Drinking water treatment residuals as an amendment to alkaline soils: Effects on bioaccumulation of heavy metals and aluminum in corn plants

A.M. Mahdy[1], E.A. Elkhatib[1], N.O. Fathi[2]

[1]*Department of Soil and Water, College of Agriculture, Alexandria University, Alexandria, Egypt*
[2]*Salinity and Alkalinity Soils Research Laboratory, Ministry of Agriculture, Cairo, Egypt*

ABSTRACT

An alum-based drinking water treatment residue (DWTR) is the by-product from the production of potable water. Land application of DWTR has received a considerable attention for its potential as a low-cost disposal alternative. A greenhouse experiment was conducted to quantify the effects of DWTR on bioaccumulation of some heavy metals in plant tissue and to determine the effects of the DWTR on soil aluminum and aluminum phytotoxicity for the corn plants in alkaline soils. The results indicated that land application of DWTR significantly decreased extractable heavy metals in all studied soils. Combined analyses of all soils and rates of DWTR application showed significant relationship between DTPA-extractable heavy metals and heavy metals uptake of corn plants. Addition of DWTR with different rates (10, 20, 30 and 40 g/kg) to different soil types did not cause aluminum phytotoxicity symptoms for corn plants grown in all studied alkaline agricultural soils because the application rates of DWTR did not increase extractable Al in amended soils > 8 mg Al/kg and the Al phytotoxicity may occur below pH 5.5. Extractable Al is associated with pH of the studied soils, combined analyses of all soils and rates of DWTR application showed a significant relationship between extractable Al and pH. Based on the results of current study, the DWTR is considered an ameliorating material for heavy metals removal from soils; however, additional studies are necessary to confirm these results under field conditions.

Keywords: land application; drinking water treatment residue (DWTR); Al; heavy metals; alkaline soils

An alum-based drinking water treatment residue (DWTR) is the by-product from the production of potable water. It consists mainly of the precipitated hydroxides of the treatment chemicals that are added to coagulate and flocculate dissolved and suspended material in the raw water source and also during the residue dewatering process (Elliott et al. 1990). The chemicals typically include $Al_2(SO_4)_3.nH_2O$.

Land application of DWTR received a considerable attention for its potential as a low-cost disposal alternative (Geertsema et al. 1994). In time when traditional disposal practices for DWTR (direct discharge to a watercource and landfilling) are under increasing environmental restrictions, land application also offers the possibility of minimizing environmental impact.

The removal of heavy metals with the aid of floc-adsorption and co-precipitation are promising processes, but the use of fresh alum may not be so advantageous because of the chemicals costs. Therefore, the idea of using DWTR is favourable. Licsko (1998) reported that biological sludge (i.e. activated alum-sludge) could adsorb up to 95% of heavy metals (Zn^{2+}, Cd^{2+}, Cr^{3+}) due to the co-precipitation mechanism.

Phytotoxic Al ion (mainly Al^{3+}) restrict crop productivity in acidic soils that cover almost 40% of world's arable land (Kikui et al. 2005). The toxic effects of Al on plants are observed in association with soluble aluminum (Al^{3+}) that is biologically available in acidic soil and water (pH < 5.5) but is biologically inactive in circumneutral to alkaline (pH 5.5–8.5) conditions. The primary toxic symptom of Al ion is root growth inhibition. Hutchinson et al. (1986) observed a dose-response relationship between wheat root length and the concentrations of Al^{3+}. In addition, Nosko et al. (1988) reported that conifers grown in Al-enriched solutions at a pH lower than 5.5 resulted in less root growth rates, shorter roots, less root mass, and lower root:shoot ratio than control. Eldhuset at al. (1987) found that the root elongation of conifers grown in Al-enriched solutions at a pH lower than 5.5 was reduced lower than control. The objectives of this study thus were to quantify the effects of DWTR on bioaccumulation of some heavy metals in plants tissue and to determine the effects of DWTR on soil aluminum and aluminum phytotoxicity for the corn plants grown in alkaline soils.

MATERIAL AND METHODS

Characterization of soils and drinking water treatment residuals (DWTR). Three soils with different properties (clay: Typic torrifluvents, sandy: Typic torripsamments and calcareous: Typic calciorthids) were selected for the study and sampled (0–15 cm depth) at three different locations. Sub-samples of the air-dried soils were ground to pass a 2-mm sieve prior to the following chemical analysis: pH and electrical conductivity (EC) as well as soluble cations and anions were determined in soil-paste extract (Richards 1954). The organic matter (OM) content was determined by dichromate oxidation method (Nelson and Sommers 1982). Cation exchange capacity (CEC) was determined by sodium saturation (1M NaOAc solution) and the adsorbed sodium was replaced by 1N NH_4OAc (Rhoades 1982). Particle size analysis was determined by the hydrometer method (Day 1965). Calcium carbonate content was determined using calcimeter (Nelson 1982). Total nitrogen was determined by the Kjeldahl digestion method (Bremner and Mulvaney 1982). Available P was extracted by 0.5M $NaHCO_3$ test (Olsen and Sommers 1982) and determined colorimetrically by molybdophosphoric blue color method (Murphy and Riley 1962). Selected properties of the three soils are summarized in Table 1.

The DWTR was obtained from the drinking water treatment plant in Kafr el-Dawar, El-Bohera Governorate. The DWTR particles were allowed to air-dry and were subsequently passed through a 1-mm sieve prior to their use in any experiment (Makris and Harris 2005). The pH was determined in DWTR-water suspension 1:2.5. Salinity was measured in DWTR-water extract 1:2. Cation exchange capacity of DWTR was determined by sodium saturation (Rhoades 1982). Organic matter content was determined by dichromate oxidation (Nelson and Sommers 1982). Total Al of DWTR was determined using the acid ammonium oxalate method (Ross and Wang 1993). Total metals were determined according to Ure (1995). Selected chemical and physical properties of DWTR are summarized in Table 1.

Incubation and greenhouse experiments. Five DWTR rates (0, 10, 20, 30 and 40 g/kg) were applied to each soil (calcareous, sandy and clayey soils) and thoroughly mixed. Soil for each treatment was transferred to a large plastic bowl. Two-thirds of the water required to obtain field capacity were initially added to the soil with a water dispenser and mixed thoroughly to form a uniform soil-DWTR-water mixture. Treated soil mixtures were then transferred to a plastic pot (2 kg/pot) and brought to field capacity. Pots were covered with perforated plastic cover and incubated at 25°C for 60 days. Moisture content of the treated soil mixture was kept constant during incubation by periodically weighing the pots and adding deionized water to compensate for evaporative loss. After the incubation period, corresponding soil samples were air-dried, crushed to pass a 2 mm sieve and stored for future analysis.

