TÜBİTAK

Research Article

Turk J Agric For
36 (2012) 720-728
© TÜBİTAK
doi:10.3906/tar-1109-26

Effect of Al compounds on soil pH and bioavailability of Al in two acid soils

Md. Toufiq IQBAL

Department of Agronomy and Agricultural Extension, University of Rajshahi, Rajshahi 6205 – BANGLADESH

Received: 17.09.2011 ● Accepted: 26.04.2012

Abstract: Two aluminum compounds, $AlCl_3$ and $Al(OH)_3$, were used to determine the effect of Al compounds on pH and bioavailability of Al in 2 acid soils. Both soils were incubated for periods of 3, 10, and 30 days. Al-tolerant (ET8) and Al-sensitive (ES8) wheat seedlings were used as a testing plant to confirm bioavailability of Al^{3+} in soil solution. Both soils were acidified through the addition of Al compounds to detect the maximum Al^{3+} toxicity level of these compounds. The results showed that the $AlCl_3$ compound increased the bioavailability of Al^{3+} in soil solutions. In contrast, $AlCl_3$ decreased bulk soil pH. This combination of high levels of extractable Al and low pH decreased the root proliferation of both ES8 and ET8. However, $Al(OH)_3$ did not change soil pH, the bioavailability of Al, or the root length of either ES8 or ET8. These findings indicated that $Al(OH)_3$ did not increase Al^{3+} activity in soil solutions. It can be concluded from this study that $AlCl_3$ and a short incubation period can be used to manipulate soil pH and the bioavailability of Al in soil for further study. However, $Al(OH)_3$ cannot be used to manipulate soil pH or the bioavailability of Al in soil.

Key words: Aluminum, bioavailability, ES8, ET8, incubation time, soil type

Introduction

Soil aluminum chemistry is quite complex and different forms of Al available in soil are involved in the retention of anions, cations, and phytotoxicity of Al ions in acid soils (Soon 1993). The type of Al compound is also responsible for producing different forms of bioavailable Al in soil (Skyllberg 1999). This availability of different forms of Al ions in soil solutions can be manipulated by the application of different types and rates of Al compounds and lime (Bache 1974). Thus, the amount of Al present in a soil solution depends on the amount and kind of Al compounds present in the soil and its reaction capacity within the soil solution (Magistad 1925).

The speciation of Al compounds is controlled by the hydrolysis of the Al^{3+} ion (Perdue 1985). During the hydrolysis process, a proton is released. This is because of the extent to which acid cations like Al^{3+} induce hydrolysis and decrease soil pH (Milne et al. 1995).

The bioavailability of Al and nutrients depends on their concentration in the soil solution (Curtin and Smillie, 1995). Incubation time can affect different Al compounds in terms of the activity of the Al^{3+} ion in soil solutions (Menzies and Bell 1988). Menzies et al. (1991) concluded that Al^{3+}, toxic to plants, reached a stable concentration in soil solutions after incubation for 1 day. Thus, understanding the

* E-mail: toufiq_iqbal@yahoo.com

effect of incubation time on the solubilization of Al compounds is necessary to study Al toxicity in plants.

In this paper, the effects of Al compounds and incubation time on soil pH and extractable Al were examined in order to select an appropriate Al compound for varying the pH and Al toxicity levels in soil and to define a preincubation time for soil amendments. Different soil pH and Al levels were achieved by incubating the soil with various amounts of $CaCO_3$, $AlCl_3$, and $Al(OH)_3$, respectively. Lime ($CaCO_3$) was used to increase soil pH and decrease soil extractable Al. Wheat genotype growth responses were also examined under conditions of high pH and low extractable Al in soil. The hypothesis of this study is that $AlCl_3$ will increase the bioavailability of Al^{3+} in soil and that a longer incubation period (more than 3 days) will have no further effects on soil pH and extractable Al.

Materials and methods

Soils and basal nutrients

This study used 2 acid soils, a Podosol and a Chromosol (Isbell 2002). The Podosol had an initial pH of 3.76 (0.01 M $CaCl_2$), a pH buffer capacity (pHBC) of 0.81 cmol kg^{-1} pH^{-1}, and an extractable Al value of 3.90 mg kg^{-1}. The Chromosol had an initial pH of 4.10 (0.01 M $CaCl_2$), a pHBC of 1.46 cmol kg^{-1} pH^{-1}, and an extractable Al value of 3.9 mg kg^{-1}. The other basic soil properties are described in Table 1. The Chromosol was mixed with sand at a ratio of 3:1 to reduce its pHBC. Podosol already has a low pHBC, so no sand was added. Both the Podosol and the Chromosol were mechanically sieved to a diameter of <2 mm. Likewise, the sand was sieved in a 600-µm sieve before being mixed with the Chromosol. The following types of basal nutrients were added in this experiment: $Ca(NO_3)_2.4H_2O$, $NaH_2PO_4.2H_2O$, K_2SO_4, $MgCl_2.6H_2O$, $MnSO_4.7H_2O$, $ZnSO_4.7H_2O$, $CuSO_4.5H_2O$, H_3BO_3, $Na_2MoO_4.2H_2O$.

