Growth and Dry Matter Partitioning of Common bean (*Phaseolus vulgaris* L.) Genotypes as Influenced by Aluminum Toxicity

Hirpa Legesse[1*], Robi Nigussie-Dechassa[2], Setegn Gebeyehu[3], Geremew Bultosa[4], Firew Mekbib[5]

[1]*Wollega University, Department of Plant Science, P. O. Box 395, Nekemte, Ethiopia*

[2] *Haramaya University, Department of Plant Sciences, P. O .Box 138, Dire Dawa, Ethiopia*

[3] *Oxfam OA HARO, P.O. Box- 25779, Addis Ababa, Ethiopia*

[4]*Department of Food Science and Technology, Botswana College of Agriculture, GABORONE, Botswana*

[5]*Haramaya University, Department of Plant Sciences, P. O .Box 138, Dire Dawa, Ethiopia*

ABSTRACT

Aims: This study was conducted to assess effects of different exchangeable aluminium concentrations on growth and dry matter partitioning of two common bean genotypes (new BILFA 58 and Roba 1) grown on lime-treated and lime-untreated acid soils.
Study Design: Factorial combinations of five rates of aluminium (0.0, 12.5, 25.0, 50.0, and 100.0 mg Al kg^{-1} soil) and two genotypes were laid out in a completely randomized design of three replications.
Place and Duration of Study: The experiment was conducted in the vegetation hall of Nekemte Soil Laboratory, western Ethiopia from July to October, 2011.
Methodology: For each treatment, four plants were raised per pot, data related to growth and dry matter partitioning of the crop were collected at 25 and 35 days after seedling emergence (DAE).
Results: Aluminium rate and genotype interaction had significantly (*P=0.01*) affected all parameters considered except relative growth rate and shoot to root weight ratio for lime-untreated soil, and specific leaf area, leaf fraction and leaf area for lime-treated soil. A significant growth reduction was found on lime-untreated soil than treated soil, particularly as aluminium applied increased. On average, application of aluminium led to 37.5, 32.9, and 35.7% reduction in absolute and relative growths, and net assimilation rates. The differences due to aluminium rate and genotype were also significant for dry matter partitioning and root to shoot ratio. On both lime-treated and untreated soils, dry matter partitioning to root was higher for new BILFA 58 than for Roba 1 at 25 and 35 DAE.
Conclusions: Application of aluminium had a significant adverse effect and decreased the growth of two genotypes under both lime-treated and untreated soils. However, growth reductions were lower on lime-treated soil than untreated soil and genotype new BILFA 58 had performed better than Roba 1 under increased soil acidity and aluminium concentration.

Key words: Aluminum toxicity, Dry matter partitioning, Genotype, Growth parameters, Lime

1. INTRODUCTION

It is estimated that over 50% of the world's potentially arable land is acidic with pH of less than 5.5 [1]. The tropics and subtropics account for 60% of the acid soils in the world. In tropical areas, about 43% of soils are acidic comprising about 68% in tropical America, 38% in tropical Asia, and 27% in tropical Africa. The factors that contribute to acid soil infertility and subsequent stunted plant growth are complex [2]. In several countries of tropical Africa, the problems caused by soil acidity and Al toxicity are severe. In response to the increasing population pressure, more acid soils are rapidly being brought into cultivation [3]. Aluminum phytotoxicity is the primary limitation to agricultural production on acid soils [4]. Aluminum toxicity is recognized as a major constraint to crop productivity in acidic soils [5]. It limits plant growth and development, and the subsequent performance of economically important crops in various parts of the world [6]. Aluminum inhibits absorption of nutrients by plant roots, especially Ca, Mg, Fe and Mo. It also limits availability of P in the soil [7] in addition to promoting Mn and H^+ toxicity [6]. The toxic effects of aluminum in the soil can be overcome through appropriate soil amendment measures such as application of lime [8]. However, to be effective, the application of lime must be repeated over seasons. In addition, most smallholder farmers growing the crop in the tropics and subtropics cannot afford to apply lime which is costly and labor-intensive [9]

Common bean is considered an aluminum and drought-sensitive crop [10]. A range of environmental factors such as low availability of nitrogen (N) and phosphorus (P) in the soil, and acid soil conditions are important factors that constrain common bean production in most areas where the crop is grown [11]. Patterns of dry matter diversion and root plasticity are considered important features influencing the ability of grain legume crops to cope with soil acidity. Growth analysis techniques have made substantial contributions to the current understanding of the physiological basis of yield differences in crops. Leaf area index [LAI], specific leaf area (SLA), leaf area ratio (LAR), net assimilation rate (NAR), absolute growth rate (AGR), relative growth rate (RGR), and indices of dry matter partitioning are some of the parameters which are often used to compare growth of plants of different species or cultivars of the same species when grown across a range of environmental conditions [12].

Developing a strategy to enhance common bean performance on soils with high aluminum levels requires prior understanding of the physiological responses of genotypes with distinct genetic background. Good progress in this field has been made during the last few decades, and competent compilations and critical reviews on several aspects have been published in this field, e.g. by Ma *et al*. [13]; Ryan *et al*. [14], and Barceló and Poschenrieder [15]. Most of the mechanisms studied are related to limited root growth and development or their consequences. Comparatively, less information exists on the effects of Al^{3+} on leaves than on roots (16). In addition, most genetic and physiological studies have focused on the major cereal crops such as wheat, rice and maize [17]. Hence, it is suggested that more attention should be paid to aerial tissues in future studies, which are important in revealing aluminum toxicity and mechanisms of plant tolerance to aluminum stress [18].

A preliminary field screening of common bean genotypes in western Ethiopia has demonstrated the presence of genetic variability among genotypes in tolerating soil aluminum stress. Studying responses of selected genotypes with contrasting tolerance to aluminum toxicity may help in generating information that could be utilized by breeding programs aimed at developing aluminum-tolerant cultivars for areas where aluminum-induced soil acidity remains a key environmental constraint to crop production. The objective of this study was to test the hypothesis that differences exist in growth, dry matter partitioning, and root to shoot weight ratio among common bean genotypes selected for soil acidity tolerance when subjected to different concentrations of soil-applied exchangeable aluminum.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The pot experiment was conducted on the premise of Nekemte soil laboratory. Nekemte is a town located in western Ethiopia at 9^{0} $08^{'}$ N latitude, $36^{0}46^{'}$ E longitude, and at the altitude of 2080 meters above sea level. According to the weather data obtained from the meteorological station of the town, the average annual rainfall of the study site was 1300 mm with 725 mm for the experimental period (July to October) and the monthly mean minimum and maximum temperatures were between 10-15^{o}C and 24 to 28^{o}C (Figure 1). The soil used for the pot experiment has a pH (H_2O) value of 4.45, exchangeable acidity of 4.92 cmol kg^{-1} soil, exchangeable aluminum of 3.1 cmol kg^{-1} soil, and acid saturation of 53.3% before applying the treatments.