Corn seeds (*Zea mays*) were sown in pots containing 2 kg of soil(s) with DWTR rates identical to those described in the incubation experiment. The seedlings were thinned to 4 seedlings per pot and deionized water was added to bring the soil moisture to 70% of field capacity. The experiment was arranged in completely randomized design with four replicates. Plants were harvested after 105 days of growth in the tested soils.

Cadmium, lead, copper and nickel extraction. The 0.005N, pH 7.3 DTPA extracting solution was used to extract available cadmium, lead, copper and nickel from soils treated with and without DWTR before cultivation (Lindsay and Norvell 1978); the values were measured by using the atomic absorption spectrometry according to Baker and Amacher (1982).

Aluminum extraction. Extractable aluminum was displaced with an unbuffered salt solution (1N KCl) from soils treated with and without DWTR before cultivation (Barnhisel and Bertsch 1982) and the extract was analyzed for Al by 8-hydroxyquinoline-butyl acetate colorimetric method (Bloom et al. 1978).

Table 1. Some physical and chemical characteristics of studied soils and DWTR

Characteristics	Units	Clay	Sandy	Calcareous	DWTR
EC	(dS/m)	2.66	3.84	2.92	1.67
pH		8.13	7.69	8.08	7.45
$CaCO_3$	(g/kg)	57.90	2.40	356.80	–
Sand	(g/kg)	596.4	868.2	740.00	–
Silt	(g/kg)	141.3	25.10	101.50	–
Clay	(g/kg)	262.30	106.70	158.50	–
Texture		SCL	LS	SL	–
OM	(g/kg)	8.50	1.00	4.60	57.00
Total N	(g/kg)	2.20	0.30	0.90	4.20
Total P	(g/kg)	0.90	0.30	0.50	1.90
Total K	(g/kg)	–	–	–	2.20
Total Al	(g/kg)	–	–	–	38.01
KCl-Al	(mg/kg)	–	–	–	28.18
Soluble P	(mg/kg)	–	–	–	0.73
Soluble Al	(mg/kg)	–	–	–	1.80
CEC	(cmol(+)/kg)	39.13	8.70	26.00	34.78
Olsen-P	(mg/kg)	24.75	2.89	18.70	24.00
Available-N	(mg/kg)	83.00	52.00	61.00	–
Available-K	(mg/kg)	350.00	70.00	301.00	–
DTPA-extractable elements:	(mg/kg)				
Cd		0.33	0.18	0.26	0.09
Ni		8.92	5.13	7.17	2.49
Pb		6.13	2.18	5.69	1.58
Cu		9.09	3.13	4.98	1.20
WHC	(g/kg)	–	–	–	470.00

EC – electrical conductivity; OM – organic matter; CEC – cation exchange capacity; WHC – water holding capacity; SCL – sandy clay loam; LS – loamy sand; SL – sandy loam

Plant analysis. Plant shoots and roots were harvested separately; immediately after harvest, shoots and roots were triple rinsed in deionized water to remove any adhering particles. Plants were oven-dried at 65°C for 48 h and dry matter yield was recorded. Plant tissues were ground in a stainless steel mill. Subsamples of ground plant material were dry-ashed and treated with $Mg(NO_3)_2.6H_2O$ 50% and distilled water, heated on hotplate, ashed in a muffle furnace at 450°C for 6 h. Ash was dissolved in 5 ml of HNO_3 (1:1), diluted to a constant volume with distilled water (Jones 2001) and analyzed for Cd, Pb, Cu, and Ni by atomic absorption spectrometry (Baker and Amacher 1982) and aluminum by 8-hydroxyquinoline-butyl acetate colorimetric method (Bloom et al. 1978).

Statistical analysis. Statistical analyses were performed using the Statistical Analysis System (SAS Institute 1994). Analysis of variance (ANOVA) techniques were used to determine the treatment effects and check for interaction. The least significant difference method was used to separate treatment means. Regression analysis was employed to determine the relationships between available heavy metals and aluminum concentrations in soils and heavy metals and aluminum concentrations in plants.

RESULTS AND DISCUSSION

Heavy metals concentration and uptake

Cadmium (Cd). Cadmium tends to be accumulated in roots more than in shoots of corn plants grown in the three DWTR-treated soils (Figure 1). Soil type, application rate and soil × rate interaction significantly affected shoots and roots Cd concentration (Figure 1). Application of DWTR at the rate of 20 g/kg significantly decreased Cd concentration in shoots and roots of corn plants grown in all the studied soils. The greatest decreases in Cd concentration in plant parts were noticed when DWTR was applied at the rate of 40 g/kg (Figure 1). The uptake of Cd by plants was significantly increased at the rates of 10 and 20 g/kg in clay and sandy soils. However, in calcareous soil, the Cd plant uptake was not affected by application rates of 10 and 20 g/kg DWTR (Figure 1). Values of DWTR higher than 20 g/kg significantly decreased Cd plant uptake in