Al compound

This study used the 2 aluminum compounds $AlCl_3$ and $Al(OH)_3$. Aluminum sulfate ($Al_2(SO_4)_3$) was not used in this experiment because the Al-SO_4 complex makes this compound less toxic (Alva et al. 1991).

Plants and their genotypic characteristics

Both Al-tolerant (ET8) and Al-sensitive (ES8) wheat genotypes were used as test plants. The ES8 and ET8 genotypes were near-isogenic (over 95%) lines differing in Al tolerance at the *ALMT1* locus (Ahn and Matsumoto 2006). The ET8 and ES8 lines were derived from a cross between the Al-tolerant cultivar Carazinho and the Al-sensitive cultivar Egret, with the resulting progeny backcrossed 8 times to Egret or derivatives of Egret (Fisher and Scott 1987).

Experimental design and treatments

The experiment was arranged factorially with the following treatments:

1) 4 $AlCl_3$ × 3 $CaCO_3$ × 2 soils × 2 genotypes,
2) 4 $Al(OH)_3$ × 1 $CaCO_3$ × 1 Podosol × 2 genotypes at 0.5 g $CaCO_3$.

Each treatment had 3 replications. The $CaCO_3$ was used to manipulate soil pH and Al levels in both soils. Both $AlCl_3$ and $Al(OH)_3$ levels were 0, 0.5, 1, and 2 g kg^{-1}. High levels of $AlCl_3$ were added to determine the maximum Al^{3+} activity within the soil solutions.

Soil incubation

Into each pot, 200 g of soil was weighed and kept to 100% field capacity by weighing the pots during incubation. The water in the soil was maintained to field capacity for both the Podosol (19% water per

Table 1. Properties of soils used in this study.

Soil type	Collection site	GPS location	EC (mS cm^{-1})	Field capacity (% water per water)	Sand %	Silt %	Clay %	Total N%	Total C%	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})
Podosol	Cranbourne, Victoria	38°06′S 145°16′E	0.113	19	92	4	4.0	0.15	3.40	14.7	10.7
Chromosol	Wagga Wagga, New South Wales	35°05′S 147°35′E	0.069	13	55	25	20	0.05	0.58	2.7	14.1

water) and the Chromosol (13% water per water). To prevent evaporation loss during the incubation period, all the pots were placed in plastic boxes covered with lids in a temperature-controlled room at 25 °C. A standing-water level of 2.5 cm was also maintained at the bottom of each box during incubation. The soils were sampled at 3, 10, and 30 days of incubation using a small core sampler that collected about 6 g per core. All holes were closed after soil collection by shaking or oscillating each pot. All collected soils were air-dried prior to taking pH and Al measurements.

Plant growth

Following the last soil sampling (at 30 days), the soil of each pot was divided into 2 equal parts (90 g each) and transferred into 2 separate 50-mL vials. The soils were properly compacted by tapping each vial while it was being filled with soil. Five uniform pregerminated seeds were placed in each vial and covered with 0.5 cm of soil from the top of the vial. Each vial contained 2 Al-tolerant (ET8) and Al-sensitive (ES8) wheat (*Triticum aestivum* L.*)* genotypes. Water was added daily by spraying each vial during the plant growth period. The plants were grown in a growth cabinet under controlled environment conditions in which the day and night temperatures were a constant 20 °C, there was 10 h of dark and 14 h of light, and the average light intensity was 210 μM photons m^{-2} s^{-1}. The plants were harvested 11 days after sowing. The roots were collected and washed with deionized water before measurements were taken.

Measurements

Soil pH was determined with a 1:5 extraction of 0.01 M $CaCl_2$ after 17 h of shaking. Extractable Al was determined in 0.01 M $CaCl_2$ using the PCV method (Kerven et al. 1989). Root length was measured and analyzed using the WinRHIZO image analysis system (Regent Instruments Inc., Quebec, Canada) (Arsenault et al. 1995).

Statistical analysis

Results were analyzed using either 2-way or 3-way analysis of variance (ANOVA) using GenStat, 5th edition (Lawes Agricultural Trust, UK).

Results

Bulk soil pH, extractable Al, and root length of wheat seedlings in Podosol

The addition of 500 mg $CaCO_3$ kg^{-1} soil increased the bulk soil pH by 0.33 units. In the soil amended with 500 mg of $CaCO_3$, the addition of $AlCl_3$ at 2000 mg kg^{-1} resulted in a pH reduction of 0.57 units. In comparison, the addition of $Al(OH)_3$ at the same rate resulted in a pH increase of around 0.05 units. Bulk soil pH is similar in soils with 500 and 1000 mg kg^{-1} $Al(OH)_3$ with 500 mg kg^{-1} $CaCO_3$ availability. However, bulk soil pH dropped significantly ($P < 0.05$) in soils with 500 and 1000 mg kg^{-1} $AlCl_3$ with 500 mg kg^{-1} $CaCO_3$ availability (Figure 1a, Table 2).

The concentration of extractable Al in bulk soil remained unchanged following the addition of $Al(OH)_3$ in a no-lime control treatment. However, it decreased significantly ($P < 0.05$) in soil with 500 mg kg^{-1} $CaCO_3$ but was not affected by the increasing addition of $Al(OH)_3$ (Table 2). In contrast, the concentration of extractable Al in bulk soil increased remarkably due to an increasing addition of $AlCl_3$ in soil with 500 mg kg^{-1} $CaCO_3$ (Figure 1b).

