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Full Length Research Paper

Effects of lime, phosphorus and rhizobia on *Sesbania sesban* performance in a Western Kenyan acid soil

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Aluminium (Al) toxicity, phosphorus (P) deficiency and low rhizobia populations limit *Sesbania* (*Sesbania sesban*) performance in tropical acid soils. The study determined the i) indigenous rhizobia populations that nodulate sesbania and ii) effects of lime (0 and 4 t/ha), P-fertilizer (0 and 60 kg/ha) and acid tolerant rhizobia (0 and inoculation) on soil and selected sesbania accessions performance in Western Kenya acid soil. Study site had acid soil, low available P, nitrogen (N) and rhizobia populations that nodulate *Sesbania* (146 cells/g soil). Lime increased soil pH, while both lime and P-fertilizer increased available P. Aluminium toxicity tolerant and P-efficient accessions (SSBSA004, SSUG3, SSUG4 and SSUG5) had faster growth, higher nodulation, shoot P, and shoot N and response to treatments than the sensitive one (SSBSA203). After 7 months of growth, SSUG3 had highest shoot length (306 cm) and dry matter (5.64 tons/ha), hence, most suitable for building poles and fuel wood. SSUG5 accumulated the highest shoot N (222 kg N/ha) and was therefore, most suitable soil N replenishment. Thus, in acid P deficient and low rhizobial population soils of Western Kenya, the use of lime, P-fertilizer, rhizobia inoculation and Al toxicity tolerant *Sesbania* are important for *Sesbania* establishment and growth.

Key words: *Rhizobia, Sesbania*, soil acidity, aluminum toxicity, lime, phosphorus.

INTRODUCTION

Sesbania [*Sesbania sesban* (L) *Merr*] is an important multipurpose tree legume that provides fuel wood, fodder for livestock and nitrogen (N)-rich biomass suitable for soil fertility replenishment. It is recommended for planting by smallholder farmers in the tropical regions of Eastern and Southern Africa, to correct soil N deficiency (Makatiani and Odee, 2007). In regions where farmers plant it, acid soils occupy 29 and 13% of the total land area in sub-Saharan Africa (SSA) and Kenya, respectively (Eswaran et al., 1997). In Kenya, most acid soils are found in the highlands East of Rift valley and Western Kenya regions (Kanyanjua et al., 2002). High soil acidity is associated with aluminum (Al), hydrogen (H), iron (Fe) and manganese (Mn) toxicities to plants in the soil solution and corresponding deficiencies of the available phosphorus (P), molybdenum (Mo), calcium (Ca), magnesium (Mg) and potassium (K) (Giller and Wilson, 1991; Jorge and Arrunda, 1997).

Soil acidity limits the growth of tree legumes and functioning of N_2-fixing symbiotic bacteria in tropical lands since both the host tree legume and rhizobia are sensitive to soil acidity (Howieson and Ewing, 1986). In many tropical acid soils, Al toxicity, poor nodulation and P deficiency are some of the major hindrances to the establishment and growth of agroforestry tree legumes (Almeida et al*.,* 1981; Gudu et al., 2009; Kisinyo et al., 2005*).* High Al inhibits root development which reduces water and mineral uptake

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that consequently leads the overall poor plant growth (Kochian, 1995; Ligeyo and Gudu, 2005). In Sesbania, Al toxicity reduces root growth, P uptake and total biomass accumulation (Gudu et al., 2009). Aluminium toxicity also adversely affects the survival of rhizobial symbionts through denaturation of their DNA (Johnson and Wood, 1990). In legumes, P deficiency reduces both the growth and N_2- fixation capacity (Sanginga et al., 1995). Low P levels in acid soils limits rhizobial population growth to only 50% and slows down the growth rate of some strains (Keyser and Munns, 1979).

Plant growth in acid soils with high Al and low P can be improved by the use of plant germplasm tolerant to Al toxicity (Viterello et al., 2005) and/or soil amendment through the use of inorganic fertilizers, manures and lime (Baligar et al., 1997). A number of Al toxicity tolerant and P efficient Sesbania and Calliandra (*Calliandra calothyrsus*) accessions growing in the Eastern Africa region acid soils have been identified (Gudu and Odago, 2003; Gudu et al., 2009). To enhance the growth and N_2 fixation of these agroforestry tree legumes in this region, compatible indigenous acid-tolerant rhizobial strains in these soils have also been identified (Muok, 1997). In addition to the use of Al toxicity tolerant and P efficient legume germplasm and/or rhizobial strains, use of lime is important for correction of soil acidity constraints so as to enhance the production of N- rich biomass in acid soils such as found in Kenya. The direct effect of lime is the increase in soil pH, Ca^{2+} and/or Mg^{2+} ions (The et al., 2006). The Ca^{2+} and/or Mg^{2+} ions contained in lime displaces H^+, Fe^{3+} Mn^{4+} and Al^{3+} ions form the negatively charged soil colloids, thus, decreasing their concentrations in the soil solution. Therefore, the increased soil available P in acid soils due to lime application is because of decrease in P sorption due to on the reduction of Fe^{3+} and Al^{3+} ions in the soil solution (Tisdale et al., 1990; van Straaten, 2002). Unfortunately, farmers in the region rarely use lime, P fertilizer, rhizobia or improved germplasm to increase the growth and N_2 fixation of tree legumes.