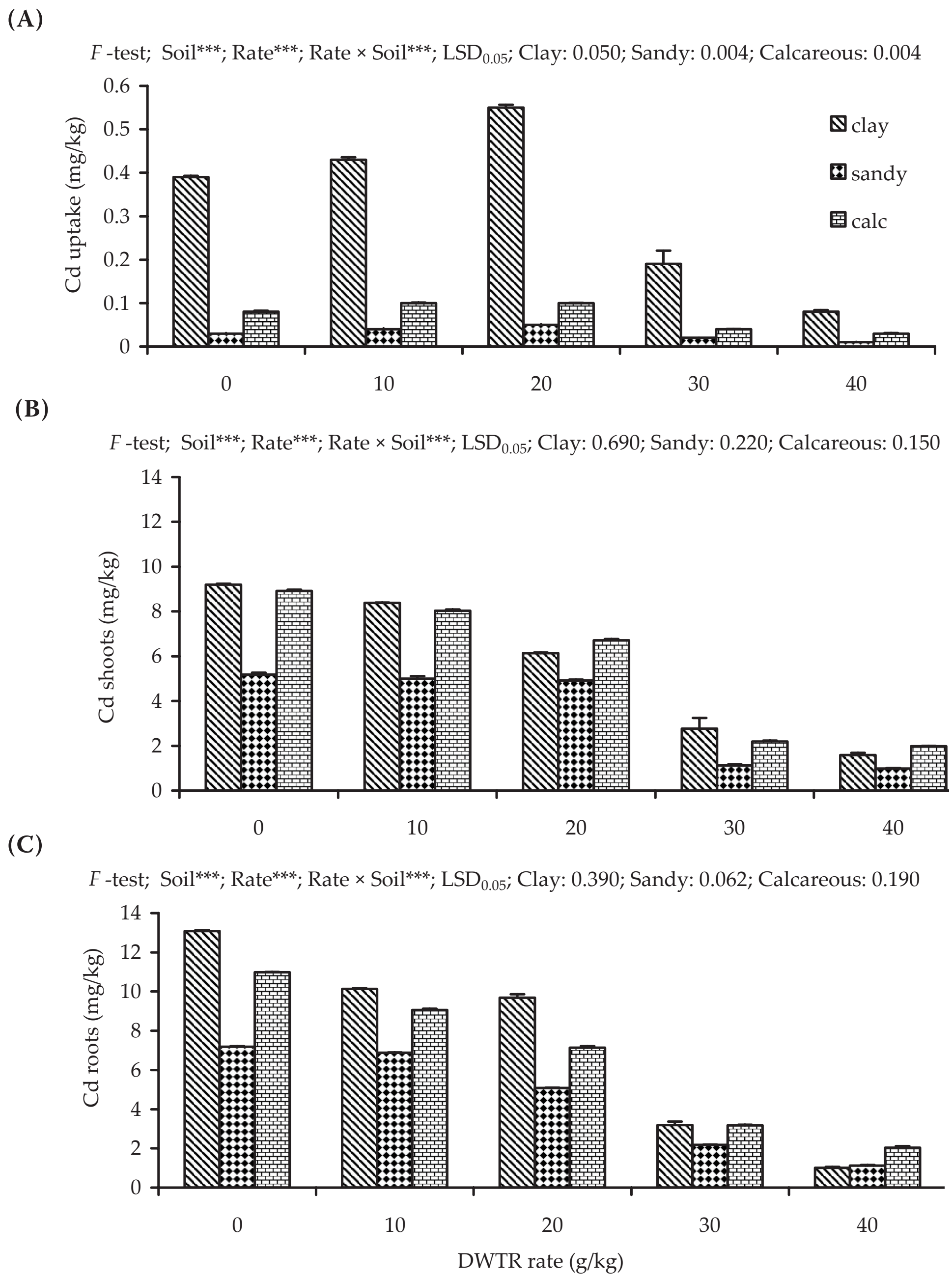

Figure 1. Effect of DWTR addition on uptake (A) and Cd concentrations in shoots (B) and roots (C) of corn plants grown in different soils. Error bars on all figures represent the standard error of the mean. Where no error bars are present, the standard error was too small to be represented as the scale of the diagram
***significant at the 0.001 probability level

all studied soils (Figure 1). The increased uptake of cadmium did not affect yield of corn plant grown in all DWTR-treated soils (Lucas et al. 1994).

Lead (Pb). Lead tends to be accumulated in the order: roots > shoots (Figure 2). Lead concentration in all parts of corn plants was significantly affected by soil, DWTR application rate and soil × application rate interaction (Figure 2). Application of DWTR at the rate of 20, 30 and 40 g/kg resulted in significant decreases in Pb concentration in shoots and roots of the corn plants grown in the three DWTR-treated soils. In contrast, the plant Pb uptake was significantly increased at the rate of 10 and 20 g/kg in all DWTR-treated soils due to the increase of dry matter production of corn plants at the same rates (Mahdy et al. 2007). Further increase of DWTR significantly decreased Pb plant uptake in all studied soils (Figure 2).

Copper (Cu). Copper tends to be accumulated in roots more than shoots of corn plants grown in all studied soils (Figure 3). Soil type, application rate and soil × rate interaction significantly affected shoots and roots copper concentration (Figure 3). In general, application of DWTR at all rates significantly decreased Cu concentration in shoots and roots of corn plants grown in all studied soils. The greatest decreases in Cu concentration in plant parts were noticed when DWTR was applied at the rate of 30 g/kg in all studied soils, and the most pronounced reduction was noticed in

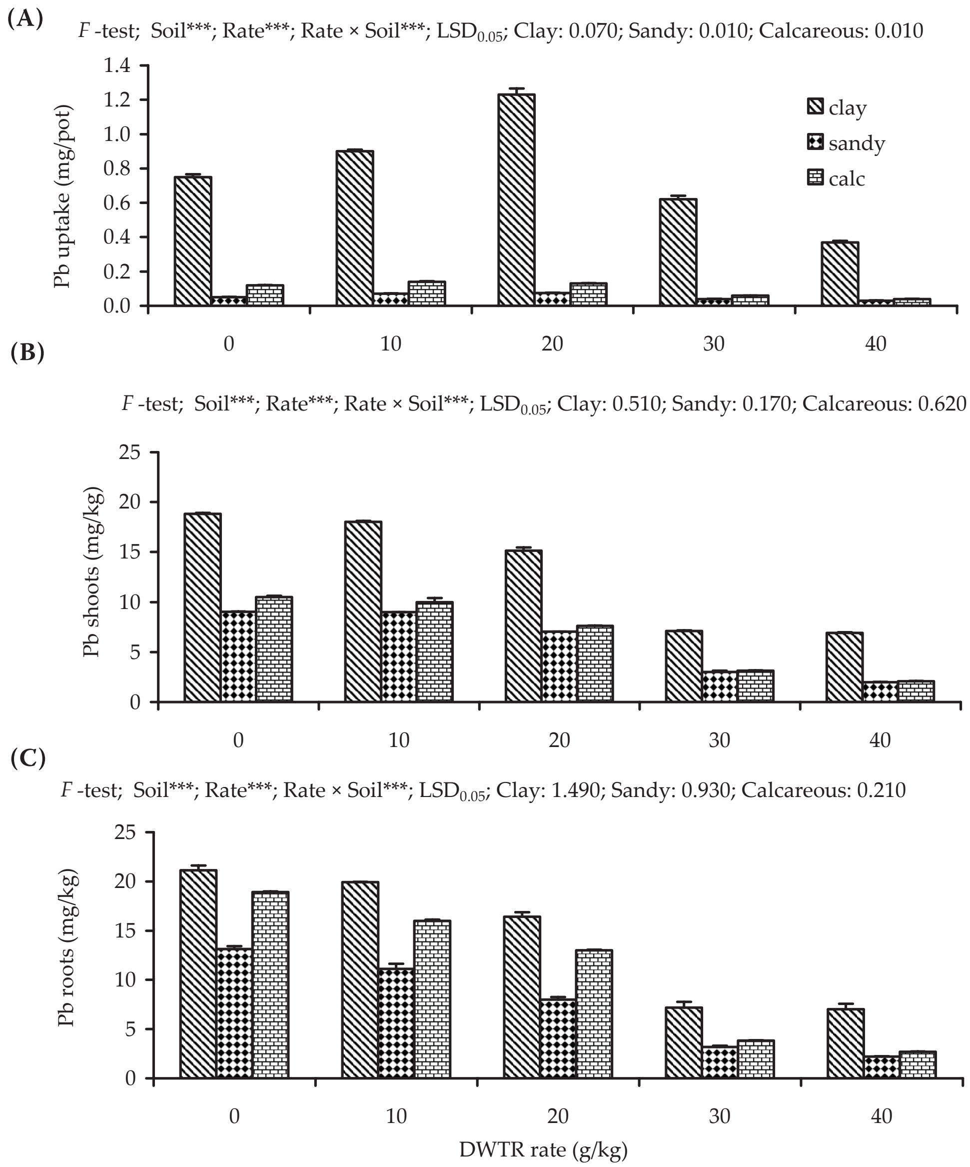

Figure 2. Effect of DWTR addition on uptake (A) and Pb concentrations in shoots (B) and roots (C) of corn plants grown in different soils. Error bars on all figures represent the standard error of the mean. Where no error bars are present, the standard error was too small to be represented as the scale of the diagram
***significant at the 0.001 probability level

