Evaluation of Aluminum Tolerance and Nutrient Uptake of 50 Centipedegrass Accessions and Cultivars

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Abstract. Centipedegrass [*Eremochloa ophiuroides* (Munro) Hack] is a native grass of China, and information on soil adaptation ranges, including acid soils, among centipedegrass cultivars is limited. Therefore, objectives of this study were 1) to conduct a preliminary evaluation of relative aluminum tolerance of 48 centipedegrass accessions plus a cultivar, TifBlair, and a common centipedegrass under aluminum (Al) stress (0 and 1500 μM Al) by using a solution culture method; and 2) to determine Al effects on nutrient uptake between resistant-group and sensitive-group accessions among the 50 accessions and cultivars. Differences were found among accessions and cultivars, and the CV of relative root weight, relative shoot weight, and relative total weight were 39.9%, 32.9%, and 33.6%, respectively. After growing 28 days in an acid subsoil, the resistant-group accessions showed much better growth than the sensitive-group accessions. The Al concentrations in roots and shoots of the two groups of accessions were increased under Al treatment, but most absorbed Al remained in roots with greater Al absorption among the sensitive group compared with the resistant group. The concentrations of phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K) in the two groups were reduced under Al stress with reductions of 59.3%, 54.8%, 47.9%, and 41.3% in shoots and reductions of 8.70%, 52.5%, 43.2%, and 34.4% in roots, respectively. Under Al stress, differences in P, Mg, and Ca concentrations were found between the two groups; however, differences were not found for K. The resistant-group accessions maintained higher concentrations of Mg and Ca than the sensitive group.

Soil acidity is a major problem in establishment and maintenance of turfgrass in many areas of the world (Foy and Murray, 1978). Aluminum (Al) toxicity has been identified as a major problem for crop production in acidic soils since 1918 (Hartwell and Pember, 1918). At soil pH of 5 or less, toxic forms of Al become soluble in the soil solution, inhibiting root growth and function and thus affecting plant growth (Kochian et al., 2005). Negative effects of Al on uptake of calcium (Ca), magnesium (Mg), and phosphorus (P) have been demonstrated in plant species, including maize (*Zea mays* L.) (Keltjens, 1995), sorghum (*Sorghum bicolor* L.) (Tan and Keltjens, 1990), and rice (*Oryza sativa* L.) (Jan, 1991). Marschner (1991) and others (Foy and Murray, 1978) demonstrated that grasses in acidic soils suffered from P,

potassium (K), Ca, and Mg deficiencies; inhibition of growth; and poor environmental stress tolerance. The negative effects of Al on plant growth and nutrient uptake for cool-season turfgrasses have been reported in several studies (Foy and Murray, 1998a, 1998b; Liu et al., 1995, 1996, 1997; Rengel and Robinson, 1989). However, few studies have examined the Al tolerance of warm-season turfgrasses (Baldwin et al., 2005; Duncan and Shuman, 1993; Liu, 2005).

Centipedegrass is a warm-season perennial grass originating from south to central China (Hanna, 1995; Hanna and Liu, 2003). Centipedegrass is often referred to as a low-maintenance turfgrass because of its lower maintenance requirement and fertility input. It has excellent heat and moderate shade tolerance and is relatively unsusceptible to diseases and insects. It has a naturally light green color and grows well on a wide range of soil types (Hanna, 1995; Hanna and Liu, 2003; James and Hanna, 1994). The centipedegrass accessions collector of this study, Dr. Jianxiu Liu, has found that centipede-

grass is well adapted to acid soils, but it also can live in slightly neutral soils and coastal areas with soil pH greater than 7. Johnson and Carrow (1992) found that centipedegrass growth was better in pH 6.7 than in pH 5.1 when the soil was poorly fertilized. Baldwin et al. (2005) reported the Al effect on growth and nutrient uptake of 10 warm-season turfgrass species, including centipedegrass, and found that growth and nutrient absorption of most turfgrasses were inhibited when Al concentrations were greater than 640 μM . Among the 10 warm-season turfgrasses studied, carpetgrass (*Axonopus affinis* Chase) was the most Al-resistant species and centipedegrass exhibited moderate Al resistance. However, a lack of information remains about Al tolerance among centipedegrass accessions or cultivars to demonstrate the genetic diversity in acid soil adaptation. Therefore, the objectives of this study were 1) to conduct a preliminary evaluation of relative aluminum tolerance of 48 centipedegrass accessions plus TifBlair centipedegrass and a common centipedegrass from the United States by using a culture solution method; and 2) to determine Al effects on nutrient uptake between resistant-group and sensitive-group accessions among the 50 accessions and cultivars screened.