2.2. Description of Planting Materials

Preliminary screening experiments were conducted in 2009 and 2010 in the field on a soil having a pH value of 4.45. Common bean genotypes named New BILFA 58 (NB 58) and Roba1 were identified as the most tolerant and sensitive genotypes to soil acidity, respectively. New BILFA 58 is a genotype with type III growth habit having large-sized seed (53 g per 100 seed) whereas Roba 1 is a small-seeded (22 g per 100 seed) commercial cultivar in Ethiopia with type II growth habit [19]

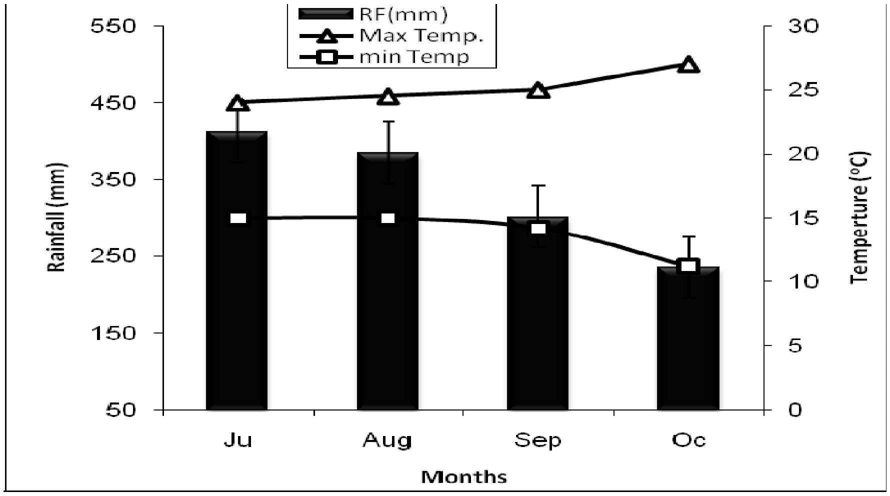

Figure 1. Rainfall distribution and mean minimum and maximum temperatures of the experimental site, during the experimental year of 2011 at Nekemte, Ethiopia

2.3. Treatments and Experimental Design

The treatments consisted of two common bean genotypes (New BILFA 58 and Roba 1) and five rates of aluminum (0.0, 12.5, 25.0, 50.0, and 100.0 mg aluminum kg^{-1} soil). The experiment was laid out as a completely randomized design with three replications per treatment. The different rates of aluminum were applied in the form of $Al_2(SO_4)_3$. The experiment consisted of two sets with similar procedures. The first set consisted of common bean plants grown on lime-treated acid soil, whereas the second set comprised common bean plants grown on lime-untreated acid soil.

2.4. Experimental Procedure

Seeds of the two common bean genotypes were sown in pots (18 x18 cm) filled with 10 kg soil. At the time of planting, the soil was fertilized with phosphorus at the rate of 92 kg P_2O_5 $hectare^{-1}$. Six seeds were sown per pot and later thinned to four plants when the first trifoliate leaves of the seedlings unfolded. Aluminum and lime were applied four weeks prior to sowing the seeds and worked into the soil. Lime was applied at the rate of 20 g pot^{-1}(9 tons $hectare^{-1}$) after determining the rate required for increasing the pH of the soil to the optimum value of 6.2 for bean growth (20), using the incubation method. Pots were watered periodically with tap water to the approximate field capacity to facilitate normal plant growth. All other recommended agronomic management practices including watering, weeding, etc were done as required.

2.5. Data Collection and Measurement

Three plants per treatment were sampled 25 and 35 days after seedling emergence (DAE). The plants were carefully dug out with their entire root system intact. The soil was separated from the roots by carefully shaking and loosening the ball of earth attached on to the roots. The roots were gently washed under a jet of tap water until they came out clean. The samples were divided into roots, stems, and leaves. The plant parts were oven-dried at 65℃ to a constant weight in a forced draft oven for 48 h to determine dry biomass yield. The dry matter partitioned to the leaves, stems, and roots of each genotype was calculated by dividing the dry weight of each plant component by the total dry weight and expressed as a percentage [(*i.e*. leaf fraction (Lf), stem fraction (Sf) and root fraction (Rf)]. Root to shoot weight ratio was also calculated by dividing the dry root biomass by the biomass of the aerial part of the plant.

2.6. Growth Analysis

Growth rate parameters for the two common bean genotypes, absolute growth rate (AGR, g day^{-1}), relative growth rate (RGR, g g^{-1} d^{-1}), net assimilation rate (NAR, g m^{-2} d^{-1}), leaf area ratio (LAR, cm^2 g^{-1}), specific leaf area (SLA,cm^2 g^{-1}) and leaf weight ratio (LWR, g g^{-1}) were calculated according to Beadle [21]. Growth data were recorded using the destructive sampling method at both harvests.

2.8. Data Analysis

Data were subjected to analysis of variance using SAS (SAS Institute, Inc., Cary, NC). Treatments means were separated by the Fisher's protected least significant difference test at P = 0.05 [22].

3. RESULTS

3.1. Effects of Aluminum on Growth Characteristics

Growth characteristics were significantly (P=0.05) influenced by the main effects of aluminum and genotype (Table 1). Similarly, aluminum interacted with genotype to influence a number of growth characteristics of the plants. On average, plants of both genotypes had significantly higher leaf area in lime-treated soil than in lime-untreated soil (Figure 2). 25 and 35 days after seedling emergence, leaf area of the genotypes under the lime-untreated soil decreased by 7.6 and 5.3%, respectively, compared to the leaf area recorded for the lime-treated soil. Furthermore, leaf area was markedly reduced in response to increasing the rate of aluminum applied in both lime-treated and lime-untreated soils. However, the magnitude of reduction was higher in lime-untreated soil (Figure 2). New BILFA 58 had higher leaf area than Roba 1 at each aluminum level both under lime-treated and lime-untreated soils (Figure 2). This effect may have resulted from the reduction in leaf area that amounted to 2.94 and 0.69% for New BILFA 58 and 15.01 and 13.2% for Roba 1 for the first and second harvests, respectively, under the lime-untreated soil.