clay soils (Figure 3). The plant uptake of Cu was strongly influenced by soil type, DWTR application rate and its interaction. Cu uptake of corn plant was significantly increased at DWTR application rates of 10 and 20 g/kg in clay and sandy soils and the DWTR application rate of 10 g/kg in calcareous soils (Figure 3). A high percentage increase in total dry matter production of corn plants was attained with DWTR application rates of 10 and 20 g/kg in all studied soils (Mahdy et al. 2007). Application of DWTR at the rates of 30 and 40 g/kg significantly decreased Cu uptake of corn plants grown in all studied soils (Figure 3).

Nickel (Ni). The Ni concentration in shoots and roots and Ni uptake of corn plants grown in DWTR-amended soils are shown in Figure 4. Nickel concentration in roots was higher than in shoots in all plants grown in all studied soils. In general, application rates of DWTR significantly decreased Ni concentration in shoots and roots (Figure 4). The greatest decrease was noticed in clay soils when the application rate of DWTR 30 g/kg was added (Figure 4). Concentration of Ni in shoots and roots was significantly affected by soil type, DWTR application rate and their interaction. Ni uptake by corn plants was strongly affected by soil type, DWTR application rate and soil × rate interaction in all studied soils (Figure 4). Application of DWTR at the rates of 10 and 20 g/kg to clay and sandy soils significantly increased Ni uptake of corn plants

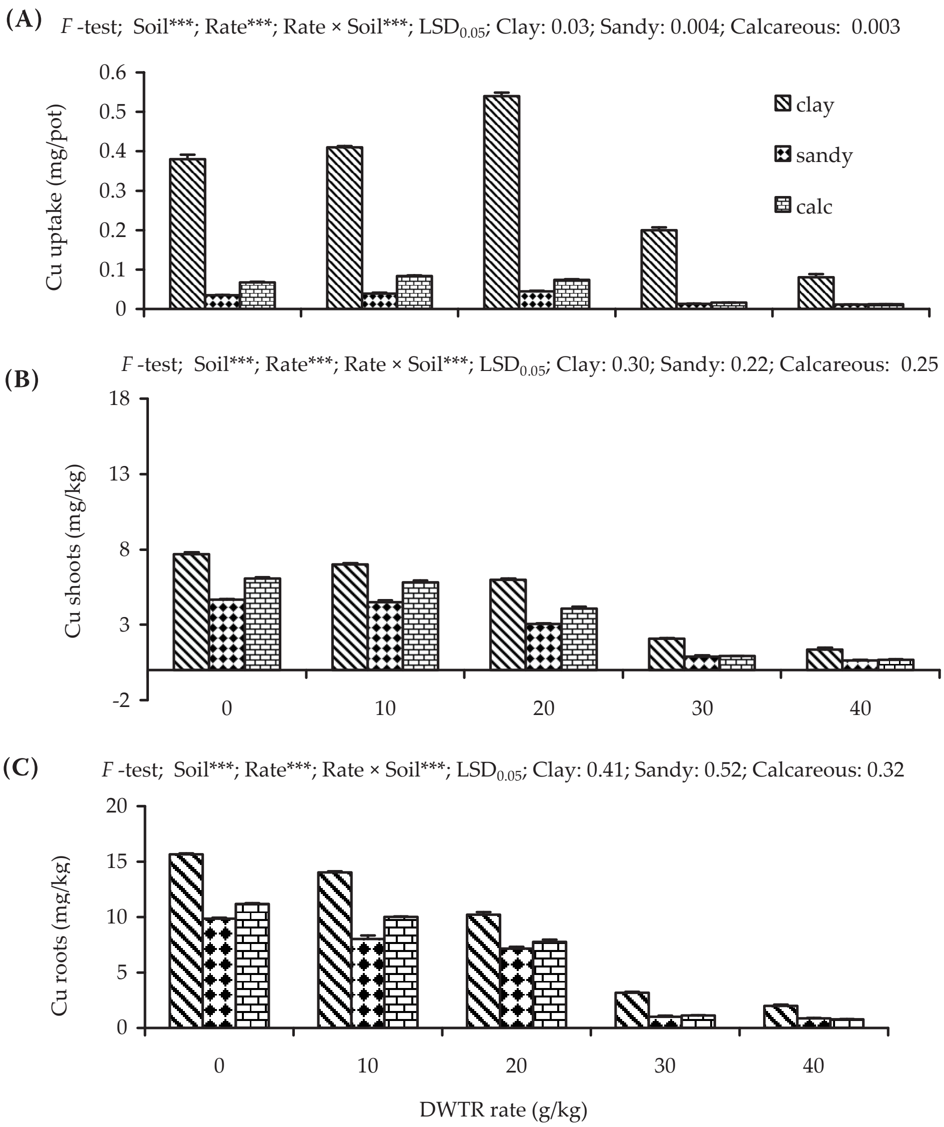

Figure 3. Effect of DWTR addition on uptake (A) and Cu concentrations in shoots (B) and roots (C) of corn plants grown in different soils. Error bars on all figures represent the standard error of the mean. Where no error bars are present, the standard error was too small to be represented as the scale of the diagram
***significant at the 0.001 probability level

because of the high percentage increase in total dry matter production (Mahdy et al. 2007). However, in calcareous soil, Ni uptake was not significantly increased at the rate of 10 g/kg; it significantly increased at the rate of 20 g/kg (Figure 4). In general, the DWTR application rates of 30 and 40 g/kg to all studied soils significantly decreased Ni uptake (Figure 4). This can be explained by floc-adsorption and co-precipitation processes that were used to remove heavy metals. Such observations are in accordance with Karthikeyan et al. (1995); they indicated that the use of alum could remove heavy metals from soil and water by the floc-adsorption process and immobilize them.

Heavy metals extractability

The Cd, Ni, Pb and Cu concentrations in DTPA extract as affected by DWTR application rates are shown in Table 2. Significant effects of soil type, DWTR application rate and soil × rate interaction were found for Cd, Ni, Pb and Cu concentrations in DTPA extract of the studied soils.