Root length of Al-tolerant and Al-sensitive wheat seedlings under soil pH and extractable Al amended by $AlCl_3$

The root lengths of both ES8 and ET8 seedlings increased significantly ($P < 0.05$) with the increase in bulk soil pH (Table 2). In contrast, the root lengths of both ES8 and ET8 seedlings dramatically decreased with the increase in extractable Al in bulk soil. There was no significant difference in root length between the genotypes for both bulk soil pH and extractable Al (Figures 2a and 2b).

Effect of incubation time on soil pH in Podosol and Chromosol

The incubation time did not differ for the 0 and 2000 mg $CaCO_3$ kg^{-1} treatments under various levels of $AlCl_3$ availability in Podosol. The incubation time differed for the 500 and 1000 mg $AlCl_3$ kg^{-1} availabilities for the 0 and 2000 mg $CaCO_3$ treatments, respectively, in Chromosol. Both soils with 0 $AlCl_3$ and 0 $CaCO_3$ become more acidic after 3 days of incubation and generally reached similar values of pH after 30 days of incubation. At 2000 mg kg^{-1} of $AlCl_3$, both soils exhibited similar changes in soil pH, which suggests

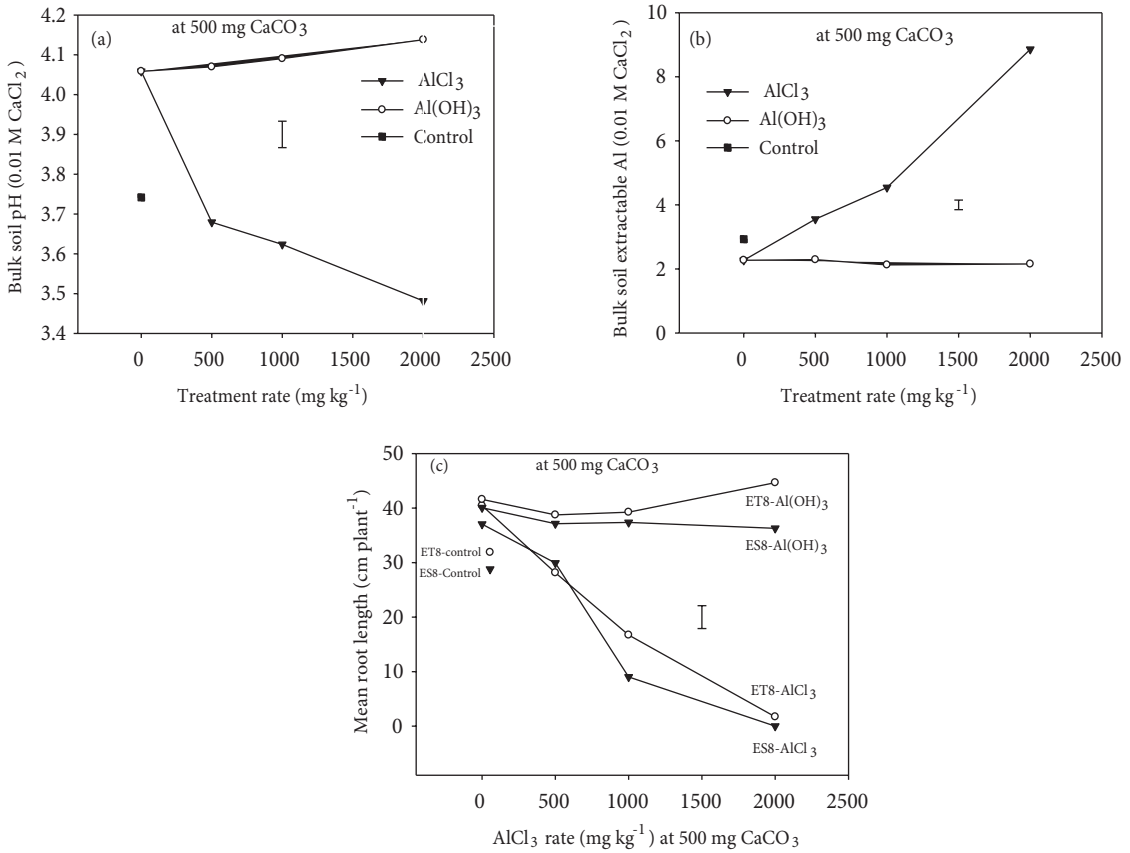

Figure 1. The effect of aluminum compounds ($Al(OH)_3$ and $AlCl_3$) on a) bulk soil pH, b) extractable Al in bulk soil, and c) root length of Al-tolerant (ET8) and Al-sensitive (ES8) wheat seedlings grown in Podosol amended with 500 mg kg^{-1} of $CaCO_3$. Vertical bars represent the least significant difference (P = 0.05) for genotype and Al compound interaction.

that the pH level did not change in 3, 10, or 30 days of incubation. The soil pH dramatically dropped due to different levels of $AlCl_3$ with 2000 mg $CaCO_3$ kg^{-1} in Podosol and Chromosol. Soil pH was similar among the 3, 10, and 30 days of incubation at different $AlCl_3$ levels with 2000 mg $CaCO_3$ kg^{-1} in Podosol (Figures 3a-3d).

