

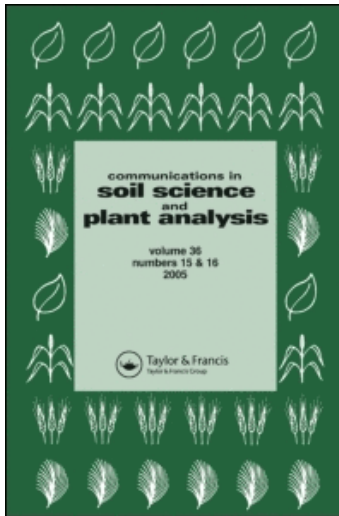
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Organic Amendment Effects on the Transformation and Fractionation of Aluminum in Acidic Sandy Soil

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Abstract: Addition of organic amendments can alleviate the level of aluminum (Al) phytotoxicity in acid soils by affecting the nature and quantity of Al species. This study evaluated the transformation of Al in an acidic sandy Alaquod soil amended with composts (10 and 50 g kg⁻¹ soil of yard waste, yard + municipal waste, GreenEdge®, and synthetic humic acid) based on soil Al fractionation by single and sequential extractions. Though the organic compost amendments increased total Al in soil, they alleviated Al potential toxicity in acidic soil by increasing soil pH and converting exchangeable Al to organically bound and other noncrystalline fractions, stressing the benefits of amending composts to improve acid soil fertility. The single-extraction method appears to be more reliable for exchangeable Al than sequential extraction because of the use of nonbuffered pH extract solution.

Keywords: Aluminum fractionation, compost, sequential extraction, single extraction

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INTRODUCTION

Soil acidity is a serious constraint to crop production throughout the world. According to von Uexkull and Mutert (1995), topsoils affected by acidity account for 30% of the total ice-free area of the world, with the Americas, Africa, and Asia accounting for the largest portions. One of the main problems of acid soils is aluminum (Al) in forms and levels that are toxic to plants and a potential risk to the environment in general, and eventually to human beings. In addition to liming, organic matter has been reported to alleviate Al toxicity by forming stable complexes (Hargrove and Thomas 1981; Hue, Craddock, and Adams 1986; Gerke 1994; Li et al. 2006). Application of composts to acidic soils can be beneficial not only for decreasing Al toxicity but also for improving chemical, physical, and biological properties of soils (Mazur, Velloso, and Santos 1983; He et al. 2000; Celik, Ortas, and Kilic 2004; Perez-Piqueres et al. 2006), increasing crop yield, and constituting an economic alternative to dispose of biodegradable materials (Tilston et al. 2005). However, few studies have been conducted to understand the mechanisms of organic amendments in reducing Al toxicity in soil.

The knowledge of Al release and transformation in the soil after application of compost is important to predict potential level of Al phytotoxicity and the possible movement of Al-organic complexes through the soil profile, because both are directly related to the chemical species of Al present and their respective activities (Vance, Stevenson, and Sikora 1995). In soil, chemically active or labile Al is present in a variety of forms that are controlled primarily by pH, mineralogical composition of the system, and the concentration and composition of the organic matter present in the soil (Kinraide 1997; Drabek et al. 2003).

The interest in Al effects on plant growth has resulted in efforts to develop methods for separating the Al species and pools (Bertsch and Bloom 1996; Bloom and Erich 1996). Among them, chemical extractions can be used to assess operationally defined Al fractions, which can be related to a potentially mobile and reactive pool of Al in a sample. Two main procedures have been employed for this purpose. One uses multiple single extractions, where solutions with different extracting power are used to obtain pools of Al (Bertsch and Bloom 1996; Alvarez, Monterroso, and Fernandez Marcos 2002; Drabek et al. 2003; Walna, Spsychalski, and Siepak 2005). In this method, a soil sample is fragmented, and each part of the sample is submitted to one of the extracting solutions. The other method is sequential extraction: submitting the same sample to successive and ordinate extractions, starting with the use of a weak extractant and then increasing the

strength at each stage of the fractionation. The method of sequential extraction suggested by Tessier, Campbell, and Bisson (1979) is widely employed for heavy-metal studies but has been reported to be also applicable to Al after some modifications (Zerbe et al. 1999; Sutherland and Tack 2002; Walna et al. 2005; Walna, Spychalski, and Siepak 2005), although the chemistry of Al interactions with mineral and organic fractions are not the same as those with heavy metals. Therefore, more information is required to prove the suitability of this method for Al fractionation studies.

The current research has attempted to evaluate the release and transformation of Al using two methods of Al fractionation within a short time after the soil was amended with representative composts.

MATERIALS AND METHODS

Experiment

The study was conducted on an acidic sandy soil (ortestein Arenic Ultic Alaquods; Soil Survey Staff 2006) from the experimental farm of Indian River Research and Education Center (IRREC-IFAS-UF), Fort Pierce, FL. The soil was collected in September 2005, at 0–20 cm deep, in an area under native vegetation constituted by prairies and sparse pine trees. The soil was air dried, homogenized, and sieved (<2 mm) prior to physical and chemical analyses. The soil contained 968, 25, and 7 g kg⁻¹ of sand, silt, and clay, respectively.

Four different sources of organic matter were used: (1) yard waste (Y); (2) co-compost (yard + municipal solid waste, YM); (3) pelletized biosolids (GreenEdge®, G); and (4) synthetic humic acid (HA). The Y and YM were collected from a composting facility in West Palm Beach, FL, in September 2005, air dried, and ground (<2-mm sieved). GreenEdge® (Green Technologies, Inc.) was a pelletized compost derived from municipal biosolids, enriched with fertilizers to obtain 6% nitrogen (N) (1.5% water-soluble N), 1.3% phosphorus (P), 3% calcium (Ca), and 1% iron (Fe). Synthetic HA was obtained from ICN Biomedicals, Inc. (Costa Mesa, Calif.).

