-0.3385	-0.0193	0.1245	-0.2998	-0.0584	0.1340
NNP at pH 5.5	-0.0861	0.1270	0.3633	-0.2192	0.0972	-0.2324
NNP at pH 6.0	0.1147	0.1148	0.3577	-0.0351	0.3238	-0.1384
NNP at pH 6.5	-0.0257	0.1697	-0.0248	-0.0092	0.0552	-0.3070
NNP at pH 7.0	0.0461	0.2171	-0.2531	0.0246	-0.0941	-0.3814
SWP at 4.5	0.1597	-0.3027	-0.0599	-0.2656	-0.0942	-0.1574
SWP at 5.0	0.1529	-0.1431	-0.0410	-0.1776	-0.1016	-0.2290
SWP at 5.5	0.1284	-0.2984	-0.0645	-0.2466	0.1580	0.1223
SWP at 6.0	0.1621	-0.2875	-0.0559	-0.0843	0.2753	-0.1311
SWP at 6.5	0.1794	-0.2185	0.1500	-0.2531	0.2112	0.1179
SWP at 7.0	-0.0720	-0.265	0.1426	-0.3058	0.0381	-0.0006
Eigenvector sum	2.78	0.89	0.72	-1.83	3.29	-1.70
% Variation	26.65	25.58	18.89	29.37	22.64	17.27

Table 6 Classification of seven soybean genotypes based on the scores of first two principal components (PC1 and PC2).

2004 planting season				2005 planting season			
Tolerant (+PC1,+PC2)	Moderately tolerant (+PC1, –PC2)	Moderately susceptible (–PC1, +PC2)	Susceptible (–PC1, –PC2)	Tolerant (+PC1,+PC2)	Moderately tolerant (+PC1, –PC2)	Moderately susceptible (–PC1, +PC2)	Susceptible (–PC1, –PC2)
Digil (+1.36, +1.45)	*Kyado* (+1.01, -2.37)	*Gembu* (-3.94, +1.29)	*TGX1448-2E* (-4.02, -1.93)	*Sebore* (+0.79, +2.24)	*Gembu* (+2.65, -3.75)	*Garikida* (-0.78, +2.03)	*Kyado* (-1.34, -2.82)
Garikida (+1.99, +2.84)	*Sebore* (2.64, -3.99)			*Digil* (+2.58, +2.82)	*Sunkani* (+1.71, -0.57)	*TGX1448-2E* (-5.61, +0.06)	
Sunkani (+0.96, +2.72)							



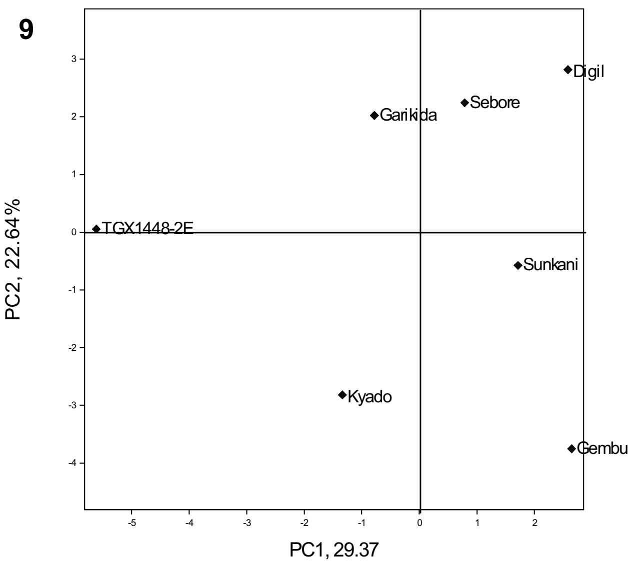


Fig. 8 First and second principal component scores (PC1 and PC2) for the identification of soybean genotypes response to soil pH in 2004 planting season.

Fig. 9 First and second principal component scores (PC1 and PC2) for the identification of soybean genotypes response to soil pH in 2005 planting season.