The study, therefore addressed soil acidity related problems through the use of lime, P fertilizer, rhizobia inoculation and acid tolerant sesbania accession to increase sesbania growth in acid soils. The study determined; i) indigenous rhizobial populations that nodulate sesbania and ii) the effects of lime, P fertilizer and acid -tolerant rhizobia on soil and the performance of selected sesbania accessions in a Western Kenya acid soil.

MATERIALS AND METHODS

Site description and soil sampling for characterization

The study was carried out in a Western Kenya acid soil, specifically at Bumala (00°01' N and 29° 93' E). Bumala is about 1430 m above the sea level. It has annual average rainfall of 900 to 2000 mm and mean annual temperature of 20.5 to 22.7°C (Jaetzold and Schmidt, 1983). Nine sub-soil samples were taken with a soil auger in a zig-zag manner from the surface 0 to 15 cm depth which, were thoroughly mixed to make a composite sample from which about 0.5 kg sample was packed in a polythene bag, labeled and taken to the laboratory for analysis. It was air-dried, passed through a 2 mm sieve and analyzed for pH, organic carbon (% C), total N (% N), available P, exchangeable bases and Al according to procedures described by Okalebo et al. (2002). At the same time, a large surface soil sample was taken as a composite from randomly sampled cores, in a 90 kg nylon bag for the greenhouse study.

Seed source and pre-treatment

Four Al toxicity tolerant and P-efficient sesbania accessions (SSBSA004, SSUG3, SSBSA004, SSUG3, SSUG4 and SSUG5) and one Al sensitive. (SSBSA203) accession were obtained from Chepkoilel University College, Kenya. Seeds were surfacesterilized in 3.5% calcium hypochlorite solutions by immersion for 6 min and rinsed three times in sterile distilled water. To enhance fast germination, seeds were then soaked in water at 90°C for 12 h to soften the seed coat andincubated at 27°C for 60 h on moist paper towels in trays.

Experiment 1: Determination of indigenous rhizobial populations at the study site

Most Probable Number (MPN) technique was used for rhizobial population determination (Woomer, 1994). Soil samples were taken from the study site as already described earlier and about 1.0 kg composite sample packed into a clean polythene bag was transported to the laboratory in ice-chest box and refrigerated at a temperature of 4°C (Wollum, 1994). Soil moisture content was determined by oven drying a sub-sample at 105°C to a constant weight. Soil sample of 100 g dry weight was put into a 1.0 L wide-neck Erlenmeyer flask containing 400 ml sterile N mineral diluents fitted with a stopper to make 1: 5 (soil: water) dilution. The flask content was then mixed using a wrist action shaker for 20 to 25 min to form initial dilution (Woomer, 1994). The initial dilution was further diluted to bring the anticipated MPN with the range of the six-step dilution assay. A 5.0 ml of the initial dilution was transferred into a sterile test tube containing 20 ml diluents to make $1:5^2$ dilution, ensuring that the soil does not settle at the bottom before the aliquot is drawn. The dilution was continued up to a series of $1:5^6$ (soil:water).

Seeds were pre-germinated as already described. Seedlings with good root development were aseptically transferred with sterile forceps to plastic growth pouches, making sure that the radical passes through the hole made in the upper section of the wick. They were inoculated when 6 days old with 1.0 ml of each dilution and replicated 4 times. About 50 ml of N-free nutrient solution was added into each growth pouch for watering the plants. Positive and negative controls consisting of pure culture of acid - tolerant rhizobial strain ASs48 and no inoculation, respectively, were included. Strain ASs48 was obtained from Kenya Forestry Research Instititue Headquarters, Nairobi, Kenya. The positive control confirms that growth conditions are appropriate for nodule development, while the negative, confirms lack of contamination. The plants were grown in a greenhouse for a further 14 days after the nodules first appeared as described by Weaver and Graham (1994). The presence or absence of nodules was recorded and the rhizobial population per gram of soil determined according to procedures described by Woomer (1994).

Experiment 2: Effects of lime, P fertilizer and rhizobia on soil and the performance of *Sesbania* seedlings ina greenhouse

The experiment was laid out in a $2^3 \times 5$ factorial in a Complete

Randomized Design (CRD), replicated 3 times to determine the effect of lime (0 and 4 tons lime/ha as calcium oxide (CaO), P (0 and 60 kg P/ha as triple supper phosphate (TSP)) and rhizobia (0 and inoculation) on the soil, nodulation and growth of sesbania accessions (SSBSA203, SSBSA004, SSUG3, SSUG4 and SSUG5). Liming material containing 21% CaO was obtained from Homa Lime Co. Ltd and TSP from MEA Co. Ltd. Soil samples in the 90 kg bag were air-dried, ground and passed through a 5 mm sieve. A 2.0 kg soil was weighed and thoroughly mixed with 0.357 g lime (~ 4 tons lime/ha) prior to filling to the polythene bags. The bags were incubated for 30 days at approximately field water holding capacity to allow for lime to react with the soil in a greenhouse at the Chepkoilel University College, Kenya. After 30 days, the soils were air-dried and all the appropriate bags for P treatment had their soils thoroughly mixed with P fertilizer 0.054 g (~ 60 kg P/ha) and watered to field capacity prior to planting. Seeds of each accession were pre-germinated as described earlier. During planting, appropriate seedlings for rhizobia treatment had their root collars inoculated with 10^9 cells/ml of acid-tolerant rhizobial strain ASs48 as already described earlier. Seedlings were grown in the greenhouse for 8 weeks at average temperatures and relative humidity in the range of 30 to 38℃ and 50 to 75%, r espectively. The test accessions were watered to field capacity throughout the growing period.