Effect of incubation time on soil extractable Al in Podosol and Chromosol

In general, the concentration of extractable Al was not affected by incubation time in Podosol. The soil extractable Al increased significantly ($P < 0.05$) with an increasing $AlCl_3$ supply along with 0 $CaCO_3$ in both Podosol and Chromosol (Table 2). The extractable Al did differ for 3, 10, and 30 days of incubation with 0 and 2000 mg $CaCO_3$ treatments in Podosol at various levels of $AlCl_3$ availability. The extractable Al concentration in Chromosol with 0 $CaCO_3$ did not differ for 3, 10, or 30 days of incubation at various levels of $AlCl_3$ availability. The extractable Al concentration in Chromosol with 2000 mg $CaCO_3$ kg^{-1} treatments differed for 3, 10, and 30 days of incubation under 1000 and 2000 mg $AlCl_3$ kg^{-1} treatments. The available Al in the soil was 2-fold higher in Podosol than in Chromosol at 2000 mg of $CaCO_3$ under different $AlCl_3$ treatments. This was because the concentration of extractable Al was originally higher in Podosol than in Chromosol. Similar to that for 0 $CaCO_3$, the effect of incubation was not significant at 2000 mg $CaCO_3$ under different $AlCl_3$ treatments for either soil (Figures 4a-4d).

Effect of $AlCl_3$ addition on mean root length in Podosol and Chromosol

The mean root length of ES8 seedlings was initially 29% greater in Chromosol than in Podosol at 0 $CaCO_3$ availability. It decreased significantly ($P <$

Table 2. Significance levels for the main and interactive effects of soil, compound, and wheat genotype on bulk soil pH, bulk soil extractable Al, incubation time, and root length.

Source of variation	Bulk soil pH	Bulk soil extractable Al	Root length
Compound	***	***	NA
Treatment	***	***	NA
Compound × treatment	***	***	NA
$AlCl_3$	NA	NA	***
$Al(OH)_3$	NA	NA	**
$AlCl_3 \times Al(OH)_3$	NA	NA	n.s.
Genotype	NA	NA	n.s.
Genotype × compound	NA	NA	n.s.
Bulk soil pH	NA	NA	***
Bulk soil extractable Al	NA	NA	***
Genotype	NA	NA	n.s.
Treatment	NA	NA	***
Soil	NA	NA	***
Treatment × soil	NA	NA	***

The symbols n.s. and *** represent $P > 0.05$ and $P \leq 0.001$, respectively. 'NA' indicates that no data are available. Values were means of 6 replicates for bulk soil pH as well as extractable Al in bulk soil (as no plant effect in bulk soil) and 3 replicates for root length. Sampling was done after 3, 10, and 30 days of incubation and plants were grown after 30 days of incubation.

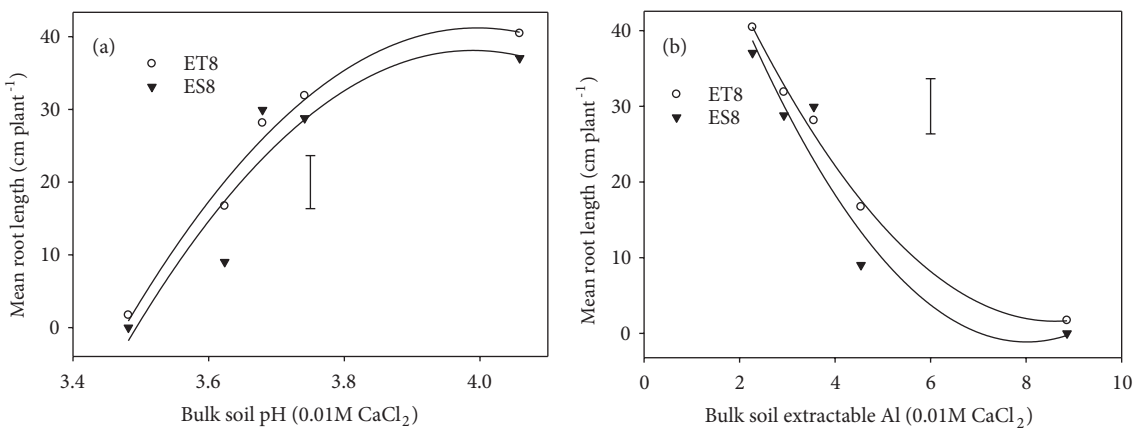

Figure 2. Changes in mean root length due to an increase in a) bulk soil pH and b) extractable Al in bulk soil for the Al-tolerant (ET8) and Al-sensitive (ES8) wheat seedlings. Data were mean values of 3 replicates. Vertical bars represent the least significant difference ($P = 0.05$) for genotype and extractable Al in both bulk soil and bulk soil pH interaction.