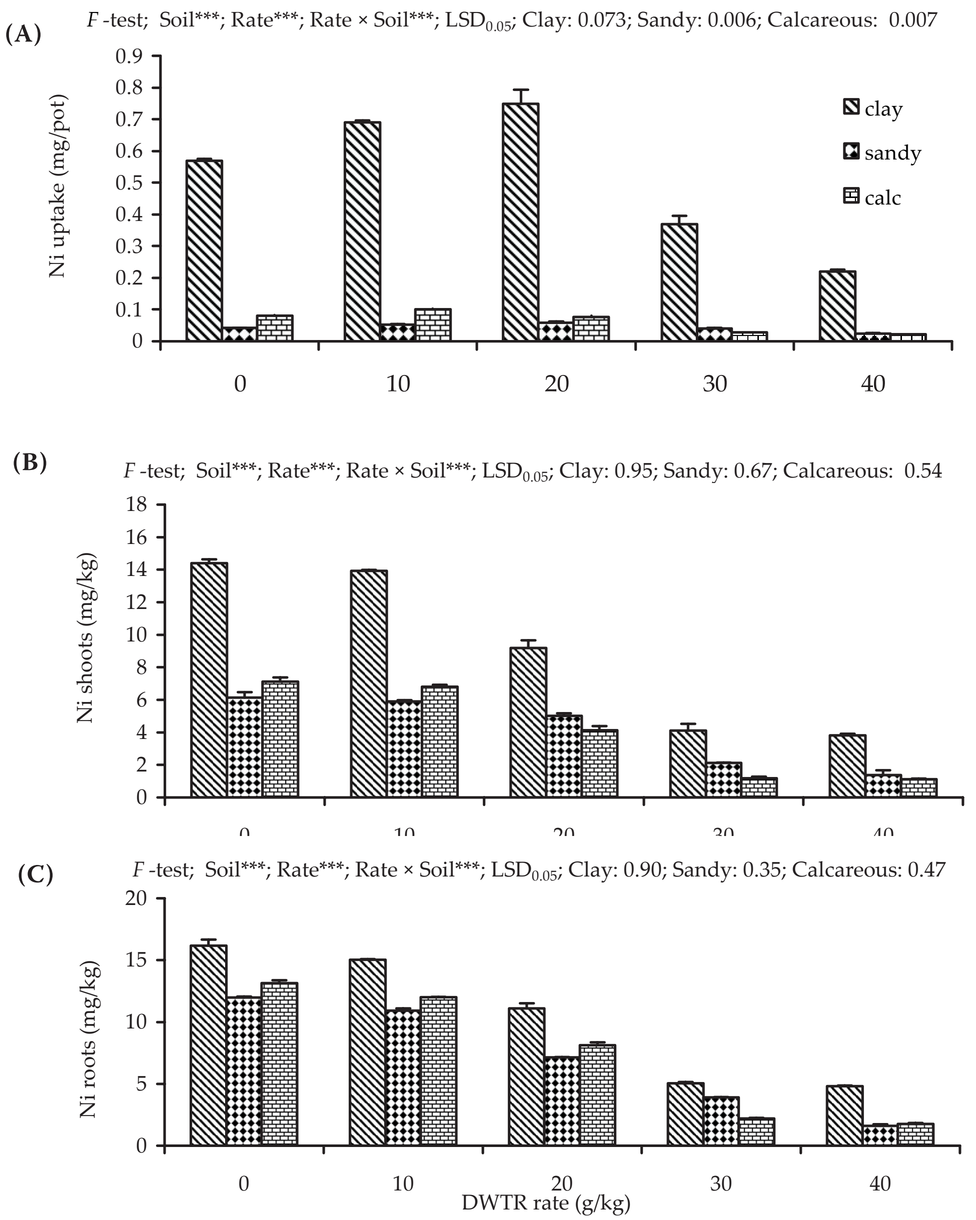

Figure 4. Effect of DWTR addition on uptake (A) and Ni concentrations in shoots (B) and roots (C) and of corn plants grown in different soils. Error bars on all figures represent the standard error of the mean. Where no error bars are present, the standard error was too small to be represented as the scale of the diagram
***significant at the 0.001 probability level

Table 2. DTPA-extractable heavy metals concentrations of the three studied soils as influenced by DWTR application rates

DWTR rate (g/kg)	DTPA-extractable heavy metal concentrations (mg/kg)			
	cadmium	nickel	lead	copper
Clay				
0	0.33	8.92	6.13	9.09
10	0.22	7.18	5.71	8.13
20	0.19	6.00	3.13	6.19
30	0.11	3.11	1.52	3.17
40	0.09	2.88	1.48	2.96
$LSD_{0.05}$	0.052	0.31	0.53	0.27
Sandy				
0	0.18	5.13	2.18	3.13
10	0.16	5.01	1.93	3.02
20	0.13	4.03	1.60	2.18
30	0.06	2.16	0.62	0.61
40	0.04	2.01	0.42	0.52
$LSD_{0.05}$	0.033	0.27	0.16	0.28
Calcareous				
0	0.26	7.17	5.69	4.98
10	0.22	6.99	5.01	4.62
20	0.17	5.82	3.80	2.93
30	0.08	2.71	0.90	0.70
40	0.06	2.31	0.72	0.67
$LSD_{0.05}$	0.033	0.29	0.27	0.17
Analysis of variance (*F*-test)	extractable Cd	extractable Ni	extractable Pb	extractable Cu
Soil	***	***	***	***
Rate	***	***	***	***
Rate × soil	***	***	***	***

***significant at 0.001 probability level

Application of DWTR at the rate of 10 g/kg significantly decreased Cd concentration in clay and calcareous soils. However, in sandy soil the Cd concentration was not significantly decreased at 10 g/kg DWTR application rate. Application of DWTR at the rate of 20, 30 and 40 g/kg significantly decreased Cd concentrations in all studied soils.

Similarly, extractable Ni concentration was significantly decreased when the DWTR application rates of 20, 30 and 40 g/kg were applied to all studied soils. However, application rate of 10 g/kg significantly decreased Ni concentration in clay soil whereas it did not have the same effect in sandy and calcareous soils (Table 2).

The application of DWTR significantly decreased Pb concentrations in DTPA extractant; at the rate of 40 g/kg the decrease from 6.13 to 1.48 mg/kg was recorded in clay soil, from 2.18 to 0.42 mg/kg in sandy soil and from 5.69 to 0.72 mg/kg in calcareous soil (Table 2).

In general, extractable Cu concentration in all studied soils was significantly decreased with increasing DWTR application rates. The greatest reduction in Cu concentration was noticed at the rate of 30 g/kg in all studied soils (Table 2). The Cu depletion was from 9.09 to 2.96 in clay soil, from 3.13 to 0.52 in sandy soil and from 4.98 to 0.69 mg/kg in calcareous soils. These results are in accordance with Chu (1999) who indicated that the use of recycled alum-sludge increased heavy metals removal rates from 79 to 96–98% with 100–180 mg/l of recycled alum-sludge. Lombi et al. (2004) indicated that DWTR was the most effective amendment in terms of decreasing metal mobility and diminishing bioaccessible metal.