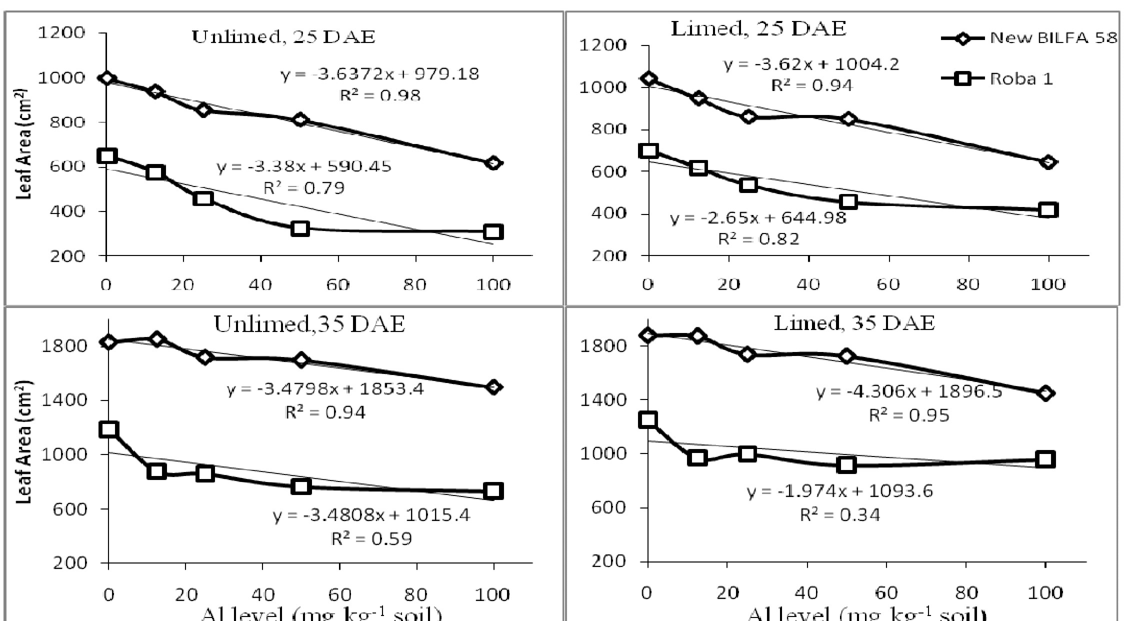

Figure 2. Leaf area (cm^2) of the two common bean genotypes grown under different levels of aluminum (Al) on lime treated (L) and lime-untreated (UL) soil 25 and 35 days after emergence (DAE)

Significant (P = 0.01) differences in absolute growth rate (AGR) and relative growth rate (RGR) were found in response to the concentrations of the applied aluminum. The absolute growth rate (AGR) and relative growth rate (RGR) also differed in response to the genotypic difference and as a result of the interaction effect of genotype and aluminum concentration on both lime-treated and lime-untreated soils (Table 1). AGR and RGR were higher for the lime-treated than for the lime-untreated soil for the genotypes. Roba 1 had relatively higher AGR and RGR in the lime-treated soil than in the lime-untreated soil (Figure 3). The data demonstrated that aluminum toxicity had a detrimental effect on growth of both genotypes. This was manifested by the considerable decreases observed in AGR and RGR in response to increasing the concentration of aluminum applied. On the other hand, application of lime reduced the effect of aluminum toxicity. However, inhibitory effects of aluminum on both common bean genotypes were observed when the concentration of aluminum applied was increased. For example, plants supplied with 100 mg aluminum kg^{-1} soil had lower AGR and RGR than plants supplied with lower levels of aluminum as well as those grown in the control treatment (Figure 3). The reductions in AGR and RGR were greater when the genotypes were grown under the lime-untreated soil than when they were grown under the lime-treated soil. AGR and RGR decreased by 37.5 and 32.9%, respectively, for the lime-untreated soil compared to the lime-treated soil.

Table 1. Mean squares of leaf area, growth analysis, and dry matter partitioned, and shoot to root weight ratio of common bean genotypes as affected by alumnuimum concentration and genotyeps on lime-treated (L) and lime-untreated (UL) soils

Parameters	Lime	Mean	Aluminum	Genotype	Al*G	Error
Leaf area (25)	UL	653.2^{b}	124305.5***	1077694.1***	6729.9*	1599.2
	L	707.1^{a}	99461***	781595***	5542^{NS}	3169.0
Leaf area (35)	UL	1303.9^{b}	129772.7***	5267391.5***	26256.9***	1647.3
	L	1377.4^{a}	106277***	3834098***	38628***	5136
Average growth	UL	0.65^{b}	0.177***	2.56***	0.0041*	0.00113
rate (AGR)	L	1.04^{a}	0.27***	3.772***	0.017*	0.0048
Relative growth	UL	0.09^{b}	0.00095***	0.00056**	0.00006^{ns}	0.00005
rate(RGR)	L	0.14^{a}	0.00021**	.0053***	0.0004***	0.00004
Net assimilation	UL	6.45^{b}	4.6***	38.943***	0.579*	0.129
rate (NAR,	L	10.03^{a}	5.14***	34.514***	1.322*	0.435
Leaf weight	UL	0.59^{b}	0.00034^{ns}	0.0036**	0.0015*	0.0004
ratio(LWR)	L	0.62^{a}	0.003	0.0021^{ns}	0.0057***	0.0008
Specific leaf area	UL	272.5^{b}	2898.6***	113365.4***	1346.2**	203.6
(SLA)	L	285.9^{a}	1831.7^{ns}	16807.9***	1888.3^{ns}	995.5
Leaf area Ratio	UL	149.1^{a}	165.8^{ns}	12972.6***	661.3***	60.3
	L	137.1^{b}	366.3**	76.3^{ns}	253.9*	62.0
Leaf fraction (25)	UL	2.45^{a}	0.52***	28.1***	0.052^{ns}	0.059
	L	2.52^{a}	0.68***	6.27***	0.026^{ns}	0.014
Leaf Fraction (35)	UL	6.22^{b}	8.73***	254.9***	0.31*	0.096
	L	7.66^{a}	9.19***	183.13***	0.34^{NS}	0.25
Stem fraction (25)	UL	1.55^{a}	0.079**	13.94***	0.018^{ns}	0.017
	L	0.89^{b}	0.58***	1.15***	0.47***	0.0203
Stem fraction (35)	UL	4.27^{b}	4.87***	82.04***	0.28^{ns}	0.15
	L	6.15^{a}	13.02***	89.58***	2.25**	0.37
Root fraction (25)	UL	0.89^{b}	0.36***	3.35***	0.011^{ns}	0.008
	L	1.12^{a}	0.428**	1.14***	0.027*	0.008
Root Fraction (35)	UL	2.35^{b}	1.55***	34.09***	0.14^{ns}	0.11
	L	3.15^{a}	3.35***	68.13***	0.22**	0.041
Shoot : Root (25)	UL	0.20^{b}	0.0048***	0.035***	0.00071*	0.0003
	L	0.33^{a}	68.21*	0.84^{NS}	89.6**	15.06
Shoot : Root (35)	UL	0.19^{b}	0.0046***	0.0134***	0.00031^{ns}	0.00043
	L	0.22^{a}	17.36**	647.35***	20.42***	2.474

Where, Al = Aluminum; G = genotype; NS - non-significant; *=P (0.01-0.05); ** = P (0.001-0.01); *** (P < 0.001)