During harvesting, shoots from each treatment were cut at the root collar and chopped into about 2 to 5 cm pieces. Roots were placed on a sieve and carefully washed under a gentle stream of tap water. Nodules were detached from the roots, their number recorded and checked for N_2 fixation effectiveness by splitting open samples from each plant. Red-pink colours (the presence of leghaemoglobin) indicated effective nodulation while whitish or greenish ones indicated ineffective nodulation. Both the shoots and roots were oven dried at 70℃ for 48 h and their dry weight recorded. Shoot P and N contents were analyzed according to the procedures described by Okalebo et al. (2002).

Experiment 3: Effects of lime, P fertilizer and rhizobia on soil and the performance of *Sesbania* plants in Bumala

The experiment was a $2^3 \times 5$ factorial in Randomized Complete Block Design (RCBD), replicated 3 times to determine the effects of lime (0 and 4 tons lime/ha), P- fertilizer (0 and 60 kg P/ha) and rhizobia (0 and inoculation) on soil, shoot nutrients and the growth of sesbania accessions (SSBSA203, SSBSA004, SSUG3, SSUG4 and SSUG5). A 4 cm diameter and 10 cm length polythene bags were used. Lime and P fertilizer were applied to the appropriate bags as already described. Seeds were pre-germinated as already described and two seedlings planted per bag. Seedlings earmarked for inoculation had their roots inoculated with rhizobial strain ASs48 as already described and grown in greenhouse for 30 days as described earlier in experiment 2. The experimental site at Bumala was ploughed, harrowedand plots 4 by 3 m demarcated. The plots were treated with lime (0 or 4 t/ha) and P (0 or 60 kg P/ha). Lime was applied 30 days before transplanting and P fertilizer during transplanting by broadcast and thoroughly mixing each of them with the soil. Seedlings were transplanted ata spacing of 0.75 within and 1.0 m between rows and guard rows between plots were maintained at 1.5 m apart. The seedlings were thinned to one per hill after a week and allowed to grow for 7 months after which their heights were measured and the shoots cut at ground level, leaving out guard row and plants at the end of each row to avoid edge effects. The shoots were cut into about 5 cm pieces as described previously. Shoot P and N contentswere analyzed according to procedures described by Okalebo et al. (2002).

Statistical analysis

The generated data were subjected to analysis of variance (ANOVA) with the general linear model (GLM) using General Statistics (GenStat, 2010). The standard error of difference between means (SED) was used to compare the treatment means. Relationships between shoot P content and shoot N, shoot P and shoot biomass and shoot N and shoot biomass were determined using regression coefficients.

RESULTS

Soil chemical characteristics and indigenous rhizobial populations of the study site

Table 1 shows soil chemical characteristics of the sample taken prior to treatment applications. The soil was strongly acid and had high Al level. It was deficient in available P and low in N, while the organic carbon was moderate. The soil rhizobial populations that nodulate sesbania was low (146 cells/g soil).

Experiment 2: Effects of lime, P fertilizer and rhizobia on the soil and performance of *Sesbania* seedlings in a greenhouse

Table 2 shows the effects of lime and P fertilizer on soil pH after 8 weeks of seedling growth in a greenhouse. Lime had positive significant ($p \le 0.001$) effect on soil pH. Table 3 shows the effects of lime and P fertilizer on available P after 8 weeks of seedling growth in a greenhouse. Both treatments had positive significant ($p \le 0.001$) effects on soil available P. Treatments effectiveness on soil available P increment followed the general increasing order of control → lime → P fertilizer →lime + P fertilizer. Thus, combined application of both lime and P fertilizer is important for sesbania seedlings establishment in P deficient acid soils such as reported in this study.

Figure 1 shows the effects of lime, P fertilizer and rhizobia inoculation on sesbania seedlings growth, nodulation, and shoot N and P contents after 8 weeks of seedlings growth in a greenhouse. All the treatments had positive significant ($p \le 0.001$) effects on seedlings growth, nodulation, shoot N and P contents. Treatments effectiveness on increasing seedlings growth, shoot P and N contents followed the general increasing order of control → rhizobia → lime → lime + rhizobia → P fertilizer → P fertilizer + rhizobia →lime + P fertilizer → lime + P fertilizer + rhizobia. Thus, combined use of lime, P fertilizer and rhizobial inoculation is important for sesbania seedlings establishment in acid, P deficient and low rhizobial population soils such as reported in this study.

Figure 2 shows the differences in growth, shoot N and P contents of sesbania accessions after 8 weeks of seedling growth in a greenhouse. There were no significant differences on seedling dry matter increase and nodulation (Figure 2a and b). Al toxicity tolerant and P efficient accessions had higher total dry matter,

Table 1. Soil chemical characteristics of the study site.

Soil pH (1: 2.5; soil: H_2O)	P‡ (mg P/kg)	% C	% N	Exchangeable cations (cmol/kg)					% Al
				K	Mg	Ca	Al	ECEC	
4.90 ± 0.03	5.42 ± 0.06	1.56 ± 0.02	0.13 ± 0.02	0.44 ± 0.01	1.62 ± 0.05	3.23 ±0.01	2.03 ± 0.02	7.32 ±0 .05	27.7 ± 0.39

‡ = bicarbonate extractable P.

Table 2. Effects of lime and P fertilizer on soil pH (1: 2.5; soil: H_2O) after 8 weeks of *Sesbania* seedlings growth in a greenhouse.