PC1 and PC2 was 52.23% (**Table 5**). PC1 loaded highly for RL at pH 4.5 (0.3348) and NNP at pH 5.0 (-0.3385) while PC2 had high loadings for RL at pH 3.5 (0.3286), FRW at pH 3.5 (0.3051), SWP at 4.5 (-0.3027) and SWP at 5.5 (-0.2984). The PC3 recorded high negative loadings for FRW at pH 7.0 (-0.3717) and NNP at pH 7.0 (-0.3814). The genotypes were classified into four distinct groups based on the scores of PC1 and PC2 (**Fig. 8; Table 6**): (i) genotypes 'Digil', 'Garikida' and 'Sunkani', with positive PC1 and PC2 scores, were classified as tolerant to low soil pH; (ii) genotypes 'Kyado' and 'Sebore', with +PC1 and –PC2, were classified as moderately tolerant; (iii) genotype 'Gembu', with –PC1 and +PC2, were classified as moderately susceptible; and (iv) genotype 'TGX1448-2E', with negative PC1 and PC2, were classified as susceptible. In 2005 planting season, the first three principal component vectors (PC1, PC2 and PC3) accounted for 69.28% of the total variation (**Table 5**). The PC1, PC2 and PC3 accounted for 29.37, 22.64 and 17.27% of the total percentage variation, respectively. The PC1 eigenvector had high negative loadings (-0.058) for paremrter, NNP at pH 4.0. The genotypes with higher and lower number of nodules at pH 4.0 were placed on the right and left of the plot, respectively (**Fig. 9**). The PC2 had high positive loadings for RL at pH 6.5 (0.3181), FRW at pH 4.0 (0.3434) and NNP at pH 6.0 (0.3238). The paremeters, FRW and NNP at pH 7.0 loaded highest in the PC3. The genotypes were also divided into four groups based on the scores of the first two principal components, which represents their level of tolerance to low soil acid conditions (**Fig. 2; Table 6**): Group I as tolerant genotypes, 'Sebore' and 'Digil', with positive PC1 and PC2 scores; Group II as moderately tolerant genotypes, 'Gembu' and 'Sunkani', with +PC1 and –PC2; Group III as moderately susceptible genotypes, 'TGX1448-2E' and 'Garikida', with – PC1 and +PC2; and Group IV as susceptible genotype, 'Kyado', with negative PC1 and PC2.

DISCUSSION

The present study examines the variation among some soybean genotypes cultivated in South-Eastern, Nigeria for their suitability to become potential candidates in offering best possible yields under acid stress soil conditions. We found substantial variation among the genotypes in most of the agronomic and yield traits evaluated at both planting seasons, indicating the existence of genotypic variation which could be positively utilized in breeding for acid tolerance for low input agriculture. Genotypic differences in different soil pH levels have been reported in crops like; pearl millet, *Pennisetum glaucum* (Flores *et al*. 1991), lucerne (*Alfalfa*), *Medicago sativa* (Zhang 2006) and wheat, *Triticum* spp. (Foy 1996; Yang *et al.* 2011). In acid soils, Little (1988) reported that plant species differ in their Al tolerance; some are inherently more tolerant than others; for example, cassava (*Manihot esculenta* Crantz), cowpea (*Vigna unguiculata* L. Walp), groundnut (*Arachis hypogea*), pigeon pea (*Cajanus cajan* L. Millsp.), potato (*Solanum tuberosum*), rice (*Oryza sativa* L.), and rye (*Secale cereale* L.). A substantial genotypic variation in acidity tolerance was found among wheat genotypes, with the root length per plant at pH 3.9 ranging from 66 to > 350 mm (Tang *et al.* 2003). Thus, our results clearly demonstrated that the soybean genotypes varied considerably in their agronomic and yield traits, irrespective of the pH levels in the soil.

The response of soybean genotypes to different soil pH levels in terms of root growth, agronomic and yield traits were observed to be significant at both 2004 and 2005 planting seasons. Indeed, it showed that variation existed across the soil pH levels evaluted, as it has been previously reported for cowpea (Ezeh *et al.* 2007), maize (Mariano and Keltjens 2004) and soybean (Munns and Fox 1977; Bushamuka and Zobel 1998). This showed that soil pH had a strong impact on the soybean root growth, agronomic and yield traits. Also, results indicated that genotypes growned at an increasing soil pH from 5.5 to 7.0 resulted in significant increase in all the traits considered. Fox *et al.* (1985) in Hawaii assessed the growth response of Jumby bean, *L. lucocephala* to varying range of soil pH from < 5 to > 7 and, found that yield increased with increasing soil pH until above pH 7.0. The simultaneous increase in the overall agronomic yield of soybean with the increase in soil pH from 5.5 to 7.0 could be attributed to an increasing nutrient (Ca, P and K) uptake which are readily available under such soil pH conditions. Tisdale *et al.* (1993) and Costello *et al.* (2003) reported that essential nutrient elements are readily available for plant use at soil pH between 5.5 and 7.0. Moreover, Franzen (1999) and Hans (2010) opined that soybeans grow best in slightly acid soil but can tolerate a wide range of soil pH between 5.8 and 7.0.