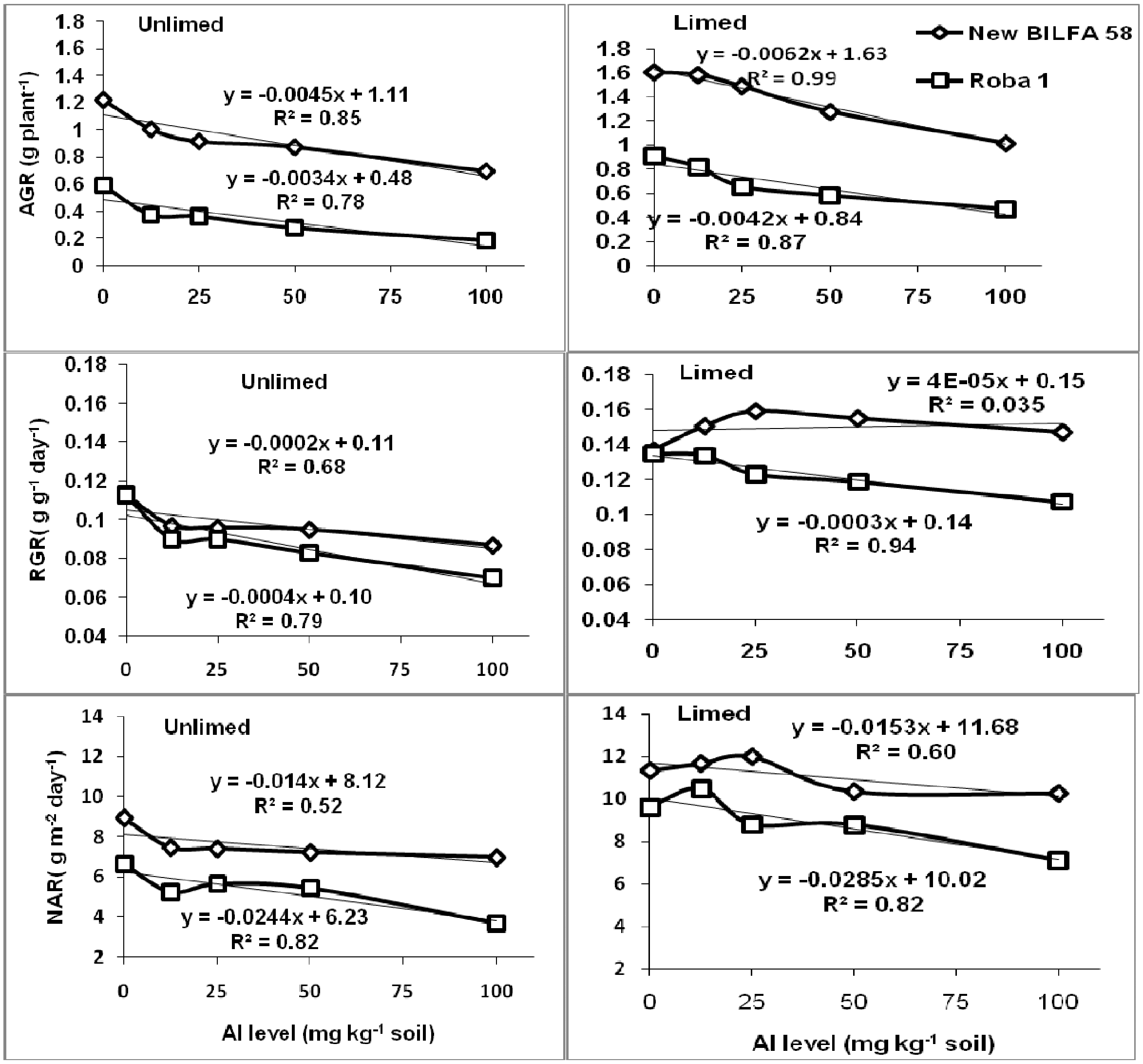

Figure 3. Absolute growth rate (g day^{-1}), relative growth rate (g g^{-1} day^{-1}) and net assimilation rate (g m^{-2} day^{-1}) of the two common bean genotypes grown under different levels of aluminum applied on lime-treated and lime-untreated soils

Both the main and the interaction effects of aluminum levels and genotypes were significant for net assimilation rate (NAR) under lime-treated and lime-untreated soil conditions. NAR decreased in response to increasing the rate of aluminum applied (Figure 3). The highest NAR was recorded for the control (no aluminum application) treatment whereas the lowest was obtained in response to applying the highest rate of aluminum under both soil liming regimes (Figure 3). The rate of reduction in NAR increased with the increase in the rates of aluminum applied, and the reduction was more pronounced for the lime-untreated soil than for the lime-treated soil. On average, the genotypes suffered about 35.7% reduction in NAR when grown on the lime-untreated soil compared to the reduction in NAR they suffered when grown on the lime-treated soil, with similar rates of aluminum application. Comparing the two genotypes, New BILFA 58 suffered a lower reduction in NAR (31.5%) than Roba 1, which suffered a 40.4% reduction in NAR when grown under different rates of aluminum on the lime-untreated soil.

Differences among the aluminum levels, between the bean genotypes, and their interaction terms were significant (*P* = 0.05) for specific leaf area (SLA) under the lime-untreated soil (Table 1). New BILFA 58 had lower specific leaf area than Roba 1 under both soil treatment conditions (Figure 4). For New BILFA 58, SLA tended to increase when the aluminum level was increased from 0 to 50 mg Al kg^{-1} soil and then declined in response to increasing the rate of aluminum to 100 mg kg^{-1} soil on lime-untreated soil. Similarly, SLA of Roba 1 increased in response to increasing the rate of aluminum except at the level of 50 mg aluminum kg^{-1} soil (Figure 4).

Both the main and the interaction effects of aluminum rate and genotype significantly (*P* = 0.05) influenced leaf area ratio (LAR) and leaf weight ratio (LWR) under lime-untreated soil condition. The main effect of aluminum rate and the interaction effect of aluminum rate and genotype were significant on LAR and LWR for the lime-treated soil**.** Higher LWR was recorded for the lime-untreated soil whereas higher LAR was recorded for the lime-treated soil (Figure 4). Higher leaf weight ratio was recorded for New BILFA 58 than Roba 1 at the different levels of aluminum applied.