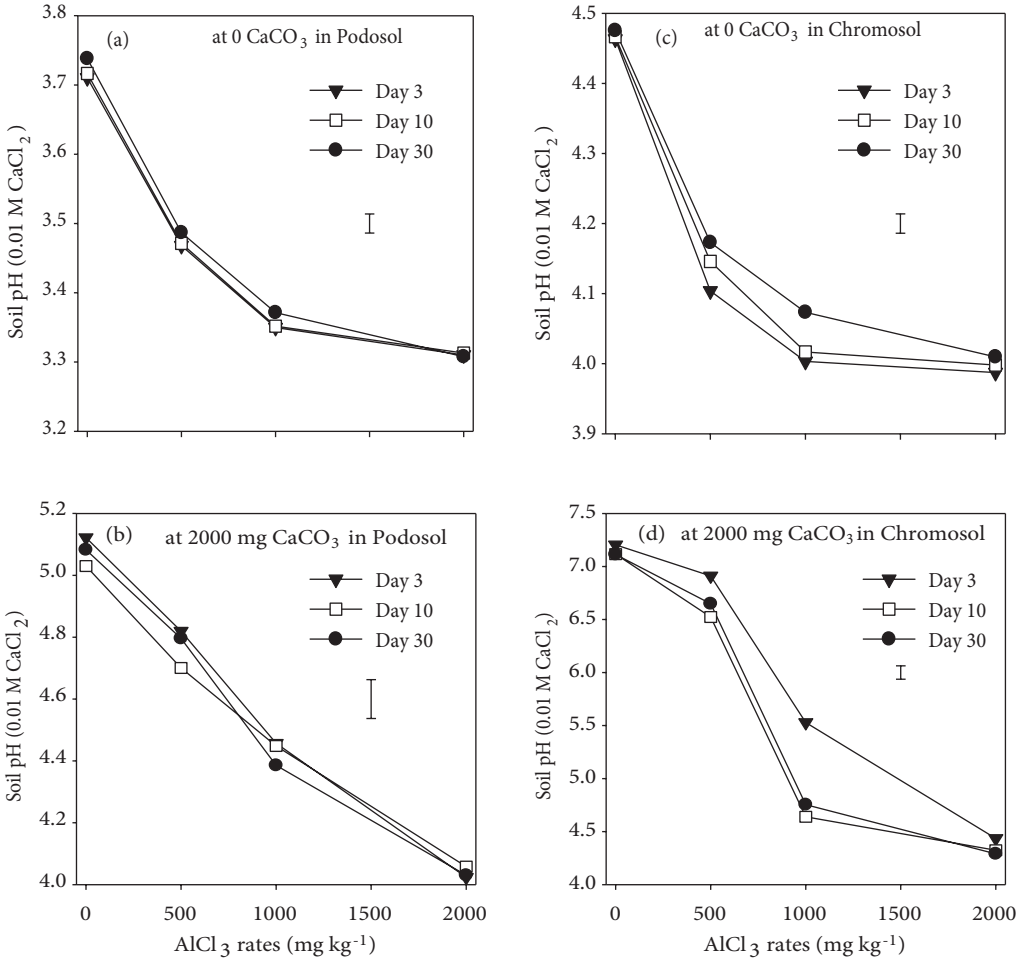

Figure 3. The effect of incubation time on soil pH for a) Podosol at 0 mg of $CaCO_3$ availability, b) Podosol at 2000 mg of $CaCO_3$ availability, c) Chromosol at 0 mg of $CaCO_3$ availability, and d) Chromosol at 2000 mg of $CaCO_3$ availability under different rates of $AlCl_3$ addition. Vertical bars represent the least significant difference (P = 0.05) for day, soil, and treatment interaction. Data were the average values of 3 replicates.

0.05) with the addition of $AlCl_3$ along with 0 $CaCO_3$ (Table 2). The mean root length of ES8 seedlings in Podosol differed significantly ($P < 0.05$) between the 0 and 2000 mg $CaCO_3$ treatments under different $AlCl_3$ availabilities (Table 2). However, the mean root length of ES8 seedlings in Chromosol did not significantly differ between the lime treatments at the 0 and 2000 mg $AlCl_3$ kg^{-1} availabilities, respectively. Similarly, mean root length did not differ between 0 and 2000 mg of $CaCO_3$ along with 2000 mg $AlCl_3$ kg^{-1} treatment in Chromosol. Moreover, the mean root length of ES8 seedlings was greater for the 0 than the 500 mg $CaCO_3$ kg^{-1} treatment with the 500 and 1000 mg $AlCl_3$ kg^{-1} treatments, respectively, in Chromosol (Figures 5a and 5b).

Discussion

Effect of Al compounds on soil acidity

The 2 Al compounds, aluminum chloride ($AlCl_3$) and aluminum hydroxide ($Al(OH)_3$), differed markedly in their ability to increase the bioavailability of Al in soil. The bulk soil pH declined and the concentration of extractable Al increased with the addition of $AlCl_3$ to the soil. In contrast, these measurements did not change with the addition of $Al(OH)_3$ to the soil. As a result, root growth of both the Al-tolerant (ET8) and Al-sensitive (ES8) wheat seedlings declined only with increasing amounts of $AlCl_3$ (Figures 1a-1c, Table 2). The differences between these 2 Al compounds can be attributed to their different solubility product