Materials and Methods

Aluminum solution screening experiment.

A total of 48 representative native accessions collected from 13 provinces in the Yangtze River Valley in China (Fig. 1) plus TifBlair centipedegrass and a common centipedegrass developed in the United States were used in this experiment. All accessions were collected by Dr. Jianxiu Liu from 1998 to 2001 and cultured at the Turfgrass Plots of Nanjing Botanical Garden Mem. Sun Yat-Set. The experiments were conducted under greenhouse conditions in Nanjing Botanical Garden Mem. Sun Yat-Set, Nanjing, Jiangsu Province, China. The greenhouse was maintained at 33 to 37 °C during the day and 25 to 28 °C at night with 90% natural sunlight and a relative humidity range of 48% to 69% during the study.

To have enough young seedlings for the experiments and a uniformity control, a pre-experimental culture was conducted. Pieces of stolons with only one bud with similar length between 5 to 6 cm were used. In each 250-mL plastic cup (6.5 cm in diameter, 9.5 cm in height) filled with quartz grits with multiple pinholes at the bottom, four similar pieces of the previously described stolons were planted. A total of 100 pieces of stolons of each accession or cultivar were planted into 25 cups, and then the cups were suspended on a foam rack, which had 54 holes cut and held as many as 54 cups. The foam racks with cups were placed on top of large containers filled with 40 L modified half-strength Hoagland nutrient solution (Hoagland and Arnon, 1956) with the following nutrient concentrations (in mM): 2.5 $\text{Ca}(\text{NO}_3)_2$, 2.5 KNO_3 , 1 MgSO_4 , and 0.5 $\text{NH}_4\text{H}_2\text{PO}_4$; and (in

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Fig. 1. The 48 collection locations of the tested centipedegrass accessions. The 10 centipedegrass accessions used for acid soil nutrition uptake analyses.

μM): 46 boron (B), 0.3 copper (Cu), 0.1 molybdenum (Mo), 9.2 manganese (Mn), 0.8 zinc (Zn), and 50 iron (Fe)-EDTA aerated continuously by using an aerating pump and was changed weekly. All plant materials were pre-experimentally cultured for 2 weeks under the greenhouse conditions described.

After 2 weeks of pre-experimental culture, similar shoot and root size plants (four to five fully open leaves and 5 to 6 cm root) were transplanted into new cups of similar sizes and materials filled in as described earlier for the preliminary solution screening experiment. Three similar individual plants of each accession or cultivar were transplanted into one cup. To avoid and minimize possible contaminations of root exudates between different accessions or cultivars (Ma et al., 1997), three cups of the same accession or cultivar were suspended on one foam board cut with three holes, which was put on the top of a 2.5-L pot (17 cm in diameter, 15 cm in height) filled with 2 L culture solution with the following nutrient concentrations (in mM): 1.25 $\text{Ca}(\text{NO}_3)_2$, 1.25 KNO_3 , 0.5 MgSO_4 , and 0.025 $\text{NH}_4\text{H}_2\text{PO}_4$; and (in μM): 46 B, 0.3 Cu, 0.1 Mo, 9.2 Mn, 0.8 Zn, and 28 Fe-EDTA. An Al concentration of 1500 μM used for this study was determined

based on findings by Baldwin et al. (2005) on 10 warm-season turfgrasses using a 1440 μM Al solution culture for 1 month with relative root mass and relative shoot mass reductions of 34% and 28%, respectively, for centipedegrass. As a result of the large number of centipedegrass accessions used in this study, which were distributed among areas from $19^\circ 01'$ to $35^\circ 01'$ north latitude in China (Liu and He, 1998) plus two U.S. centipedegrasses, only a control and 1500 μM Al ($\text{AlCl}_3 \cdot 6\text{H}_2\text{O}$) were used. The pH of nutrient solutions of both concentrations was adjusted daily to 4.0 ± 0.2 (HCl or NaOH) and measured by using a portable pH meter (JENCO 6010; INC Technical Incorporated, Cincinnati, OH). All solutions were aerated continuously by using an aerating pump and solutions were changed every 3 d. All the nutrient solution was prepared with DD H_2O and the duration of treatment lasted 28 d. All the screened accessions and cultivars were arranged as a randomized complete block design with three replications.