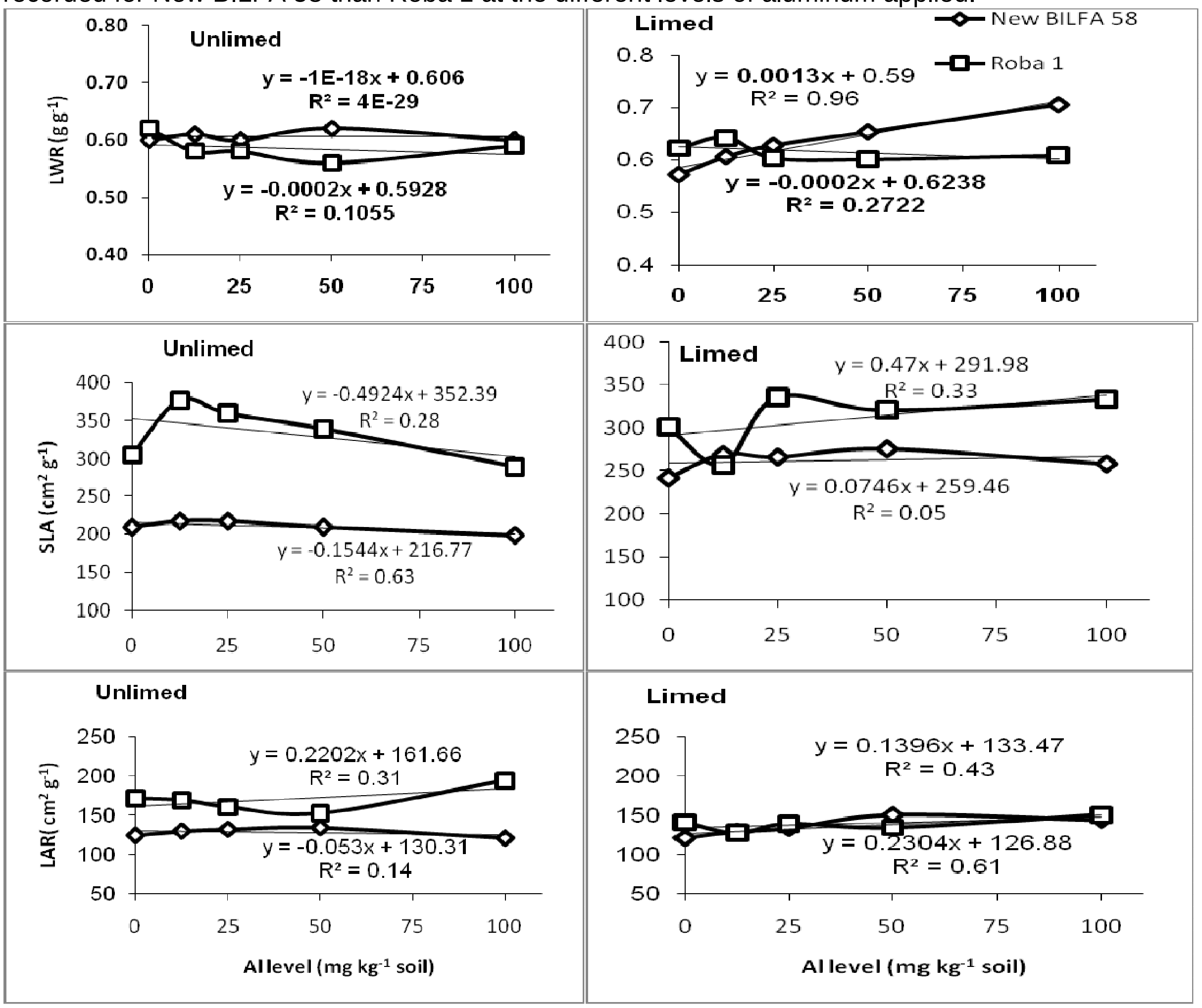

Figure 4.Leaf weight ratio (g g^{-1}), specific leaf area (cm^2 g^{-1}) and leaf area ratio (cm^2 g^{-1}) of the two common bean genotypes grown under different levels of aluminum applied on lime-treated and lime-untreated soils

3.2. Dry Matter Partitioning

Highly significant differences (P = 0.001) among the aluminum levels and genotypes were found for the dry matter partitioned to the leaf, stem and root at the first and second harvests in both lime-treated and lime-untreated soils (Table 1). However, aluminum rate and genotype interacted to significantly (P = 0.05) influence leaf (25 DAE) in the lime-untreated soil. The interaction effect of the two factors significantly influenced also the dry matter partitioned to stems and roots for the first and second harvests in the lime-treated soil (Table 1). The proportion of dry matter partitioned to leaf, stem, and root was higher for New BILFA 58 than for Roba 1 for both harvests and liming regimes (Figure 5). Higher dry matter partitioned to the leaf was found for plants grown under the lime-treated soil condition 25 DAE compared plants grown under the lime-untreated soil. Proportionally, more dry matter was allocated to the stem 35 DAE than 25 DAE regardless of the liming regime. New BILFA 58 had higher root proportion than Roba 1 at both harvesting times and under the two soil liming regimes (Figure 5). As the applied aluminum was increased from 0 to 100 mg aluminum kg^{-1} soil, the dry matter produced by each plant part was significantly reduced for both genotypes and liming regimes. However, the reduction was higher for Roba 1 in the lime-untreated soil (Figure 5).

3.3. Root to Shoot Weight Ratio

The main effects of aluminum rate, genotype, and their interactions (except for lime-treated soil) were significant (P = 0.05) on root to shoot weight ratio 25 DAE under the two soil liming regimes (Table 1). The trends were more or less similar 35 DAE under both soil liming regimes. Root to shoot weight ratio was higher 25 DAE compared to the root to shoot weight ratio observed 35 DAE. Moreover, plants grown on the lime-treated soil had significantly higher root to shoot weight ratio than those grown on lime-untreated soil (Figure 6). At both harvesting times and under the two soils liming regimes, root to shoot weight ratio decreased in response to the increasing rate of aluminum applied, with New BILFA 58 having higher ratio than Roba 1.

.