The genotypes showed poor agronomic and yield performance as the soil pH decreased from 5.5 to 3.5 indicating that the genotypes are sensitive to acidic soil conditions. Increase in soil acidity was observed to have a deleterious effect on the root growth and the overall growth and development of the soybean genotypes. The result agrees with the reports of Reddy and Dunn (1987), Taylor (1988), Mossor-Pietraszewska (2003) and Duressa *et al.* (2011) that high levels of soil acidity can reduce root growth, reduce nutrient availability to plant, affect crop protectant activity and thus, would result in poor plant growth and reduction in the agronomic yield. As pH decreases calcium, magnesium, phosphorus and copper become less available for plant. Reed (1996), Preece and Read (2005) and Brady and Weil (2008) have shown that calcium, magnesium, phosphorus and copper are needed in large quantities in the development of the plants. The observed negative effect of low pH on the soybean could also be linked to the Al and Mn toxicities. These elements are found to be highly soluble under acid soil conditions and, their solubility increases with the increase in the soil acidity. According to Kochian *et al.* (2004), the limiting factors for plant growth in acid soils include the toxic levels of aluminum (Al), manganese, and iron (Fe), as well as deficiencies of some essential elements, such as phosphorus (P), nitrogen, potassium (K), calcium (Ca), magnesium, and some micronutrients. They further stated that Al toxicity, Mn toxicity and P deficiency are the most important due to their ubiquitous existence and overwhelming impact on plant growth. Zeigler *et al.* (1995) and Eswaran *et al.* (1997) reported that acidic soils characterised by low pH and excess of aluminium and manganese hamper crop production in the tropical and sub tropical areas. The aluminum toxicity affects the plant roots growing in the acid soil by disrupting the metabolically active cells at the root apex (Ryan *et al.* 1993; Sivaguru and Horst 1998; Ryan *et al*. 2005) which would result in the inhibition of root elongation (Ciamporová 2002). The phytotoxic levels of Al in the soil solution is expected when soil pH is < 5.0 to 5.5 (Adams 1981). Studies have also shown that at low soil pH, phosporus and some essential micronutrients which are needed by the plant for its proper growth and development are found to be less available at pH < 5.5 (Kamprath 1984; Foy 1992; Kochian *et al*. 2004; Akinrinde *et al*. 2005).

Genotypes responded diffrently on the root growth across all the soil pH levels in both 2004 and 2005 planting seasons. It demostrates strong influence of soil pH on each of the genotypes. The results showed that differences in acidity tolerance exist among the soybean genotypes and thus, would be efficiently exploited by the soybean breeders to develop acid tolerant and high yielding genotypes. Munns and Fox (1977) and Bushamuka and Zobel (1998) validated this results by reporting that the root growth of soybean genotypes responded differently to acid sub soils. The genotypes initiated poor root growth at soil pH<5.5 suggesting that acid soils inhibits root growth. Hecht-Buchhololz *et al*. (1990) had observed reductuion of tap root elongation and development of stubby lateral roots with swollen root tips in acidic soil. In acid soils, Al and Mn concentration is high and have been reported to have an inhibitory effects on the root growth (Jayasundra *et al.* 1998; Reynolds *et al.* 2001) and crop performance (Ezeh *et al.* 2007). Fageria (1985) observed differential responses in root growth among the rice genotypes to different levels of Al^{3+} while Delhaize *et al.* (1991) reported significant inhibitory effect of Al^{3+} on root growth in wheat genotypes. Suthipradit *et al*. (1990) observed that the tap root elongation of soybean and cowpea was decreased remarkedly with increasing total Al concentration in solution. Under acidic soil conditions, active, phytotoxic forms of Al are released to the soil solution to levels that can inhibit root growth and damage roots (Delhaize *et al*. 1993).