Rates of lime (t/ha)	Rates of P fertilizer (kg P/ha)		
	0	60	Mean
0	4.98 ± 0.14	5.05 ± 0.07	5.02^b
4	5.67 ± 0.05	5.53 ± 0.03	5.60^a
Mean	5.33^a	5.29^a	
SED lime		***	
SED P fertilizer		ns	
SED lime × P fertilizer		*	

* = significant, **** = very highly significant and ns = not significant.

nodulation, shoot P and N contents of 0.16 to 0.50 gm, 1 to 3 nodules, 0.8 to 1.4 mg P and 15 to 24 mg N per seedling compared to Al toxicity sensitive one. However, there were significant differences on shoot N and P contents among the accessions (Figure 2c and d).

Experiment 3: Effects of lime, P fertilizer and rhizobia on the performance of *Sesbania* in Bumala soil

Table 4 shows the effects of lime and P fertilizer on soil pH after 7 months of *Sesbania* growth at Bumala. Lime had positive significant ($p \leq 0.001$) effect on soil pH, while the effect of P fertilizer was negative and insignificant. Table 5 shows the effects of lime and P fertilizer on soil.

Both treatments had positive significant ($p \leq 0.001$) effects on soil available P. The mean soil available P increments were 92 and 209% due to lime and P fertilizer applications, respectively. It is on plots where both lime and P fertilizer were applied that soil available P was still above the critical value (10 mg P/kg bicarbonate extractable P) necessary for healthy plant growth, 7 months after treatment applications. Therefore, both lime and P fertilizer applications are important for high soil available P in acid and P deficient soils, necessary for healthy *Sesbania* growth.

Figure 3 shows the effects of lime, P fertilizer and rhizobia inoculation on sesbania plants growth, shoot N and P contents after 7 months of growth in Bumala soil. All the treatments had positive significant ($p \leq 0.001$) effects on plant growth, shoot P and N contents. After 7 months of growth, lime alone increased sesbania plants shoot length, dry matter, and P and N contents by 18, 36, 36 and 73%, respectively as compared to the control. P fertilizer alone increased sesbania plants shoot length, dry matter, and P and N contents by 26, 94, 69 and 182%, respectively compared to control. Rhizobial inoculation alone increased *Sesbania* plants shoot length, dry matter, and P and N contents by 11, 26, 5 and 36%, respectively as compared to control. Thus, treatments effectiveness on increasing plants growth, shoot P and N contents followed the general increasing order of control→ rhizobia → lime → lime + rhizobia → P fertilizer → P fertilizer+ rhizobia →lime + P fertilizer → lime+ P

Table 3. Effects of lime and P fertilizer on soil available P after 8 weeks of *Sesbania* seedlings growth in a greenhouse.

Rates of lime (t/ha)	Rates of P fertilizer (kg P/ha)		
	0	60	Mean
0	5.60 ± 0.03	14.85 ± 0.69	10.23[b]
4	8.77 ± 0.58	30.57 ± 1.34	19.67[a]
Mean	7.19[a]	22.71[b]	
SED lime		***	
SED P fertilizer		***	
SED lime × P fertilizer		***	