An acid soil culture experiment with 10 selected accessions. The 10 accessions used for evaluation difference in nutrition uptake were planted in acid subsoil for confirming

the results by culture solution method in the greenhouse mentioned. The acid subsoil, collected from Red Soil Ecological Experiment Station of Chinese Academy of Sciences, has a pH of 4.5 (ratio of soil to water is 1:1 and KCl-extractable Al is $11.6 \text{ cmol} \cdot \text{kg}^{-1}$), 0.27% organic matter, 0.056% total nitrogen, $5.41 \text{ mg} \cdot \text{kg}^{-1}$ available P, and $54.41 \text{ mg} \cdot \text{kg}^{-1}$ available K. The acid subsoil was air-dried and put into the pot (16 cm in diameter, 12 cm in height), and each pot contained 1000 g acid subsoil. The acid subsoil was treated with CaCO_3 to adjust its pH to 5.8 and used as a control. Fertilization with NH_4NO_3 and KH_2PO_4 added N, P, and K at 100, 109, and $137 \text{ mg} \cdot \text{kg}^{-1}$ of the soil, respectively, for both limed and nonlimed soils. The 10 accession stolons with one bud on each piece of stolon were uniformly planted in each pot. Each accession was repeated in three pots. After 1 week of growth, six stolon pieces with the similar size and appearance were retained in each pot and grown for 28 d.

The relative dry shoot mass (RSW), relative dry root mass (RRW), and relative dry total biomass (RTW) in acid subsoil were obtained and calculated in the same method as in culture solution method mentioned

previously taking one pot as a replication. All pots were arranged in a randomized complete block design with three replications.

Date collection and analyses. After 28 d of Al treatment, roots and shoots were separated and washed with deionized water to remove any residual soil or nutrients and then oven-dried at 80 °C for 48 h and weighed. The dried roots and shoots were used for nutrient uptake analyses by determining the individual nutrient concentrations. The RSW, RRW, and RTW were calculated using the following formulas, respectively: (dry root or shoot mass in one cup with Al/dry root or shoot mass in one cup without Al) × 100% (dry root + shoot mass in

one cup with Al/dry root + shoot in one cup without Al) × 100%. All relative values were based on the controls.

Values of the relative growth parameters (RSM, RRM, RTM) were submitted to analysis of variance procedures and parameters. Means were separated using Duncan's multiple range test ($\alpha = 0.05$). As a result of the difficulty in handling all 50 accessions and cultivars for nutrient uptake analyses, only five most Al-resistant and five most Al-sensitive accessions were artificially chosen for comparing differences in plant uptake of Al, P, Mg, Ca, and K when exposed to Al based on the list provided in Table 1. For individual nutrient concentration analyses,

the dry shoots and roots of the chosen accessions were ground. From the ground material, 0.2 g was weighed and placed into a 100-mL tube and digested with 5 mL 87% HNO₃ + 13% HClO₄ for 12 h, and then the digestion tubes were heated in a sequential procedure (80 °C 40 min, 100 °C 60 min, 120 °C 80 min, 140 °C 100 min, 160 °C 120 min, and 180 °C until the samples were totally dried). The samples were then removed from the digestion tube by adding 50 mL 5% HNO₃ and shaken vigorously. The concentrations of P, Mg, Ca, K, and Al of the sample solutions were analyzed by ICP-AES (Zhao et al., 1994). The relative concentrations of P, Mg, Ca, K, and Al were calculated using the

Table 1. Relative root mass, shoot mass, total biomass of 50 accessions and cultivars treated with or without aluminum (0 or 1500 µM at pH 4.0) in culture solution for 28 d.