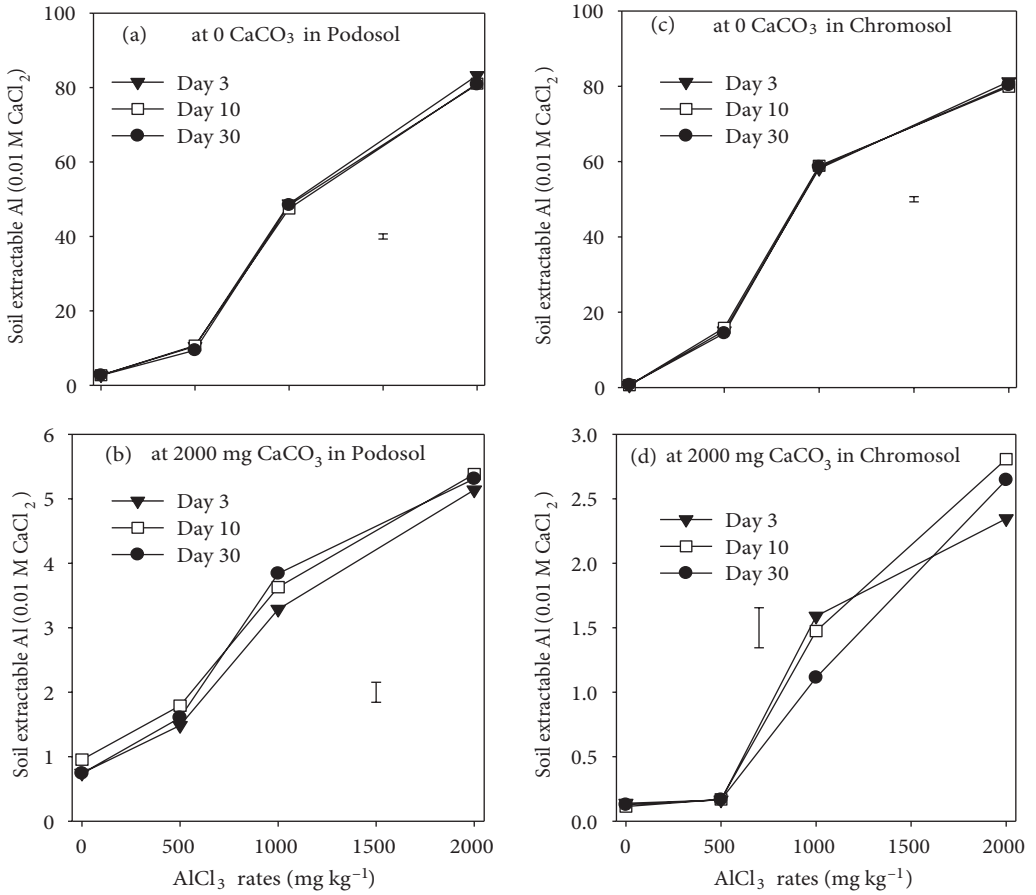

Figure 4. The effect of incubation time on soil extractable Al for a) Podosol at 0 mg of $CaCO_3$ availability, b) Podosol at 2000 mg of $CaCO_3$ availability, c) Chromosol at 0 mg of $CaCO_3$ availability, and d) Chromosol at 2000 mg of $CaCO_3$ availability under different rates of $AlCl_3$ addition. Vertical bars represent the least significant difference (P = 0.05) for day, soil, and treatment interaction. Data were the average values of 3 replicates.

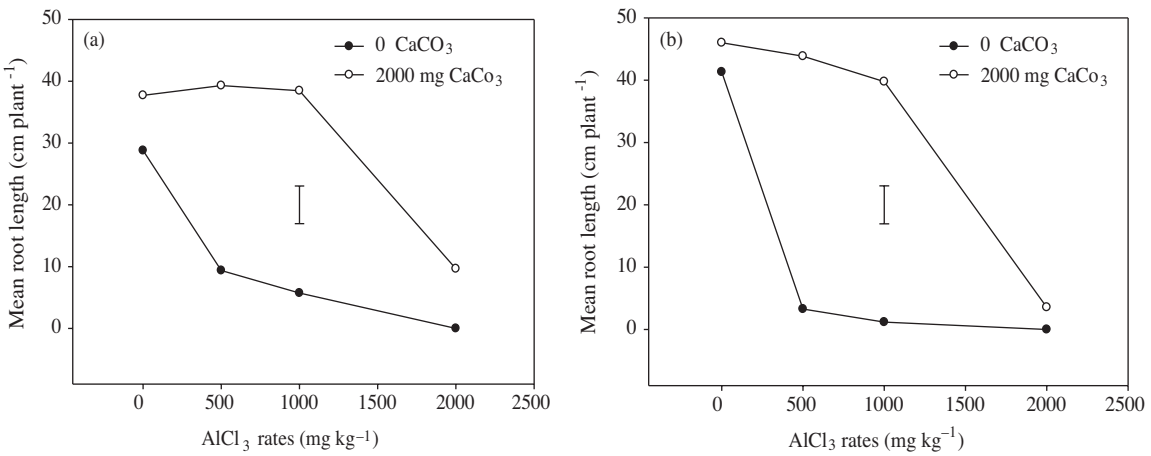

Figure 5. The effect of $AlCl_3$ addition on the mean root length of Al-sensitive (ES8) wheat seedlings grown for 11 days in a) Podosol and b) Chromosol. The soils were incubated for 30 days prior to commencement of the plant growth experiment. Vertical bars represent the least significant difference (P = 0.05) for soil × treatment interaction. Data were the average values of 3 replicates.

constants (K_{sp}). The K_{sp} values for $AlCl_3$ and $Al(OH)_3$ at 25 °C are 2.04×10^4 and 1.8×10^{-33}, respectively (Chang 2010). Thus, the mass of $AlCl_3$ that will dissolve in 100 mL of water at 25 °C is 111 g, whereas $Al(OH)_3$ practically does not dissolve in water (Budavari 1989).