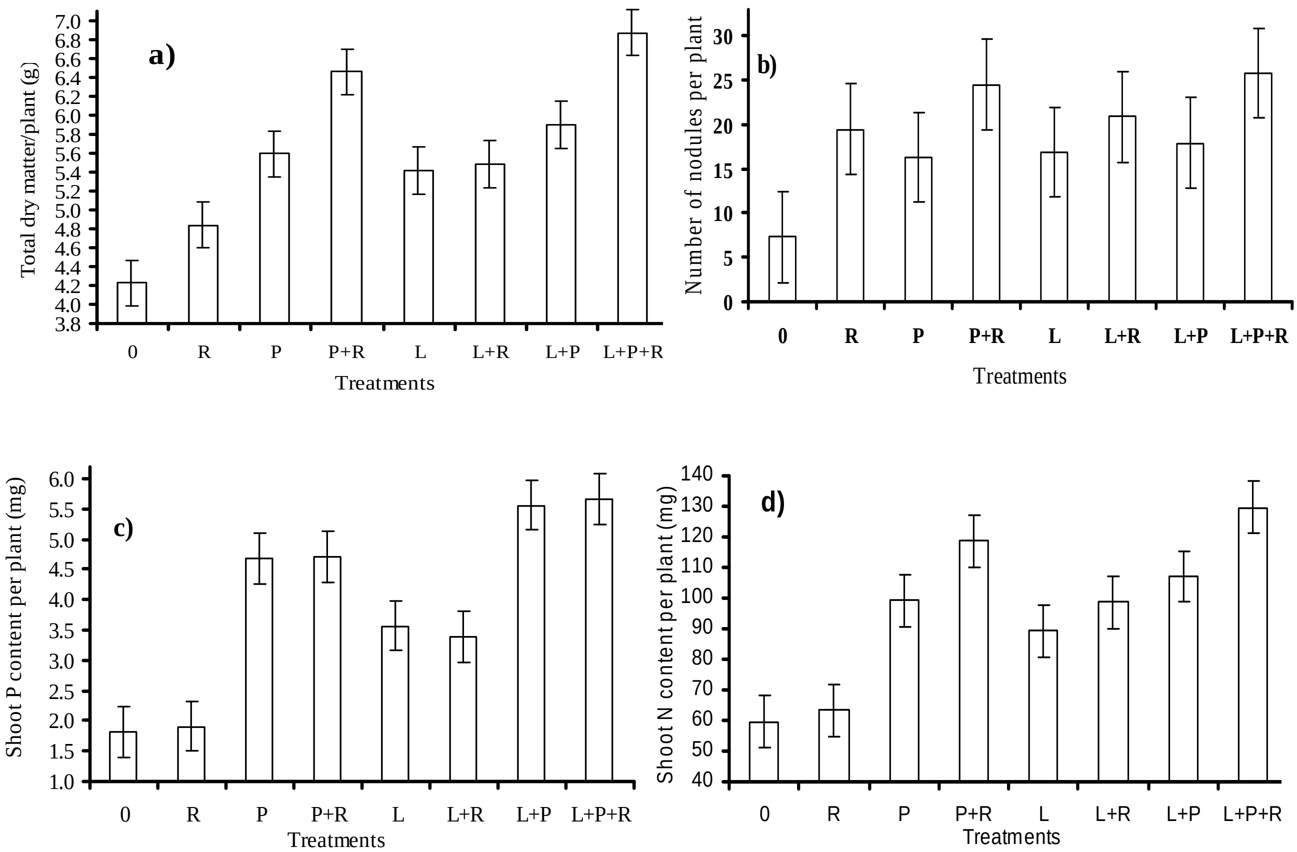

Figure 1. Effects of lime, P and rhizobia on sesbania seedlings growth, nodulation and nutrient contents after 8 weeks of growth in a greenhouse; a) total dry weight, b) number of nodules, c) shoot P content, and d) shoot N content, 0 = Control, L = 4 tons lime/ha, P = 60 kg P/ha and R = rhizobial inoculation; Error bars indicate SED ($_{0.001}$).

fertilizer + rhizobia. Thus, combined application of lime, P and rhizobial is important for sesbania growth in acid, P deficient and low rhizobial population soils such as Bumala.

Figure 4 shows the differences in growth, shoot N and P contents of sesbania accessions after 7 months growth in Bumala. Aluminium toxicity tolerant and P efficient accessions had higher shoot length, dry matter, P and N contents in the range of 22 to 45 cm, 1.3 to 2.0 t/ha, 3.4 to 5.4 kg P/ha and 66 to 113 kg N/ha, respectively compared to Al sensitive one. Accession SSUG3 had the highest shoot length and dry matter of 306 cm and 5.64 t/ha, respectively, thereby, making it most suitable for use as building poles and fuel wood by farmers (Figure 4a and b). Accession SSUG5 had the highest shoot N accumulation of 222 kg N/ha and will therefore, be most suitable for N rich biomass transfer for soil N replenishment (Figure 4d). Accessions SSUG3 and SSUG5 had shoot P contents of about 10.8 and 10.1 kg P/ha, respectively making both of them suitable for P rich

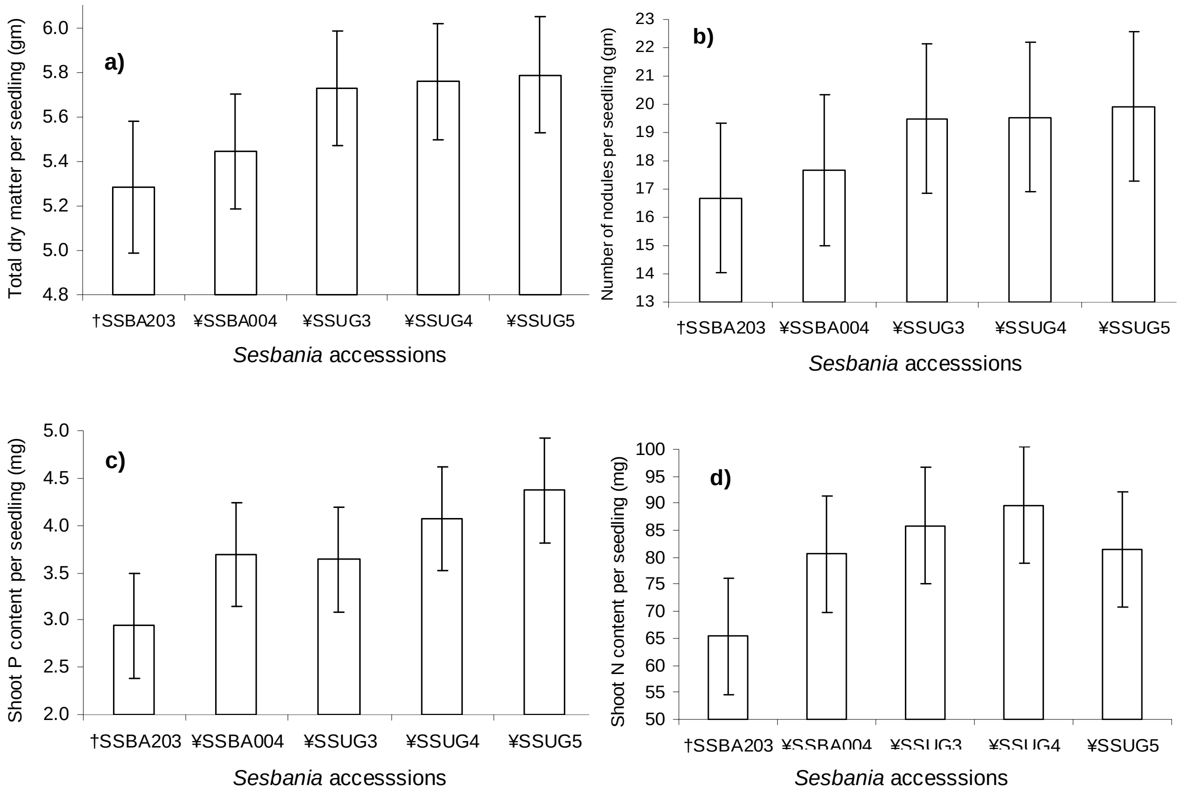

Figure 2. Sesbania accessions shoot growth and nutrient contents after 8 weeks of growth in a greenhouse; a) total biomass($p \leq 0.034$), b) nodulation($p \leq 0.05$), c) shoot P content($p \leq 0.01$), and d) shoot N content ($p \leq 0.212$), † = Al sensitive, ¥ = Al toxicity tolerant and P efficient; error bars indicate SED.