Accession	Collecting site	Latitude	Longitude	Relative root mass (%)	Relative shoot mass (%)	Relative total biomass (%)
E041	Lingchuan Guangxi	25°28'	110°17'	107.7 a ^z	78.5 a	80.5 a
E014	Nanchang Jiangxi	28°42'	119°54'	97.2 b	72.3 ab	74.1 ab
E136	Longli Guizhou	26°27'	107°01'	93.7 b	62.5 a-f	67.4 a-e
E072	Guilin Guangxi	25°18'	110°16'	89.7 bc	66.7 a-d	68.8 a-d
E076	Huahui Hunan	27°31'	110°03'	87.6 bcd	72.1 abc	73.2 abc
E007	Fuzhou Fujian	26°05'	119°06'	83.0 cde	53.1 b-h	56.2 b-j
E077	Zhangjiajie Hunan	29°16'	110°12'	79.6 def	64.0 a-e	65.5 a-f
E180	Lanxi zhejiang	29°31'	119°30'	79.3 def	48.6 d-i	50.4 d-k
E137	Guiyang Guizhou	26°35'	106°37'	77.8 d-g	53.4 b-h	55.0 c-j
E117	Boluo Guangdong	23°21'	114°18'	74.9 e-h	58.0 b-g	59.0 b-h
E131	Yiyang Hunan	28°24'	112°27'	74.4 e-i	52.3 b-i	53.9 d-j
E129	Ningxiang Hunan	28°14'	112°36'	72.9 e-j	52.4 b-i	53.7 d-j
E035	Chuxian Anhui	32°18'	118°20'	72.1 f-k	58.3 b-g	59.5 b-g
E071	Liuzhou Guangxi	24°18'	109°26'	71.2 f-l	50.1 d-i	52.3 d-j
E039	Lushan Jiangxi	28°36'	116°00'	71.0 f-l	56.9 b-h	57.8 b-i
E158	'TifBlair'	—	—	69.0 f-m	52.6 b-i	53.7 d-j
E140	Qionglai Sichuan	30°24'	103°41'	68.9 f-m	51.9 b-i	53.3 d-j
E062	Fuyuan Guangdong	24°58'	113°15'	68.5 f-m	51.0 c-i	52.2 d-j
E079	Shien Hubei	30°15'	109°22'	67.9 g-m	50.9 c-i	52.6 d-j
E157	Common	—	—	67.7 g-m	50.8 c-i	52.3 d-j
E084	Anshun Guizhou	26°14'	105°54'	67.4 g-m	50.2 d-i	51.7 d-j
E013	Yongtai Fujian	25°50'	119°06'	67.3 g-n	51.4 b-i	52.5 d-j
E022	Wuxi Jiangsu	31°35'	120°20'	66.1 h-o	47.7 d-i	48.8 d-k
E126	Changsha Hunan	28°10'	112°49'	65.6 h-p	49.8 d-i	51.3 d-k
E074	Yongzhou Hunan	26°16'	111°37'	65.3 h-p	54.7 b-h	55.7 b-j
E064	Yingde Guangdong	24°06'	113°30'	64.3 h-p	46.5 d-i	47.8 e-k
E030	Ningguo Anhui	30°08'	119°00'	63.8 h-p	49.9 d-i	50.8 d-k
E189	Guangde Anhui	30°52'	119°32'	63.3 i-q	47.7 d-i	48.9 d-k
E152	Luoshan Henan	32°11'	114°33'	62.9 j-q	47.8 d-i	49.0 d-k
E078	Yichang Hubei	30°35'	111°00'	61.2 k-q	47.1 d-i	48.2 e-k
E033	Tunxi Anhui	29°43'	118°20'	61.2 k-q	41.4 f-i	42.9 g-k
E051	Yixing Jiangsu	31°22'	119°49'	59.8 l-r	46.6 d-i	47.8 e-k
E151	Xinyang Henan	31°50'	114°04'	59.5 l-r	45.9 d-i	46.8 f-k
E121	Chuzhou Anhui	32°22'	118°06'	59.0 m-r	46.5 d-i	47.5 e-k
E090	Nanshan Park Chongqing	29°32'	106°33'	58.3 m-s	44.1 e-i	45.7 f-k
E021	Hangzhou Zhejiang	30°20'	119°54'	57.7 m-t	45.5 d-i	46.5 f-k
E092-1	Yubei Chongqing	29°32'	106°33'	56.0 n-t	44.9 d-i	45.7 f-k
E185	Fuyang Zhejiang	30°20'	119°54'	55.6 o-t	45.7 d-i	46.5 f-k
E142	Huoqiu Anhui	31°45'	116°06'	54.6 p-t	37.3 ghi	38.3 ijk
E107	Queshan Henan	32°43'	113°59'	52.4 q-u	44.9 d-i	45.5 f-k
E143	Gushi Henan	32°10'	115°37'	49.8 r-u	45.1 d-i	45.5 f-k
E016	Jinhua Zhejiang	29°07'	119°32'	49.6 r-u	43.3 e-i	43.7 g-k
E109	Xuyu Jiangsu	32°56'	118°46'	49.1 r-v	40.8 f-i	41.3 g-k
E156	Lianyungang Jiangsu	34°44'	119°21'	47.8 s-v	40.1 ghi	40.7 g-k
E080	Qianjiang Hubei	30°27'	112°48'	47.3 s-v	36.7 ghi	37.6 ijk
E046	Suzhou Jiangsu	31°16'	120°34'	46.7 t-w	35.7 hi	36.6 jk
E027	Lianyungang Jiangsu	34°36'	119°12'	43.6 uvw	42.2 e-i	42.3 g-k
E184	Putoshan Zhejiang	30°01'	122°30'	42.2 uvw	38.6 ghi	39.0 h-k
E089	Xinjin Sichuan	30°14'	103°48'	38.6 vw	39.7 ghi	39.6 g-k
E006	Nanjing Jiangsu	32°03'	118°52'	36.6 w	30.9 i	31.5 k
Range of variation (%)				36.6–107.7	30.9–78.5	0.531–80.5
CV (%)				39.9	32.9	33.6
F value				20.31**y	2.63**	3.31**