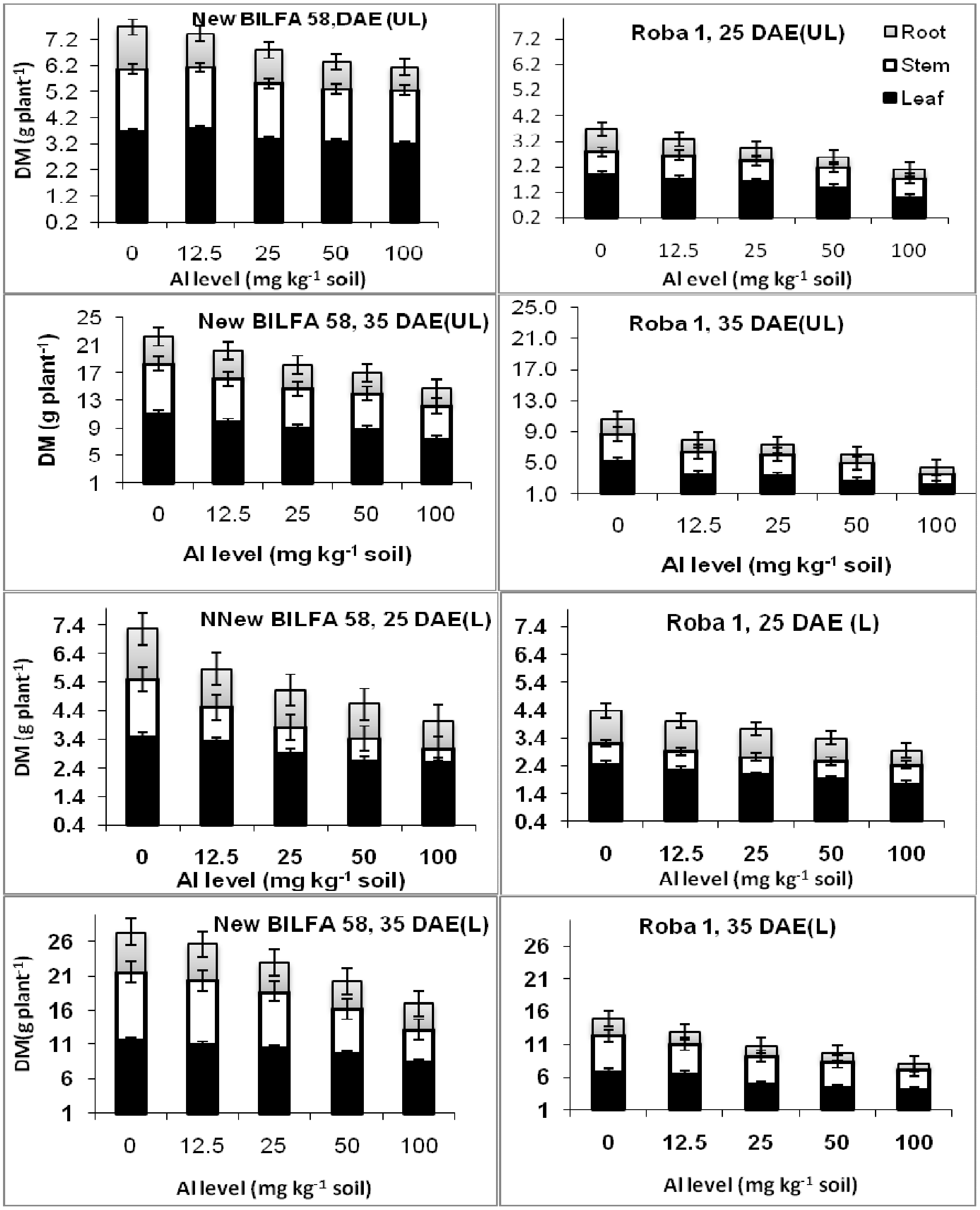

Figure 5. Dry matter (DM) partitioned (g plant^{-1}) to leaves, stems and roots of two common bean genotypes (New BILFA 58 and Roba 1) grown under different aluminum (Al) levels on lime-treated (L) and lime-untreated (UL) soils 25 and 35 days after emergence (DAE).

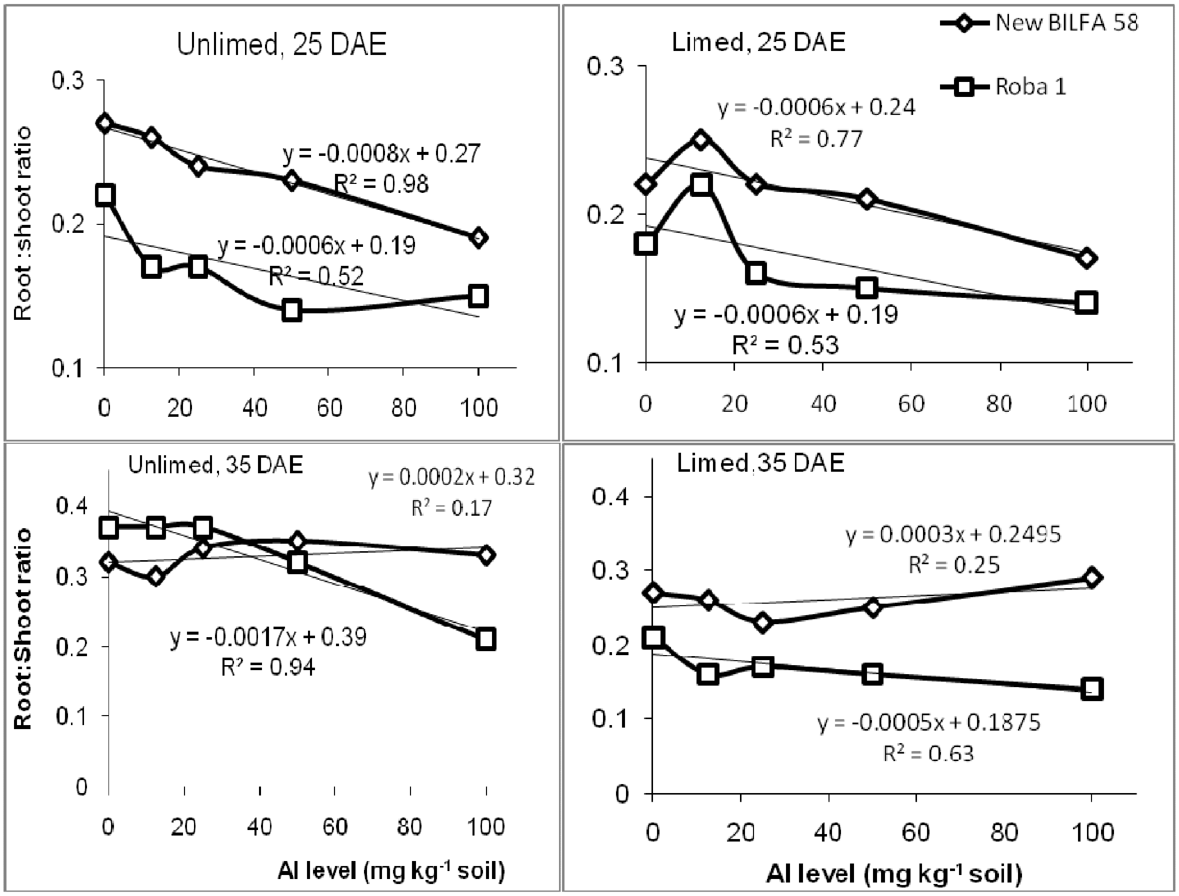

Figure 6. Root to shoot weight ratio of the two common bean genotypes in response to different levels of aluminum under lime-treated and lime-untreated soils 25 and 35 DAE

4. DISCUSSION

Soil acidity significantly reduced the overall growth of the common bean genotypes irrespective of their genetic difference. This was manifested by the reductions observed in the different growth parameters of the plants belonging to both genotypes in response to the increased concentration of aluminum applied. Leaf areas of both genotypes were adversely affected by the increased concentration of soil-applied aluminum under both liming regimes. Leaf development of Roba 1 was more adversely affected than that of New BILFA 58 at all levels of aluminum application for the lime-untreated soil. Consistent with the results of this study, several studies revealed that aluminum toxicity induced leaf necrosis [23]; [18], leaf yellowing [24], stunted leaf growth [6] and late leaf maturity. [25]. Increase in leaf area from 25 to 35 DAE onward was higher for New BILFA 58 than Roba 1. The results of this study revealed that the rate of aluminum applied was inversely related to leaf area development for both genotypes. This result is corroborated by that of Thornton *et al*. [26] who reported that aluminum application reduced the expansion rate of leaves by up to 50% in seedlings of honey locust (*Gleditsia triacanthos* L.) .