Table 4. Effects of lime and P fertilizer on soil pH (1:2.5; soil: water) after 7 months after *Sesbania* growth in Bumala.

Rates of lime (tons/ha)	Rates of P fertilizer (kg P/ha)		
	0	**60**	**Mean**
0	4.66 ± 0.04	4.63 ± 0.02	4.65[b]
4	5.46 ± 0.05	5.34 ± 0.02	5.40[a]
Mean	5.06[a]	4.99[a]	
SED lime		***	
SED P fertilizer		ns	
SED lime × P fertilizer		ns	

Table 5. Effects of lime and P fertilizer on soil available P after 7 months of *Sesbania* growth in Bumala.

Rates of lime (t/ha)	Rates of P fertilizer (kg P/ha)		
	0	**60**	**Mean**
0	4.87 ± 0.12	7.63 ± 0.25	6.25[b]
4	6.16 ± 0.39	12.27 ± 1.04	9.22[a]
Mean	5.52[a]	9.95[b]	
SED lime		****	
SED P fertilizer		****	
SED lime × P fertilizer		****	

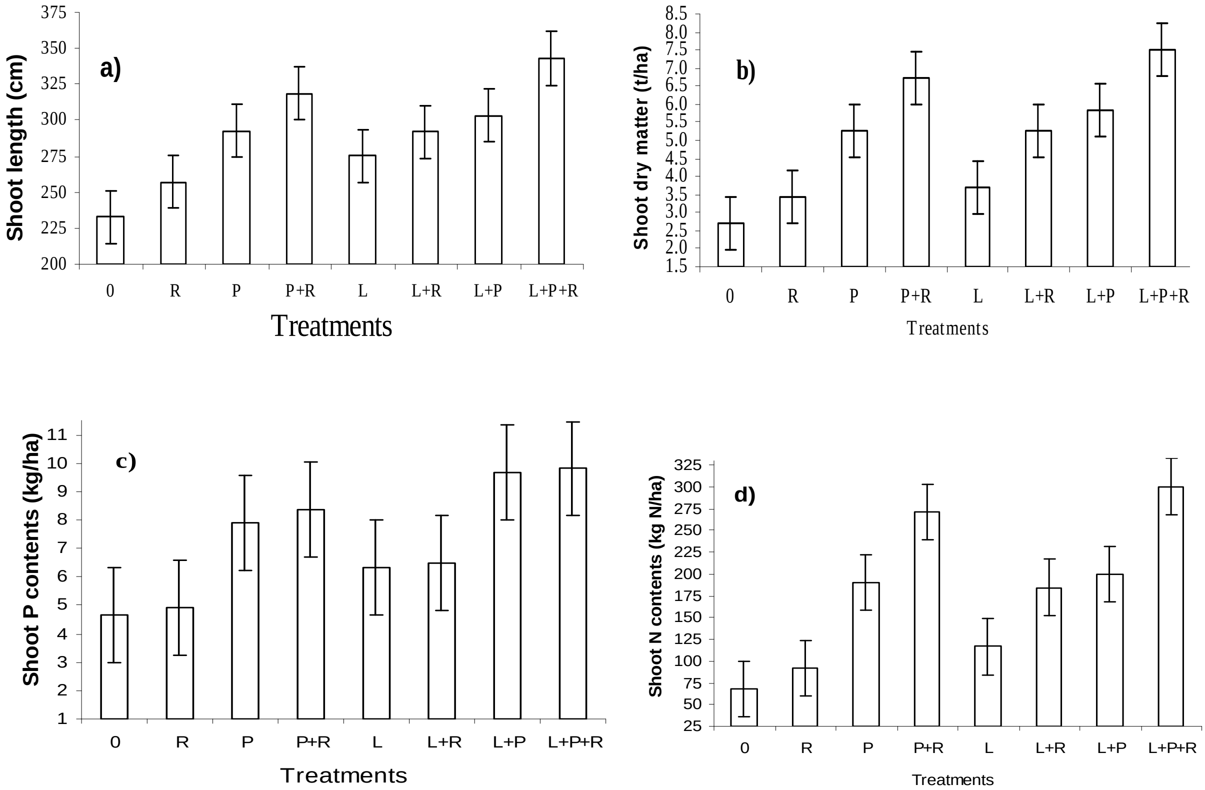

Figure 3. Effects of lime, P and rhizobia on *Sesbania* growth and nutrient contents after 7 months of growth in Bumala; 0 = control, L = 4 tons lime/ha, P = 60 kg P/ha and R = rhizobial inoculation; error bars indicate SED ($_{0.001}$).