In 2005 planting, seed emergence was significantly delayed at pH 3.5 and 4.0 due to inhibitory effect of Al^{3+} on the seed germination. Al^{3+} is readly avalaible in acid soils. Alamgir and Akhter (2009) reported that Al^{3+} affects seed germination of different varieties of wheat (*Triticum aestivum* L.), and the inhibitory effect increased with the increase in Al^{3+} concentration. It has been reported that Al^{3+} at different concentrations showed differential inhibitory effect on seed germination of white spruce, *Picea glauca* (Nosko *et al.* 1988), pigeon pea, *Cajanus cajan* (L.) Millsp (Narayanan and Syamala 1989) and wheat, *Triticum aestivum* L. (Lima and Copeland 1990). The PH increased with increasing soil pH. The lowest PH values were observed among the genotypes at soil pH of 3.5 whereas the tallest genotypes were obtained at soil pH of 6.5 and 7.0 at both planting seasons. This results indicates that soil acidity caused severe reduction in plant stature; as a result, PH was less than 3 cm at both 2004 and 2004 plantings. This agrees with the report of Leinonen (1996) that low soil pH causes stunting growth in plant. In this study, nodules were not observed at pH 3.5 and pH 4.0. The failure to nodulate among the soybean genotypes at the soil pH of 3.5 and 4.0 could be attributed to low number of rhizobia and probably failure of the rhizobia to attach and infect the root hairs. Soil acidity as reported by Graham (1998) can limit growth and persistence of rhizobia, the nitrogen fixing bacteria. Evans *et al.* (1988) compared rhizobium trifolii and root nodulation in acid and limed soils and observed that increasing the soil pH increased both the rate at which *Rhizobium trifolii* colonized soil and the frequency of nodules/g root (NF). Thus, numbers of *R. trifolii* were greater in lime soil when compared to the acidic soil. Therefore, the observed reduction in the number of nodules under acid stressed soil conditions could be linked to the inhibitory effects of Al^{3+} on the nodule formation. Wood *et al*. (1984) studied the effects of aluminium on the *Trifolium repens* var Huia-*Rhizobium trifolii* strain HP3 symbiosis and found out that Al^{3+} reduced or inhibited root elongation at pH < 5.0 and, the *Rhizobium* multiplication in the rhizosphere and nodule formation were also inhibited at pH < 6.0.

The agronomic and yield traits of all the genotypes were severely reduced under acid stressed conditions and, this was supported by Elrashidi *et al.* (1997) and Beegle and Lingenfelter (1995) who reported that low soil pH (< 5.5) inhibit in root growth and other agronomic yield characters due to the negative impact of AL, Mn and Fe on plant growth and development. A study carried out by Dai *et al.* (2011) revealed that at pH of 4.3, germination ratio, plant height, root length, and plant dry weight of some Tibetan wild barley genotypes were severely reduced as compared to when the plants were grown at pH 6.0. Moreover, all the seven genotypes had defined soil pH optima, below the point of which growth and seed yield were remarkedly reduced. Based on these, characterization and identification of the soybean genotypes for acid tolerant become very partinent so as to generate soybean genotypes that may be introduced into the breeding programmes for acid tolerant. PCA is perhaps the most useful statistical tool for screening multivariate data with significantly high correlations (Johnson 1998). In this study, PCA was adopted to identify parameters that best differentiated cultivars for acid tolerance using the derived eigenvectors and, would help to assess the grouping patterns caused by the discriminating variables. Recently, PCA has been applied as a tool for tolerance evaluation in crops like cotton, *Gossypium* spp. (Kakani *et al.* 2005; Liu *et al.* 2006), *Capsicum* species (Reddy and Kakani 2007) and groundnut, *Arachis hypogaea* L. (Kakani *et al*. 2002). Our findings revealed that the first three principal components explained 71.12 % of the total variability in response to soil pH in the 2004 planting season. Thus, the magnitude of variation observed was high enough for the index evaluation of the soybean genotypes for acid tolerance using their respective principal component scores. The cluster analysis applied to the principal components divided the cultivars into four distinct groups (**Fig. 4; Table 5**). The PC1 eigenvector variable for the RL at pH 4.5 has high positive loadings, while variables NNP at pH 5.0 and NNP at pH 4.5 have high negative loadings. In the 2005 planting, the first three principal components accounted for 69.28% of the total variation. The first component explaining 29.37% of variance is positively and negatively correlated with FRW at pH 4.5 and NNP at pH 4.0, respectively. In the 2005 planting, the PC1 classified and distinguished the score of the genotypes on the basis of their root length, fresh root and number of pods at soil pH of 4.0 and 4.5. The second principal component explaining 22.64% of total variance is highly positively correlated with FRW at pH 4.0 thus explains contrast among the genotypes based on their response at soil pH 4.0, while the third component which explains only 17.27% of total variance is negatively correlated with FRW at pH 7.0 and NNP at pH 7.0. These results indicated that in PC1 vectors, genotypes high values of rootlength at pH 4.5 and high number of pods at pH 4.5 and 5.0 do not necessarily performed best with respect to above traits. But, they were found to perform best in the root growth parameters and number of pods per plant at pH 4.5 and 5.0. Thus, genotype tolerance to acid stressed soil conditions results from higher root vigour and improved seed yield under the acid condition. These results are important because presumably genotypes that had vigorous root growth and higher number of pods at the soil pH < 5.0, would have a greater ability to grow in acid soils. Jayasundra *et al.* (1998) reported that Al^{3+} stress in acid soils inhibits plant root growth. Moreover, tolerance in plant refers to the ability of the plant to produce a high yield in a soil that has deficiency or toxicity of a particular element compared to a standard plants (Graham 1984). The results showed that genotypes that had higher root length and number of pods maintained higher seed yield at pH moderatly lower pH compared with those that had lower root length and number of pods. This result agrees with earlier report of Macuha and Rychtarik (1999) that length and weight of roots were the best criterion for selecting Al^{3+} tolerant wheat varieties. Acid tolerant varieties of wheat have been reported to exhibit a higher rate of root growth activities under acid stressed conditions (Alamgir and Akhter 2009).