Application of aluminum resulted in a significant decline in absolute and relative growth rates of both genotypes grown under the lime-treated and the lime-untreated soils. However, the reduction was relatively less for New BILFA 58 than Roba 1. This result demonstrate that aluminum-tolerant genotypes exhibit better growth performance under strongly acidic soil condition when lime is applied than genotypes with less aluminum tolerance. Corroborating these results, [27] reported beneficial effects of increasing Ca concentration in the nutrient solution and liming on plant growth under aluminum stress.

That the NAR value of New BILFA 58 was higher than that of Roba 1 demonstrated that the former was more efficient in producing dry matter under aluminum stress than the latter. On average, New BILFA 58 had higher NAR than Roba 1, demonstrating the inherently higher photosynthetic efficiency of the genotype over a range of growing conditions. Higher NAR for plants grown on the lime-treated soil than those grown on the lime-untreated soil could be due to decreased toxicity effect of aluminum under the former than the latter condition. Higher NAR of the genotypes under the lime-treated soil condition could be attributed to improved availability of nutrients needed for growth and development of the crop. The reduction in biomass yield under the lime-untreated soil especially for Roba 1 led to higher leaf area ratio compared to the leaf area ratio observed under the lime-treated soil. In contrast, New BILFA 58 produced relatively higher biomass yield and leaf area under the two soil liming regimes. In contrast, aluminum application did not have a significant effect on leaf weight ratio on the lime-untreated soil. This may be attributed to the reduction in both total biomass yield and leaf biomass yield of the plants of both genotypes in response to the increased concentration of the applied aluminum. The higher SLA of Roba 1 under both lime-treated and lime-untreated soils could be ascribed to the higher reduction in leaf biomass the genotype than its leaf area under both soil liming regimes. On the other hand, New BILFA 58 had relatively higher leaf biomass yield and leaf area under both soil liming regimes, which may have led to lower SLA.

Results from several studies revealed genotypic variability in plant growth, physiology, and quality in response to aluminum application [28; 29]. Leaf area, absolute growth rate, relative growth rate, and net assimilation rate of the common bean genotypes differed and decreased in response to the increased application rate of aluminum. However, the growth performance of the common bean genotype New BILFA 58 was less adversely affected than that of Roba 1 by soil acidity and aluminum application. Therefore, these growth indices appear to be useful in germplasm screening for aluminum tolerance.

In nutrient deficient plants, maintenance of export of photo-assimilates from the source leaves to the other parts of the plant increases the dry matter partitioned to the roots and allows continued growth and development of the plant [30]. The same phenomenon may have led to the increased dry matter partitioning to the roots rather than the shoots of New BILFA 58 genotype when increased concentrations of aluminum were applied to the growth medium. Possession of a larger root fraction by New BILFA 58 could explain why the genotype performed better than Roba 1 under the aluminum stress condition. That plants grown on the lime-treated soil had significantly higher root to shoot weight ratio than those grown on the lime-untreated soil demonstrates the adverse effect of aluminum on root growth of the bean plants. This may be attributed to aluminum-induced inhibition of root elongation rate as a result of decreased root cell expansion as suggested by (31). New BILFA 58 genotype maintained higher root to shoot weight ratio under aluminum stress than Roba 1 demonstrates the superior performance of the genotype when grown on a strongly acidic soil. Consistent with the results of this study, genetic differences in root biomass, root to shoot weight ratios, and root biomass distribution have been reported for common beans [32, 33]. The genetic traits could be exploited to discern genotypes that are tolerant to aluminum toxicity. The results of this study demonstrated that the common bean genotypes studied in this experiment varied in the ability to partition biomass to roots or shoots depending on the degree of soil acidity (aluminum toxicity). Thus, there is considerable potential for improving or selecting common bean genotypes for tolerance to soil acidity (aluminum toxicity) through genetic manipulation based on the pattern of assimilate partitioning to roots or shoots.

5. CONCLUSION

With the increase in the concentration of aluminum applied, almost all growth parameters decreased under the contrasting soil liming regimes. However, the reduction in the growth parameters was lower for the lime-treated soil than for the lime-untreated soil. The reduction was less also for the genotype New BILFA 58 than Roba 1. Dry matter partitioning to different parts of the common bean genotypes bean plant was also affected by aluminum depending on the rate applied and the growth stage of the crop considered. Relatively higher biomass was partitioned to roots by New BILFA 58 than Roba 1 on both lime-treated and lime-untreated soils. Dry matter partitioning to roots in response to the increased concentration of aluminum applied to the soil was higher at 25 DAE than at 35 DAE. Lime application generally improved growth and dry matter partitioning of the genotypes, possibly through decreasing the toxic effect of aluminum and improving the availability of nutrients for uptake by the roots of the common bean plants.

Liming ameliorates soil acidity and reduces the detrimental effects of aluminum toxicity. However, it cannot be a permanent solution to the problem of soil acidity due to economic reasons particularly for smallholder farmers in developing countries. Therefore, selecting and growing common bean genotypes that are tolerant to aluminum toxicity, such as New BILFA 58, could lead to increased production of the crop in the humid tropics, where aluminum toxicity is a serious threat to enhancing household and national food security. Furthermore, such genotypes could be used in breeding programs to develop common bean varieties for profitable production of the crop on acid soils.

6. ACKNOWLEDGEMENTS

The authors are grateful to the financial grant provided by the Ethiopian Ministry of Education for this PhD research work, which led to the writing of this article. We would like to thank also Haramaya University for facilitating the research work. We would also acknowledge the assistance of staff members and laboratory technicians at Nekemte soil laboratory in analyzing soil samples and conducting the green house pot experiments.

AUTHORS' CONTRIBUTIONS

The first author, Hirpa Legesse, designed the PhD research, developed the protocol of the experiment, collected the data, performed the statistical analysis, interpreted the results, and wrote the first draft of the article. The remaining authors commented on the protocol, evaluated the experimental setup, assessed, supervised, and monitored all research activities. The co-authors also edited and commented on the manuscript.

.