^zValues within a column followed by the same letter are not different at the 5% level of probability based on Duncan's multiple range test.

* $P < 0.05$ significant difference; ** $P < 0.01$ significant difference; NS = no significant difference.

Table 2. Relative root mass, shoot mass, total biomass of five resistant accessions and five sensitive accessions grown in acid subsoil for 28 d.

Accessions	Relative root mass (%)	Relative shoot mass (%)	Relative total biomass (%)
E041	82.0 c ^z	85.5 ef	84.4 e
E014	77.5 bc	80.5 ef	79.8 de
E136	66.4 b	86.3 f	79.2 de
E072	67.8 b	67.9 cd	67.9 c
E076	68.7 b	74.0 de	72.3 cd
E046	47.9 a	49.6 ab	49.0 ab
E027	45.4 a	62.0 c	56.4 b
E184	45.6 a	48.5 ab	47.7 ab
E089	51.1 a	56.8 bc	54.9 b
E006	41.4 a	44.1 a	43.5 a
F value	17.13**y	17.74**	22.69**

^zValues within a column followed by the same letter are not different at the 5% level of probability based on Duncan's multiple range test.

^y**P* < 0.05 significant difference; ***P* < 0.01 significant difference; NS = no significant difference.

following formula: (concentrations of P, Mg, Ca, K, or Al in one cup with Al/concentrations of P, Mg, Ca, K, or Al in one cup without Al) × 100%. All statistical analyses were conducted by SPSS10.0 (SPSS10.0 Software in Medical Statistics, 2003).

Results and Discussion

Growth of the 50 centipedegrass accessions and cultivars studied was adversely affected when exposed to 1500 μM Al for 28 d (Table 1). The root morphology and appearance were abnormal with coralloid branches and poor root hairs being observed. There were significant differences in RRW, RSW, and RTW among the 50 accessions and cultivars. The variation ranges of the RRW, RSW, and RTW were 36.6% to 107.7%, 30.9% to 78.5%, and 31.5% to 80.5% respectively, and the coefficients of variation were 39.9%, 32.9%, and 33.6%, respectively. Based on the results of RRW as the evaluation parameter, the accessions from China, E041, E014, E136, E072, E076, and E007, were more resistant than TifBlair and the common centipedegrass used in the study, whereas 14 accessions from China were more sensitive than TifBlair and the common centipedegrass. Based on the results of RSW, the Chinese accession E041 was more resistant than TifBlair and the common centipedegrass. Based on RTW, E041, E014, and E076 were more