Combined analyses of all soils and rates of DWTR application showed a significant relationship between DTPA-extractable heavy metals and heavy metals uptake of corn plants (Figure 5). Relationships between the concentrations of Ni, Cd, Pb, and Cu in shoots and roots of corn plants and metals extracted by 0.005M DTPA were variable (Figure 5). The strength of the correlation between metal concentrations in plants and extractable levels in soils was greater for roots (Ni: $r = 0.95$, Cd: $r = 0.95$, Pb: $r = 0.95$, Cu: $r = 0.92$) than shoots

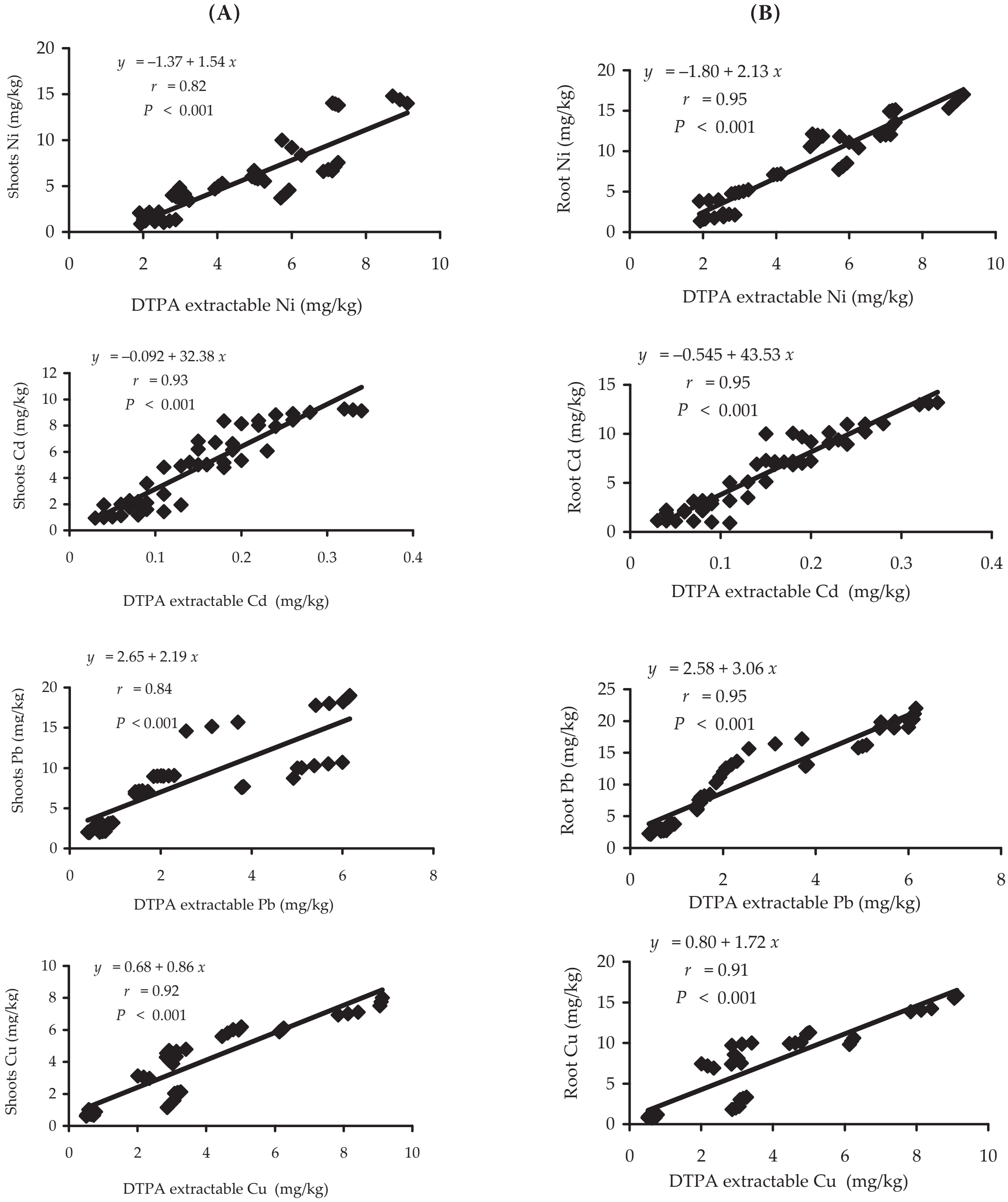

Figure 5. Relationships between DTPA-extractable trace metals and trace metals concentrations of shoots (A) and roots (B) of corn plants grown in the three studied DWTR-treated soils

Table 3. KCl-extractable Al and Al concentrations and plant uptake of corn plants grown in the three studied soils as influenced by DWTR application rates

DWTR rate (g/kg)	Extractable Al (mg/kg)	Plant Al concentration (mg/kg)		Al uptake (µg/pot)
		roots	shoots	
Clay				
0	1.03	1.01	0.50	24.50
10	1.90	1.13	0.57	33.91
20	2.99	2.01	1.18	107.03
30	4.78	2.91	1.93	184.29
40	8.13	8.17	5.13	314.65
$LSD_{0.05}$	0.17	0.11	0.61	27.62
Sandy				
0	0.13	0.71	0.41	2.84
10	0.57	0.80	0.49	4.15
20	1.62	1.21	0.81	9.72
30	3.03	1.98	1.03	20.08
40	6.16	6.15	4.99	86.56
$LSD_{0.05}$	0.10	0.11	0.19	4.49
Calcareous				
0	0.08	0.52	0.33	3.39
10	0.41	0.61	0.39	5.46
20	1.13	1.08	0.73	11.96
30	2.98	1.70	0.90	20.37
40	5.50	5.14	3.56	69.47
$LSD_{0.05}$	0.18	0.12	0.57	8.58
Analysis of variance (*F*-test)	EA	RAC	SAC	AU
Soil	***	***	***	***
Rate	***	***	***	***
Rate × soil	***	***	***	***

EA – extractable Al; RAC – root Al concentration; SAC – shoot Al concentration; AU – Al uptake
***significant at the 0.001 probability level

(Ni: $r = 0.82$, Cd: $r = 0.93$, Pb: $r = 0.84$, Cu: $r = 0.91$) in all studied elements.

It can be concluded that the reduction in extractable heavy metals could be explained by the floc-adsorption process which was used to remove heavy metals (Cd, Cu, Ni and Pb) as well as the co-precipitation process, in which the formation of a mixed solid phase by the incorporation of a heavy metal ion into the crystal lattice of another precipitating solid phase (i.e. DWTR) is expected (Karthikeyan et al. 1995).

Aluminum concentration and uptake

Al concentrations and plant uptake of corn grown in the three soils as influenced by water treatment residuals application rates are shown in Table 3.