The chemical properties of the $AlCl_3$ and $Al(OH)_3$ compounds and their solubility in the soil solution are responsible for the differences in their effects on soil pH and extractable Al. The dissociation of $AlCl_3$ ($AlCl_3 \rightarrow Al^{3+} + 3Cl^-$) initiates acidity due to the reaction of Al^{3+} with water in the soil solution ($Al^{3+} + 2H_2O \rightarrow Al^{3+}(OH)^{2+} + 2H^+$). Thus, $AlCl_3$ dissociates to Al^{3+} in the soil solution and increases both the bioavailability of Al in the soil and of Al^{3+} in the soil solution. This Al^{3+} also reacts with water to form mononuclear hydroxy-Al species ($Al(OH)^{2+}$), releasing H^+ ions and lowering the soil pH (Serrano 2003). In complete contrast, $Al(OH)_3$ does not dissolve in the soil solution at pH 4.0-6.0, and so it does not increase the bioavailability of Al in soil solution. This experiment demonstrates that $AlCl_3$ is the preferred compound for manipulating different levels of bioavailability of Al^{3+} in soil. It was therefore used in subsequent experiments in this study.

The effect of incubation time

Increasing incubation time from 3 to 30 days did not markedly affect the level of soil pH (Figures 3a-3d) or extractable Al (Figures 4a-4d), with the exception of 2000 mg of $CaCO_3$ in Chromosol, following the addition of $AlCl_3$ to the soils in this study. There was a rapid decrease in the pH and an increase in extractable Al in both soils after the application of $AlCl_3$; the effects stabilized during the measurement on day 3 and remained constant over the 30-day incubation period. The high solubility of $AlCl_3$ means that it quickly dissociates in water followed by the hydration of Al^{3+} forming mononuclear hydroxyl-Al species like $Al(OH)^+_2$ (Richens 1997). Likewise, Tanaka et al. (1987) reported that the chemical species of Al changed as soon as an $AlCl_3$ solution was added to the soil.

Other studies have reported similar effects of incubation time for inorganic and organically complexed forms of Al. Thus, neither organic nor inorganic Al significantly changed with incubation time and both remained stable for periods of time. For example, Menzies et al. (1991) incubated soil samples at 28 °C from 1 to 64 days. They found that soil pH and extractable Al did not change significantly with the extended (up to 64 days) incubation times. They also reported that the plant-toxic monomeric Al (Al^{3+}) reached a stable concentration in soil solution after 1 day of incubation. It should be pointed out that they did not manipulate soil Al. They just collected 5 acid soils of widely divergent chemical and physical characteristics and incubated them at 28 °C from 1 to 64 days. Similarly, Menzies and Bell (1988) also found that incubating a Krasnozem surface soil at 28 °C for 1 day was sufficient to attain an equilibrium condition for most ions, similar to that present under field conditions. Moreover, they did not manipulate soil Al but incubated soils for a period of up to 16 days. These findings indirectly suggest that short incubation periods are required for experiments in which the activity of Al^{3+} in soil is manipulated. Thus, a short incubation would allow Al^{3+} concentrations to stabilize in the soil solutions.

Effect of soil type

The Podosol was an inherently more acidic soil than the Chromosol in this experiment. The Podosol had a lower pH (3.8 in 0.01 M $CaCl_2$) and a higher concentration of extractable Al (3.9 mg kg^{-1}) than Chromosol. Even when 2000 mg of $CaCO_3$ was applied to both soils, the Podosol still had a lower pH and a higher extractable Al level than the Chromosol (Figures 3 and 4, Table 2). Thus, there was less root proliferation of the Al-sensitive wheat (ES8) seedlings in the Podosol than in the Chromosol both with and without $CaCO_3$ addition, due to the lower pH and higher extractable Al (Figures 5a and 5b, Table 2).

This particular acidic Podosol soil was collected from the surface layer of soil at Cranbourne, Victoria, Australia. Its acidity, with a low pH and high extractable Al, markedly reduced the growth of wheat roots. In 2 preliminary experiments (data not presented), it was not possible to demonstrate differences in root growth between the Al-sensitive ES8 and more Al-tolerant ET8 wheat genotypes as the root growth of both genotypes was markedly suppressed by the acidic properties of this surface soil. A soil with less acidic properties will be needed for subsequent experiments, in which the differential effects of acidic soil properties on these 2 genotypes

will be studied. Therefore, another Podosol collected from the subsoil at Frankston, Victoria, with an initial pH of 4.5 and extractable Al of 5.0 mg kg^{-1}, will be used in subsequent experiments involving the manipulation of Al concentrations using the addition of $AlCl_3$.