resistant than TifBlair and the common centipedegrass, whereas Chinese accession E006 was more sensitive than TifBlair and the common centipedegrass. According to the information referencing TifBlair registration (Hanna et al., 1997), TifBlair is an Al-tolerant cultivar. A greater genetic diversity in Al tolerance among the 48 screened accessions collected in China was identified through this research. The results indicate a promising potential for future enhancement of Al resistance among centipedegrass accessions and cultivars. The variation in Al tolerance among centipedegrass accessions from China were greater than expected, which could be partially explained by centipedegrass being a native grass in China and other Asian countries. It was observed that accessions showing less Al stress were from acid soil areas in China such as Guangxi, Jiangxi, and Guizhou Provinces where soil types are mainly lateritic red soils (Xiong and Kui, 1987). Other accessions showing more sensitivity to Al stresses were naturally distributed in slightly acid soil or neutral soil areas such as Jiangsu and Henan Provinces, in which soil types were mainly yellow-brown and Fluvo-aquic soils (Xiong and Kui, 1987). Liu et al. (1995) reported that the midwest ecotype Kentucky bluegrass (*Poa pratensis* L.) exhibited greater sensitivity to Al among seven ecotypes and could be attributable, in part, to these midwest habitats of origin where soil pH is typically near neutral.

The correlations among the RRW, RSW, and RTW were significant (*r* = 0.699, 0.803, and 0.843 at *P* < 0.01, respectively), so all three parameters could be used to evaluate the Al tolerance of centipedegrass accessions and cultivars, which is similar with several previous studies (Baldwin et al., 2005; Liu et al., 1995, 1996, 1997).

According to the results of the multiple comparisons in Table 1, the five accessions (E041, E014, E136, E072, and E076) more resistant to Al (resistant group) and five accessions (E006, E089, E184, E027, and E046) more sensitive to Al (sensitive group) were artificially chosen to determine the effect of Al on uptake of P, Mg, Ca, K, and Al. The 10 accessions selected were grown in acid subsoil to evaluate the genetic diversity related to nutrient uptake under Al stress. There is a dearth of such information in the literature.

Significant differences were found between the resistant group and sensitive group of accessions when grown in acid subsoil for 28 d (Table 2). The resistant group of accessions demonstrated better growth than the sensitive-group accessions, which was consistent with results found earlier in the solution culture screening. However, Al had negative effects on uptake of P, Mg, Ca, and K for both groups. The Al concentrations in shoots and roots of two groups were significantly higher than that of the control after Al treatment. A remarkable increase of 1.3 to 2.1 times in shoots and 7.0 to 15.2 times in roots (Table 3) indicates significant Al uptake among centipedegrasses. The results also indicate that Al is primarily retained in roots when absorbed by centipedegrasses with a relatively small amount being transported to shoots. The shoot Al concentrations of the five resistant-group accessions were significantly lower than the five sensitive-group accessions, which agreed with previous reports that absorbed Al in crops and turf-grasses was transported to shoots slowly after being taken up by roots of resistant species or cultivars (Foy and Murray, 1998a; Kochian et al., 2005; Rengel and Robinson, 1989).

There was a significant negative effect of Al on P concentrations in shoots when exposed to Al for 28 d. An average reduction

Table 3. The phosphorus (P), magnesium (Mg), calcium (Ca), and potassium (K) concentrations (RT/control %) and aluminum (Al) concentration (RT/control) of resistant-group and sensitive-group accessions affected by Al at 1500 μM in culture solutions for 28 d.