Al tends to be accumulated in roots more than shoots. Similarly, the study of Kabata-Pendias and Pendias (1992) showed that Al is likely to be concentrated in the root. Root staining techniques showed that Al accumulates principally in the

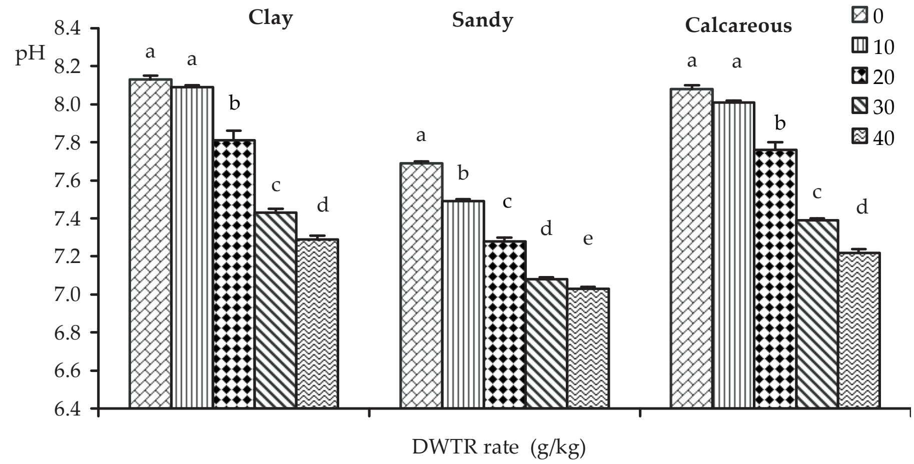

Figure 6. Effect of DWTR addition on pH of the three studied soils. Error bars on all figures represent the standard error of the mean. Where no error bars are present, the standard error was too small to be represented as the scale of the diagram. Letters above bars indicate that means with the same letter are not significantly different at the 0.05 probability level according to the LSD

root tips of the main root and lateral root tissue (Matsumoto et al. 1976).

Soil type and application rates of DWTR and their interaction significantly affected plant Al concentration (Table 3). Al concentration in root and shoots of corn plants grown in the three studied soils increased in a stepwise fashion with increasing DWTR. However, Al concentrations in all plant tissues are well below the maximum tolerable levels of dietary Al for domestic animals and humans (200–1000 mg/kg) (National Research Council 1980). The total aluminum uptake was significantly increased at the application rates of 20, 30 and 40 g/kg DWTR in clay and sandy soils.

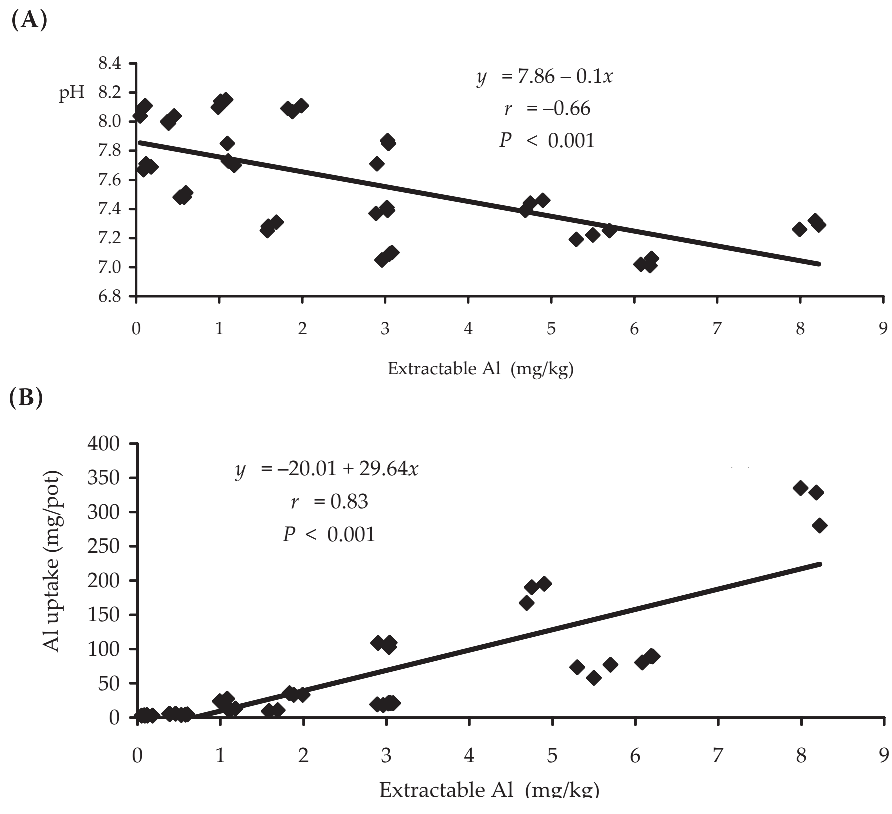

Figure 7. Relationships between extractable Al and pH (A) and Al uptake (B) of corn plants grown in the three studied DWTR-treated soils

However, the application of DWTR at the rate of 10 g/kg did not significantly affect Al uptake in all studied soils. In calcareous soils, the application of DWTR at the rates of 30 and 40 g/kg significantly increased Al uptake, whereas lower rates did not significantly affect Al uptake (Table 3). Aluminum toxicity has become a highly visible topic evolving from studies of acidic soils and aquatic environments. On the alkaline side, there was very little evidence for the existence of Al^{3+} species other than the tetrahedral $Al(OH)_4^-$ over the entire accessible pH ranges (Swaddle 2001). As the pH of studied soils ranged between 7.69 to 8.13, the phytotoxiciy symptoms of corn plants did not occur in plants grown in DWTR-treated soils (Table 3).

Aluminum extractability and pH

Since alum-based DWTR contains Al, there may be a concern that land application of DWTR will increase extractable Al and may increase the potential for Al phytotoxicity. Such increase in Al extractability was due to pH decrease (Figure 6). Sparling and Lowe (1996) indicated that the extractable Al was increased with decreasing soil pH.

In all studied soils, Al concentrations before cultivation were significantly increased with increasing DWTR application rates (Table 3). However, application rates of DWTR did not increase extractable Al in soils amended with more than 8 mg Al/kg (Table 3). Extractable Al concentrations above 270 mg Al/kg in soils are often toxic to plants (Andersson 1988, Ritchie 1995).

Significant soil type, DWTR rate and soil × rate interaction effects were found for Al concentration of the studied soils. The increase of extractable Al in studied soils followed the trend clay > sandy > calcareous (Table 3).

Clay soil showed a non-significant decrease in soil solution pH from 8.14 to 8.09 after the addition of 10 g/kg DWTR. Increasing the amendment rate from 10 to 40 g/kg significantly decreased pH to 7.29 (Figure 6). In general, the application of DWTR at the rates of 20, 30 and 40 g/kg significantly decreased soil pH in all studied soils (Figure 6). However, sandy soil showed a significant decrease in soil pH at the rate of 10 g/kg DWTR. This is because of the small buffering capacity of sandy soils compared with clay and calcareous soils.