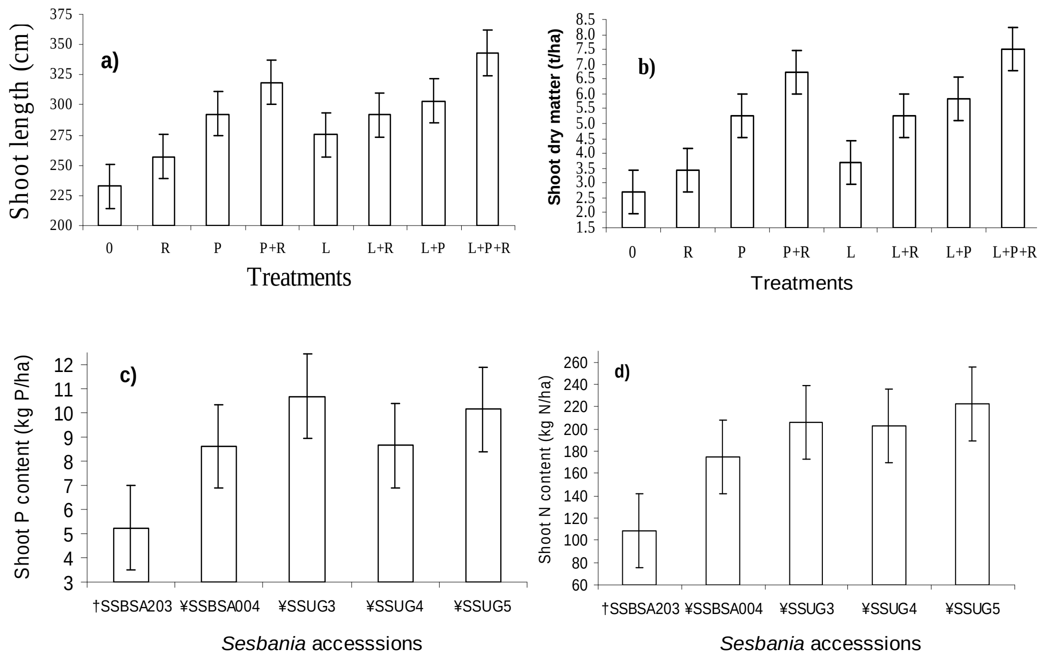

Figure 4. Sesbania accessions shoot growth and nutrient contents after 7 months of growth in Bumala;a) shoot length ($p \leq 0.064$) b), shoot biomass($p \leq 0.021$), c) shoot P content ($p \leq 0.024$)and d) shoot N content ($p \leq 0.008$), † = Al toxicity sensitive and ¥ = Al toxicity tolerant and P efficient; error bars indicate SED.

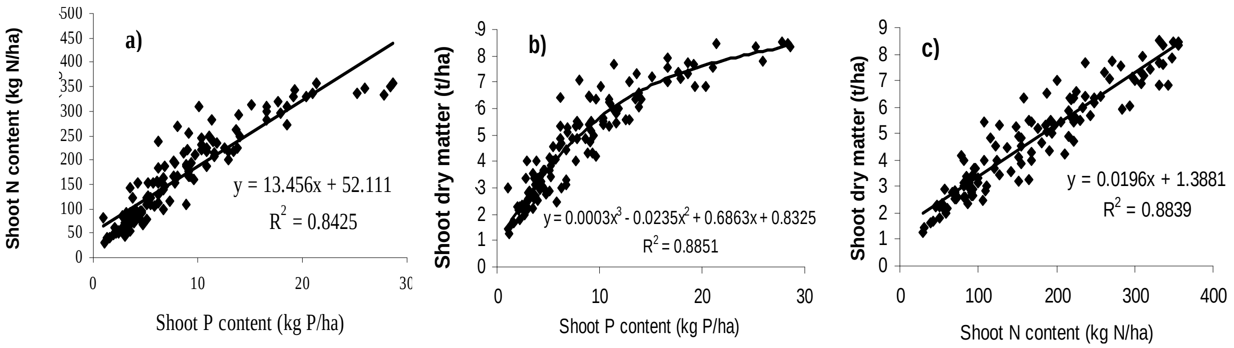

Figure 5. Regression coefficients betweens; a) total shoot P and N contents, b) shoot P and biomass and c) shoot N and shoot biomass after 7 months of growth in Bumala soil.

biomass transfer for soil P replenishment in P deficient soils such as these (Figure 4c) . There were high correlations between shoot P and shoot N (r = 0.920), shoot P and shoot biomass (r = 0.941) and also shoot N and shoot biomass (r = 0.940) (Figure 5a, b and c).

DISCUSSION

The soil was strongly acid since pH between 4.5 and 5.0 was regarded as strongly acidic according to Kanyanjua et al. (2002). It had high levels of Al since levels > 2.0 cmol/kg such as reported in this study are regarded as toxic for most plants (Landon, 1984). Exchangeable base cations and ECEC were both low since Ca < 4.0, K < 0.6 and CEC < 15 cmol/kg soil are considered low according to Landon (1984). The soil had low available P since < 10 mg/kg bicarbonate extractable P is considered inadequate for healthy plant growth according to Olsen et al. (1954). Acid soils with high Al^{3+} ions, low base cations and CEC are characteristics of highly weathered soils, which have lost most of the base cations due to high rainfall, are common in Kenya and other tropical areas. As a result, they have high levels of Fe and Al sesquioxides that lead to high P fixation resulting to low available P such as reported in this study of Buresh et al. (1997), Jaetzold and Schmidt (1983), Kanyanjua et al. (2002), Landon (1991), van Straaten (2002) and Sanchez et al. (1997). In the humid/sub-humid tropics, leaching of base cations by high rainfall and parent materials of acid origin are mainly responsible for soil acidification (van Straaten, 2002).