The soybean genotypes were classed as tolerant, moderately tolerant, moderately susceptible and Susceptible . Genotypes with PC1 < -1 and PC2 < 1 were classified as tolerant, those with PC1 value of -1 to +1 and PC2 > 1 as intermediate, and the susceptible genotypes were those with PC1 > +1 and PC2 > 1. Genotypes with a negative PC1 and PC2 score (< 1) all had high maximum performance for RL at pH 4.5, NNP at pH 5.0, RL at pH 3.5, FRW at pH 3.5, SWP at 4.5 and SWP at 5.5 in 2004 planting and, NNP at pH 4.0, FRW at pH 4.0, FRW at pH 4.5 and NNP at pH 6.0 in 2005 planting, which should contribute to greater low soil pH tolerance. Thus, 'Digil', 'Garikida' and 'Sunkani' are acid-tolerant genotypes while 'TGX1448-2E' acid-susceptible during 2004 planting. In 2005 planting, 'Sebore' and 'Digil' are tolerant to low soil pH while 'Kyado' is susceptible. Under low soil pH conditions, the soybean root growth and agronomic traits did not perform well. This means that the acid tolerant genotypes did not only show good root growth but also performed well in the agronomic traits under the acid stress conditions. This result showed that genotypes with good root growth and high number of pods were selected. Kuswantoro *et al.* (2010) reported that acid soil effects showed different root growth responses, where the tolerant genotypes had higher root length, and susceptible genotypes had suppression on root growth. Root length in response to Al stress in acid affected soils has been used to assess Al tolerance of sorghum genotypes (Furlani and Clark 1981; Ohki 1987), wheat (Kerridge *et al.* 1971), soybean (Hanson and Kamprath 1979), rice (Sivaguru and Paliwal 1994) and many other temperate legumes (Blamey *et al.* 1990); Edmeades *et al.* 1991; Mackay *et al.* 1991).

Waines and Ehdaie (2010) and Abera (2009) Ethiopian established a high positive correlation between root length and number of nudules under acid stressed conditions in wheat (*Triticum* spp.) and barley (*Hordeum vulgare* L.), respectively. This suggests that root length and number of nodules could be useful tools for testing genotype tolerance to soil acidity. The ability of plants to produce roots profusely and produce higher number of nodules under acid soil conditions (pH < 5.5) could be used as a tool to identify high-acid tolerance in soybean genotypes. These results are important because genotypes that grew vigorously in acid stressed conditions or have larger root systems would have greater mining power for nutrients and this could translate to higher yield in acid soils. Large root systems are known to have a greater capacity for absorbing water and minerals, as they are able to explore a larger rhizosphere (Lynch 1995; Osmont *et al*. 2007), resulting to to higher seed yield. However, genotypes with low root vigor at soil pH < 5.5 would be less able to explore the soil, possess a consequently smaller area for absorbing water and minerals, a smaller capacity for growth, and increased sensitivity to acid soils. The higher root growth and yield at low pH levels were due to higher essential mineral uptake. Therefore, the ability of soybean genotypes to perform well under acid stressed conditions could be effectively utilized as a parameter for selecting acid tolerance soybean genotypes which can be utilized in future breeding programmes.

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