REFERENCES

1. Bot AJ, Nachtergaele FO, Young A. Land Resource Potential and Constraints at Regional and Country Levels. Food and Agricultural Organization of the United Nations, Rome, 2000, pp. 114.
2. Yang ZB, Rao IM, Horst WJ. Interaction of aluminum and drought stress on root growth and crop yield on acid soils. Plant Soil.2013; DOI 10.1007/s11104-012-1580-1.
3. Beebe S, Ramirez J, Jarvis A, Rao IM, Mosquera G, Bueno JM, Blair M. (2011) Genetic improvement of common beans and the challenges of climate change. In: Yadav SS, Redden RJ, Hatfield JL, Lotze-Campen H, Hall AE (eds) Crop adaptation to climate change, 1st edn. Wiley, New York, pp 356–369.
4. Rao IM, Wenzl P, Arango A, Miles J, Watanabe T, Shinano T, et al. Advances in developing screening methods and improving aluminum resistance in common bean and *Brachiaria.* R. Bras. Agrociência, Pelotas. 2008; 14:4-4.
5. Ryan PR, Delhaize E. The convergent evolution of aluminum resistance in plants exploits a convenient currency. Funct. Plant Biol. 2010; 37,275-284.
6. Wang J, Raman H, Zhang G, Mendham N, Zou M. Aluminum tolerance in barely (*Hordeum vulgare* L.): Physiological mechanisms, genetic and screening methods. *Journal of Zhejiang University Science*. 2006; 7:769-787.
7. Poschenrieder C, Gunse B, Corrales I, Barcelo J. A glance into aluminum toxicity and resistance in plants. *Science of the Total Environment*. 2008; 400: 356–368.
8. Pandey S, Ceballos H, Magnavaca R, Bahia Filho AFC, Duquevargas J, Vxinasco LE. Genetics of tolerance to soil acidity in tropical maize. Crop Sci.1994; 34:1511–1514.

9. Butare L, Rao IM, Cajiao C, Polania J, Cuasquer J, Beebe S. Phenotypic evaluation of interspecific recombinant inbred lines (RILs) of Phaseolus species for aluminum resistance and shoot and root growth response to aluminum–toxic acid soil. Euphytica.2011; DOI 10.1007/s10681-011-0564-1.
10. Beebe SE, Rao IM, Cajiao C, Grajales M. Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. Crop Sci.2008; 48:582–592.
11. Graham PH, Rosas JC, de Jensen EC, Peralta E, Tlusty B. Acosta-Gallegos, et al. Addressing edaphic constraints to bean production: the bean/cowpea CRSP project in perspective. *Field Crop Research.* 2003;82 :179-192.
12. Kumar A, Bernier J, Verulkar S, Lafitte HR, Atlin GN. Breeding for drought tolerance: Direct selection for yield, response to selection and use of and lowland- adapted populations drought-tolerant donors in upland. *Field Crops Research*.2008; 107:221- 231.
13. Ma JF, Ryan PR, Delhaize E. Aluminum tolerance in plants and the complexing role of organic acids. *Trends Plant Sci*.2001; 6: 273-278.
14. Ryan PR, Delhaize E, Jones DL. Function and mechanism of organic anion exudation from plant roots. *Annual Review of plant physiology and plant molecular Biology.2001;*52**:** 527-560.
15. Barcelo J, Poschenrieder C. Fast root growth responses, root exudates, and internal detoxification as clues to the mechanisms of aluminum toxicity and resistance: a review. *Environ Exp Bot*. 2002; 48(1)**:**75-92.
16. Marjorie RD, Miren A, and Maria de, ML. Short-term Aluminum Stress Differentially Affects the Photochemical Efficiency of Photo-system II in High bush Blueberry Genotypes. *Journal of the American Society for Horticultural Science*, 2009; 134(1):14-21.
17. Kochian LV, Pin˜eros MA, Hoekenga OA.The physiology, genetics and molecular biology of plant aluminum resistance and toxicity. Plant Soil. 2005;274:175–195.
18. Zhang XB, Peng L, Yang YS, Gen-Di Xu. Effect of Al in soil on photosynthesis and related morphological and physiological characteristics of two soybean genotypes. *Botanical Studies*.2007; 48:435-444.
19. Centro International de Agricultura Tropical (CIAT). Catalogue of advanced bean lines from CIAT, 2nd ed. Macro Antonio Rodriguiz, Hectar Fabio Rairez, Maria Clara Valencia, Oswaldo V.Vovsest and W. White (comps). CIAT, 1995, Cali Colombia p.298.
20. Fageria NK. Response of upland rice, dry bean, corn, and soybean to base saturation in cerrado soil. *Rev. Bras. Eng. Agric. Amb*.; 2001, 5:416–424.
21. Beadle CL. Growth analysis. Photosynthesis and production in a changing environment: a field and laboratory manual (ed. by D.O. Hall), pp. 36–46. Chapman & Hall, London,1993.
22. SAS Institute Inc. SAS/STAT User's Guide: Version 9.1th edn. SAS Institute Inc., Cary, North Carolina.2004.
23. Roy AK, Sharma A, Talukder G. Some aspects of aluminum toxicity in plants. *Bat. Rev*. 1988; 54:145-178.
24. Foy CD. Physiological effects of hydrogen, aluminum and manganese toxicities in acid soils, in: Adams F. (Ed.), Soil Acidity and Limiting, Second Edition, *American Society of Agronomy*. Madison, Wisconsin, 1984, pp. 57–97.
25. Rout GR, Samantaray S, Das P. Aluminum toxicity in plants: A review. *Agronomie*.2001; 21:3-21.
26. Thornton FC, Schaedle M, Raynal DJ. Effects of aluminum on growth, development, and nutrient composition of honey locust seedlings. *Tree Physiol*., 1986; 2:307-316.
27. Yu GT, Qin SC. Effect of organic manure on soil aluminum toxicity and nutrient absorption of winter wheat. *Plant Nutrition and Fertilizer Science*.1998; 4:57-62.
28. Tang CE, Rengel Z, McGann B. Growth response to subsurface soil acidity of wheat genotypes differing in aluminum tolerance. Plant Soil. 2001; 236(1): 1-10.
29. Liu P, Yang YS, Xu GD, Zhu SL. The effect of aluminum stress on morphological and physiological characteristics of soybean root of seedling. Chin J Oil Crop Sci. 2004; 26(4): 49-54.
30. Cakmak I, Hengeler C, Marschner H. Partitioning of shoot and root dry matter and carbohydrates in bean plants suffering from phosphorus, potassium and magnesium deficiency. *J Expl Bot*, 1994; 45: 1245-1250.

31. Doncheva S, Amenos M, Poschenrieder C, Barcelo´ J. Root cell patterning: a primary target for aluminum toxicity in maize. J Exp Bot; 2005, 56 (414):1213–1220.
32. Fageria NK. *The Use of Nutrients in Crop Plants*. CRC Press, New York.2009. pp 430.
33. Blair MW, Lopez-Marın HD, Rao IM. Identification of aluminum resistant Andean genotypes of common bean (*Phaseolus vulgaris* L.). Braz J Plant Physiol; 2009, 21(4):291–300.