Soil organic carbon and total N were low since organic C < 4.0% and total N < 0.2% are regarded as low (Landon, 1991). Nitrogen is the most limiting nutrient to plant production in mainly SSA soils (Bekunda et al., 1997), Kenya included. Most soil N is derived from organic matter mineralization. Low organic carbon and total N in Western Kenya soils is due to high temperatures and soil moisture availability that favour rapid organic matter decomposition (Jaetzold and Schmidt, 1983). Acid soils with pH < 5.5, commonly found in Western Kenya have high levels of Al^{3+} ions toxic to plants (Sale and Mokwunye, 1993). High Al such as reported in this study generally reduced sesbania root growth, P uptake and biomass accumulation by 75, 88 and 83%, respectively (Gudu et al., 2009). It also adversely affected the survival of rhizobia in acid soils, thus, reducing their populations (Johnson and Wood, 1990). Therefore, the low rhizobial populations in this soil could be partly due to Al toxicity. Normally, indigenous rhizobia populations below 10^3 cells per g soil are regarded as inadequate for effective nodulation and healthy legume growth (Mulongoy and Ayanaba, 1986). Thus, soil acidity, P deficiency, low N and rhizobial populations make Bumala soil unable to sustain healthy sesbania establishment and growth.

Lime application increased soil pH and available P, while P fertilizer decreased soil pH and increased available P. This was because Ca^{2+} ions contained in lime displaced the H^+, Mn^{4+}, Fe^{3+} and Al^{3+} ions from the soil adsorption sites resulting into increase in soil pH. Therefore, the increase in soil available P was because of reduction in P fixation by Al and Fe oxides due to the effect of lime (Kamprath, 1984; van Straaten, 2002). P fertilizer increased soil available P due to its effect on increasing solution P while the decrease in soil pH was due to the release of H^+ ions during its dissolution (Tisdale et al., 1990). Reduction in nutrient toxicities and corresponding increase in nutrient availabilities as a result of lime creating a conducive environment for sesbania growth, rhizobial growth and activity. Increased nodulation, growth and N_2 fixation due to lime application have been reported in sesbania and other legumes in acid soils (Kisinyo et al., 2005; Kodiango et al., 2007; Rajasree and Filial, 2001; Unkovich et al., 1996). Phosphorus fertilizer increased nodulation and plant growth because P is essential in energy transfer processes in living organisms. Phosphorus is vital for microbial population growth and activity (Keyser and Munns, 1979) and plant metabolic processes essential for growth (Tisdale et al., 1990). Rhizobial inoculation increased nodulation and plant growth because of the low rhizobial population that effectively nodulate sesbania at the study site. Normally, when the indigenous rhizobia population is below 10^3 cells per gm, inoculation is necessary for effective nodulation and healthy legume growth (Mulongoy and Ayanaba, 1986). In low rhizobial population Kenyan soils, inoculation of sesbania with rhizobia have been reported to increase nodulation and growth (Gudu et al., 2009; Makatiani and Odee, 2007; Muok, 1997). A combination of lime, P and rhizobia gave the highest nodulation, growth and nutrient uptake compared to either of them applied alone as was also reported for an Indian acid soil (Rajasree and Filial, 2001).

Aluminum toxicity tolerant and P efficient accessions had faster growth, higher shoot N and P contents than the Al toxicity sensitive one. In a similar study, sesbania accessions tolerant to Al toxicity and P efficient were reported to have faster growth, higher shoot P and shoot N contents than the Al sensitive ones in a Kenyan acid soil (Gudu et al., 2009). The observed differences in nodulation, growth, shoot N and P contents among the Al toxicity tolerant and P use efficient accession is an important selection tool for identifying most suitable one for fuel wood, building poles and N rich biomass for soil N replenishment in acid soils such as in Western Kenya.

There was high correlation between shoot P and N because both nutrients are required for vital processes such as photosynthesis and protein synthesis in plants among others (Tisdale et al., 1990). The high correlation between shoot P content and shoot biomass accumulation is because P is essential for energy transfer processes in plants. Phosphorus deficiency limits photosynthesis which leads to reduction in biomass accumulation (Neil, 1991). Such high correlation between shoot P and biomass have been reported among sesbania seedlings in a Kenyan acid soil (Gudu et al., 2009). The high correlation between shoot N and biomass is because N is essential for vegetative growth in plants (Tisdale et al., 1990).

Conclusions

Soil acidity, P deficiency, low N and indigenous rhizobial population limits sesbania establishment and growth in acid soils. Therefore, use of lime, P fertilizer, acid-tolerant rhizobial strains and Al toxicity tolerant which are P efficient sesbania accessions are important for healthy seedlings establishment and growth in acid soils. Differences among Al toxicity tolerant sesbania accessions which are P efficient can be used to select most suitable accessions for wood fuel, building poles and N-rich biomass for soil N replenishment in acid soils common in Western Kenya. Accession SSUG3 had the highest shoot length and dry matter of about 306 cm and 5.64 t/ha, respectively, and is therefore, most suitable for building poles and fuel wood for farmers. Accession SSUG5 had the highest shoot N accumulation of 222 kg N/ha and would therefore be most suitable for N rich biomass transfer for soil N replenishment. Therefore, in P deficient acid soils, use of lime, P fertilizer, rhizobia and also Al toxicity tolerant and P efficient sesbania accessions are important for healthy establishment and growth of sesbania in cid soils such as found in Western Kenya.

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