One type of Al compound affected soil pH and Al^{3+} activity in soil solution. The $AlCl_3$ compound increased the concentration of extractable Al and decreased pH in soil. The root length of ES8 and ET8 decreased during $AlCl_3$ treatments due to increases in the bioavailability of Al^{3+} in the soil. In contrast, $Al(OH)_3$ had no effect on soil pH or the activity of Al^{3+} in soil solution. As a result, ES8 and ET8 had similar root proliferation with or without the addition of $Al(OH)_3$. Moreover, no remarkable incubation effect was found for any of the treatments regarding soil pH and extractable Al. Therefore, for successive experiments, a short incubation period with an increased temperature (7 days at 30 °C) was selected for soil incubation and $AlCl_3$ was chosen to manipulate soil available Al (Iqbal et al. 2010).

Acknowledgment

The author is thankful to the Australian government and La Trobe University for providing an International Postgraduate Research Scholarship (IPRS) and a La Trobe University Postgraduate Research Scholarship (LTUPRS). The author is also grateful to the Australian Society of Soil Science Inc. (ASSSI) for student support to attend the 19th World Soil Congress in Brisbane, Australia.

References

Ahn SJ, Matsumoto H (2006) The role of the plasma membrane in the response of plant roots to aluminum toxicity. Plant Signal Behav 1: 37-45.

Alva AK, Kerven GL, Edwards DG, Asher CJ (1991) Reduction in toxic aluminum to plants by sulfate complexation. Soil Sci 152: 351-359.

Arsenault JL, Pouleur S, Messier C, Guay R (1995) WinRHIZO™, a root-measuring system with a unique overlap correction method. Hort Sci 30: 906.

Bache BW (1974) Soluble aluminium and calcium-aluminium exchange in relation to the pH of dilute calcium chloride suspensions of acid soils. J Soil Sci 25: 320-332.

Budavari S (1989) The Merck Index, 11th ed. Merck, New Jersey, USA.

Chang R (2010) Chemistry. McGraw Hill, New York, USA.

Curtin D, Smillie GW (1995) Effects of incubation and pH on soil solution and exchangeable cation ratios. Soil Sci Soc Am J 59: 1006-1011.

Fisher JA, Scott BJ (1987) Response to selection for aluminium tolerance. In: Priorities in Soil/Plant Relations Research for Plant Production (Eds. PGE Searle and BG Davey). University of Sydney, Sydney, Australia, pp. 135-137.

Iqbal MT, Sale P, Tang C (2010) Phosphorus ameliorates aluminium toxicity of Al-sensitive wheat seedlings. In: Proceedings of the 19th World Congress of Soil Science, Brisbane, Australia, pp. 92-95.

Isbell, RF (2002) The Australian Soil Classification. CSIRO, Collingwood, Victoria, Australia.

Kerven GL, Edwards DG, Asher CJ, Hallman PS, Kokot S (1989) Aluminium determination in soil solution. II. Short-term colorimetric procedures for the measurement of inorganic monomeric aluminium in the presence of organic acid ligands. Aust J Soil Res 27: 91-102.

Magistad OC (1925) The aluminum content of the soil solution and its relation to soil reaction and plant growth. Soil Sci 20:181-226.

Menzies NW, Bell LC (1988) Evaluation of the influence of sample preparation and extraction technique on soil solution composition. Aust J Soil Res. 26: 451-464.

Menzies NW, Bell LC, Edwards DG (1991) Effects of incubation time and filtration technique on soil solution composition with particular reference to inorganic and organically complexed Al. Aust J Soil Res 29: 223-238.

Milne CJ, Kinniburgh DG, de Wit JCM, van Riemsdijk WH, Koopal LK (1995) Analysis of proton bonding by a peat humic acid using a simple electrostatic model. Geo Cos Acta 59: 1101-1112.

Perdue EM (1985) Acidic functional groups of humic substances. In: Humic Substances in Soil, Sediment and Water (Eds. GR Aiken, DM McKnight, RL Wershaw, P MacCarthy). Wiley, New York, USA, pp. 493-526.

Richens DT (1997) The Chemistry of Aqua Ions. Wiley, New York, USA.

Robinson RA, Britton HTS (1931) The amphoteric nature of aluminium hydroxide. J Chem Soc: 2817-2820.

Serrano E (2003) Banana soil acidification in the Caribbean coast of Costa Rica and its relationship with increased aluminium concentrations. In: Banana Root System: Towards a Better Understanding for its Productive Management, Proceedings of an International Symposium (Eds. DW Turner, F Rosales), San Jose, Costa Rica, pp. 142-148.

Skyllberg U (1999) pH and solubility of aluminium in acidic forest soils: a consequence of reactions between organic acidity and aluminium alkalinity. Eur J Soil Sci 50: 95-106.

Soon YK (1993) Fractionation of extractable aluminum in acid soils: a review and a proposed procedure. Com Soil Sci Plant Anal 24:1683-1708.

Tanaka A, Tadano T, Yamamoto K, Kananura N (1987) Comparison of toxicity to plants among Al^{3+}, $AlSO_4^+$ and AlF complex ions. Soil Sci Plant Nutr 33: 43-55.