Accession	Al		P		Mg		Ca		K	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
E041(T) ^z	1.27 a ^y	6.98 a	55.3 b ^y	86.4	51.8 cd	58.4	63.3 e	71.0 c	64.1	70.3
E014(T)	1.48 ab	7.55 ab	52.4 b	92.1	55.5 d	51.7	60.5 e	63.2 bc	55.9	59.8
E136(T)	1.39 ab	7.62 ab	50.0 b	89.8	48.9 bcd	49.5	56.2 de	60.6 abc	61.6	68.7
E072(T)	1.30 ab	9.12 b	52.8 b	86.9	50.5 cd	50.8	60.8 e	66.6 bc	57.7	63.8
E076(T)	1.56 bc	8.07 ab	49.5 b	93.3	47.9 bcd	48.5	56.9 de	55.2 ab	62.6	70.4
E006(S)	2.06 e	15.18 d	27.7 a	89.0	36.7 a	39.6	41.1 ab	52.1 ab	57.9	66.1
E089(S)	2.09 e	14.98 d	28.4 a	92.0	38.4 ab	41.0	39.3 a	50.8 ab	60.3	67.1
E184(S)	1.74 cd	13.69 cd	31.8 a	95.6	41.5 abc	44.0	44.6 abc	52.0 ab	50.3	52.9
E027(S)	1.82 cde	14.04 cd	29.5 a	92.8	39.1 ab	49.9	47.1 bc	45.4 a	56.7	66.2
E046(S)	1.85 de	12.39 c	30.1 a	95.4	41.2 abc	41.7	50.6 cd	51.7 ab	59.5	71.2
Mean	1.65	10.96	40.7	91.3	45.2	47.5	52.1	56.8	58.7	65.6
F value	12.78**x	40.37**	18.15**	NS	3.68**	NS	13.93**	2.78*	NS	NS

^zT = resistant group; S = sensitive group.

^yValues within a column followed by the same letter are not different at the 5% level of probability based on Duncan's multiple range test.

^x**P* < 0.05 significant difference; ***P* < 0.01 significant difference; NS = no significant difference.

in P of 59.3% in shoots and 8.7% in roots was observed. The P concentration of the resistant group was significantly higher than the sensitive group (Table 3). The results indicate that there was less influence of P concentration in the resistant group compared with the sensitive group. Also, there was less influence of P in roots compared with shoots after Al treatment. Baldwin et al. (2005) reported that Al stress reduced both shoot and root P concentrations of centipedegrass and the results of this study also confirmed that conclusion. It was reported that formation of P–Al complexes caused a reduction in root influx of P and transportation to shoots, consequently decreasing P accumulation in plant (Pfeffer et al., 1986). So, the assumption is that the formation of P–Al complexes might occur in both resistant-group and sensitive-group accession roots. However, the higher P concentrations (RT/control %) of the resistant group might be explained by mechanisms that ameliorate Al toxicity and reduce the formation of P–Al complexes, consequently increasing the transport of P to shoots and improving use of P in roots. Organic acid and phenolic compounds can form complex Al compounds resulting in reduced Al toxicity (Kochian et al., 2005), but higher P concentrations (RT/control %) of the sensitive group were found as well and this could be the result of the formation of complex P–Al compounds. However, additional experiments are needed to further explore P and Al relationships among centipedegrass and other turfgrass species.

There was a remarkable negative effect of Al on Mg, Ca, and K concentrations in shoots and roots in the two groups with an average reduction of 54.8%, 47.9%, and 41.3% in shoots and 52.5%, 43.2%, and 34.4% in roots, respectively (Table 3). When plants are exposed to Al, Mg and Ca uptake has been significantly inhibited (Marschner, 1995). Rengel and Robinson (1989) reported that Al-resistant annual ryegrass (*Lolium multiflorum* Lam.) cultivars could maintain greater uptake of Ca and Mg than sensitive ryegrass cultivars. Eduardo and Willem (2005) observed the same phenomenon in maize. Our study agreed with these findings. There were some controversies about the Al effect on K. Gassmann and Schroeder (1994) reported that Al inhibited plant uptake of K and decreased K concentrations in shoots and roots, because Al was considered a cation channel inhibitor and could subsequently result in the deficiency of K in shoots. However, Rengel and Robinson (1989) found that the K concentrations increased after a lower dosage of Al stress treatment with annual ryegrass.

Further research is needed to evaluate centipedegrass accessions on acid soils, including turf quality, drought stress, low temperature stress, and other environmental stresses. It is also meaningful to study Al tolerance mechanisms of resistant-group accessions such as P and Al relationships, the function of root secretions, and intracellular resistance mechanisms. Furthermore, to improve overall turf quality and morphological characteristics such as leaf width, plant height, recuperative ability, and pest resistance among centipedegrass accessions and cultivars, the Al-resistant group should be evaluated under field conditions to identify potential for further enhancement of this economically important turfgrass species.

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