Combined analyses of all soils and rates of DWTR application showed a significant relationship between extractable Al and pH ($r = -0.66$, $P < .001$; Figure 7A) and Al uptake ($r = 0.83$, $P < 0.001$; Figure 7B).

It can be concluded that land application of DWTR to all studied soils significantly decreased extractable heavy metals and did not cause aluminum phytotoxicity for corn plants grown in alkaline agricultural soils because the application rates of DWTR did not increase extractable Al in amended soils up to 8 mg Al/kg. Based on the results of our experiment, the DWTR is considered an ameliorating material for heavy metals removal from soils; however, additional studies are necessary to confirm these results under field conditions.

REFERENCES

Andersson M. (1988): Toxicity and tolerance of aluminum in vascular plants: a literature review. Water Air Soil Pollut., *39*: 439–462.

Baker D.E., Amacher M.C. (1982): Nickel, copper, zinc and cadmium. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Barnhisel R., Bertsch P.M. (1982): Aluminum. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Bloom P.R., Weave R.M., McBride M.B. (1978): The spectrophotometric and fluorometric determination of aluminum with 8-hydroxyquinoline and butyl acetate extraction. Soil Sci. Soc. Am. J., *42*: 712–716.

Bremner J.M., Mulvaney C.S. (1982): Nitrogen-total. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Chu W. (1999): Lead metal removal by recycled alum-sludge. Water Res., *33*: 3019–3025.

Day P.R. (1965): Particle fraction and particle size analysis. In: Black A.C., Evans D.D., Ensminger L.E., White J.L., Clark F.E. (eds.): Methods of Soil Analysis, Part I. American Society of Agronomy, Madison.

Eldhuset T., Goransson A., Ingestad T. (1987): Aluminum toxicity in forest tree seedlings. In: Hutchinson T.C., Meems K.M. (eds.): Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems, Vol. G16, NATO ASI Series. Springer-Verlag, Berlin: 401–409.

Elliott H.A., Dempsey B.A., Maille P.J. (1990): Contents and fractionation of heavy metals in water treatment sludges. J. Environ. Qual., *19*: 330–334.

Geertsema W.S., Knocke W.R., Novak J.T., Dove D. (1994): Long-term effects of sludge application to land. J. AWWA, *85*: 11–64.

Hutchinson T.C., Bozic L., Munoz-Vega G. (1986): Responses of five species of conifer seedlings to aluminum stress. Water Air Soil Pollut., *31*: 283–294.

Jones J.B. (2001): Laboratory Guide of Conducting Soil Tests and Plant Analysis. CRC Press, Boca Raton.

Kabata-Pendias A., Pendias H. (1992): Trace Elements in Soils and Plants. CRC Press, Boca Raton.

Karthikeyan K.G., Elliott H.A., Cannon F.S. (1995): Enhanced metal removal from wastewater by coagulant addition. In: Proc. 50th Purdue Industrial Waste Conf., West Lafayette, USA.

Kikui S., Sasaki T., Maekawa M., Miyao A., Hirochika H., Matsumoto H., Yamamoto Y. (2005): Physiological and genetic analysis of aluminum tolerance in rice, focusing on root growth during germination. J. Inorg. Biochem., *99*: 1837–1844.

Licsko I. (1988): The use of sludge and sulphide to remove heavy metals from sewages before activated sludge treatment. Water Sci. Technol., *20*: 285–292.

Lindsay W.L., Norvell W.A. (1978): Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J., *42*: 421–428.

Lombi E., Hamon R.E., Wieshammer G., McLaughlin M.J., McGrath S.P. (2004): Assessment of the use of industrial by-products to remediate a copper- and arsenic-contaminated soil. J. Environ. Qual., *33*: 902–910.

Lucas J.B., Dillaha T.A., Reneau R.B., Novak J.T., Knolke W.R. (1994): Alum-sludge land application and its effect on plant growth. J. AWWA, *86*: 11–75.

Mahdy A.M., Elkhatib E.A., Fathi N.O. (2007): Drinking water treatment residuals as an amendment to alkaline soils: Effects on the growth of corn and phosphorus extractability. Int. J. Environ. Sci. Tech., *4*: 489–496.

Makris K.C., Harris W.G. (2005): Time dependency and irreversibility of water desorption by drinking water treatment residuals: implication for sorption mechanisms. J. Colloid Interface Sci., *294*: 151–154.

Matsumoto E., Hiasawa F., Torikai H., Takakaski E. (1976): Localization of absorbed aluminum in pea roots and its binding to nucleic acid. Plant Cell Physiol., *17*: 127–137.

Murphy J., Riley J.P. (1962): A modified single solution for the determination of phosphates in natural waters. Anal. Chim. Acta, *27*: 31–36.

National Research Council (1980): Mineral Tolerance of Domestic Animals. National Academy of Sciences, Washington, D.C.

Nelson D.W., Sommers L.E. (1982): Total carbon, organic carbon and organic matter. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Nelson R.E. (1982): Carbonate and gypsum. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Nosko P., Brassard P., Kramer J.R., Kershaw K.A. (1988): The effect of aluminum on seed germination and early seedling establishment, growth, and respiration of white spruce (*Picea glauca*). Can. J. Bot., *66*: 2305–2310.

Olsen S.R., Sommers L.E. (1982): Phosphorus. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Rhoades J.D. (1982): Cation exchange capacity. In: Page A.L., Miller R.H., Keeney D.R. (eds.): Methods of Soil Analysis. American Society of Agronomy, Madison.

Richards L.A. (1954): Diagnosis and Improvement of Saline and Alkaline Soils. USDA Agricultural Handbook No. 60, US Government Printing Office, Washington, D.C.

Ritchie G. (1995): Soluble aluminum in acidic soils: principles and practicalities. Plant Soil, *171*: 17–27.

Ross G.J., Wang C. (1993): Acid ammonium oxalate method. In: Carter M.R. (ed.): Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton.

SAS Institute (1994): SAS/STAT User's Guide, Version 6.4. SAS Inst., Cary.

Sparling D.W., Lowe T.P. (1996): Environmental hazards of aluminum to plants, invertebrates, fish and wildlife. Rev. Environ. Contam. Toxicol., *145*: 1–127.

Swaddle T.W. (2001): Silicate complexes of aluminum (III) in aqueous systems. Coord. Chem. Rev., *219–221*: 665–686.

Ure A.M. (1995): Methods of soil analysis for heavy metals in soils. In: Alloway B.J. (ed.): Heavy Metals in Soils. Blackie Academic and Professional, London.

Received on March 12, 2008

Corresponding author:

Dr. Ahmed Mohamed Mahdy, Alexandria University, College of Agriculture, Department of Soil and Water, 21545 Alexandria, Egypt
phone: 002 035 904 684, fax: 002 035 904 684, e-mail: amahdy73@yahoo.com