The soils were amended with Y, YM, G, and HA each at two rates: 10 and 50 g kg⁻¹ soil (w/w). The mixtures were homogenized, placed in plastic bags, and incubated for 30 days at room temperature (22 °C), with soil moisture adjusted and maintained at 10% w/w (equivalent to 70% of the field capacity) by monitoring the weight of the bags. There were three replicates for each treatment, arranged in a complete randomized design.

Analyses

Samples of soil and organic amendments were submitted to analysis of pH (H₂O, 2:1 water–solid ratio) and electrical conductivity (EC) using an Orion pH conductivity meter; total organic carbon (TOC) and total nitrogen (TN) using a CN Analyzer (Vario Max, Elementar, Edison, N.J.); exchangeable hydrogen (H⁺) + Al³⁺, extracted with 1 M potassium chloride (KCl) (50 mL in 2.5 g soil, shaken for 30 min) and titrated with sodium hydroxide (NaOH); and Al extractable by Mehlich III. Dissolved organic carbon was determined in soil solution obtained from column leaching in a study conducted simultaneously with the same samples of the present study and published elsewhere (Vieira et al. 2008). Analysis of total Al content in the composts was performed using inductively coupled plasma—atomic emission spectrometry (ICP-AES, Ultima JY Horiba, Edison, N.J., USA) after digestion with nitric acid following EPA Method 3050 (U.S. Environmental Protection Agency 1987).

Subsamples from the incubation bags were collected at 0, 7, 14, 21, and 28 days of incubation and analyzed for pH, EC, and exchangeable H⁺ and Al³⁺, using the same methods cited previously. At the end of 28 days of incubation, subsamples were taken, air dried, and analyzed for Al fractionation based on Drabek et al. (2003) and Walna, Spsychalski, and Siepak (2005).

Al Pools with Single Extraction

Known amounts of incubated soil samples were extracted with five different extractants (Figure 1) to obtain the corresponding forms of Al in the soil. After extraction, suspensions were centrifuged for 30 min at 1700 g and filtered through a 0.45- μ m membrane, and Al concentration in the supernatant was determined using ICP-AES.

Al Fractionation by Sequential Extraction

The method employed for the sequential extraction, depicted in Figure 2, is part of the Tessier's method (Tessier, Campbell, and Bloom 1979) adapted by Zerbe et al. (1999) and Walna, Spsychalski, and Siepak (2005). Samples contained in centrifuge test tubes of 50-mL capacity were agitated in a horizontal shaker with a water thermostat with adjustable temperature. After each extraction stage, the sample was centrifuged for 30 min at 1700 g, and the supernatant was transferred to a calibrated test tube with a hermetic cap. The solid remaining in the original test tube was washed with 5 mL of deionized water and again centrifuged for 30 min; the supernatant solution was combined with the first portion of the

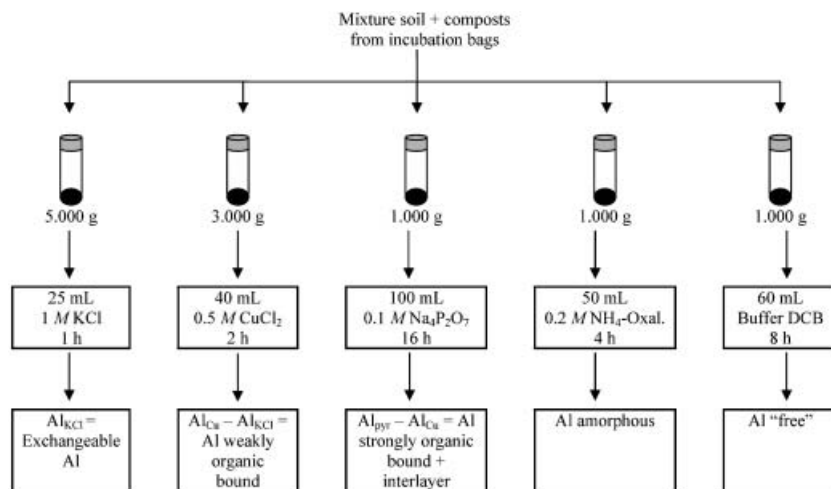


Figure 1. Diagram of the single extraction procedure employed for Al fractionation. Adapted from Drabek et al. (2003) and Walna, Spychalski, and Siepak (2005).

extract. Solutions from the first three extractions were acidified with four drops of concentrated nitric acid and stored at 4 °C prior to analysis.

Statistical Analysis

Results of Al fractions were statistically analyzed by one-way analysis of variance (ANOVA) with three replicates, using SAS version 8.02 (Statistical Analysis System Institute, Cary, N.C.). Treatment means were separated by the Duncan multiple range test ($P < 0.05$). Relations among Al pools were evaluated by means of a determination coefficient (r^2).

RESULTS AND DISCUSSION

Soil and Organic Amendment Characteristics

Samples of HA had the highest pH (9.56) among the composts, whereas G had the lowest one (Table 1). Samples of Y and YM had intermediate and similar values of pH. Usually, after the process of composting, pH of cured composts tends to be neutral or slightly alkaline (Day and Shaw 2001). The G compost had the highest value of EC, with values similar to HA, and both were two times higher than those of Y and YM. Readings of EC were performed simultaneously with those for pH, standing for 30 min after distilled water was added to the samples and the suspension was stirred

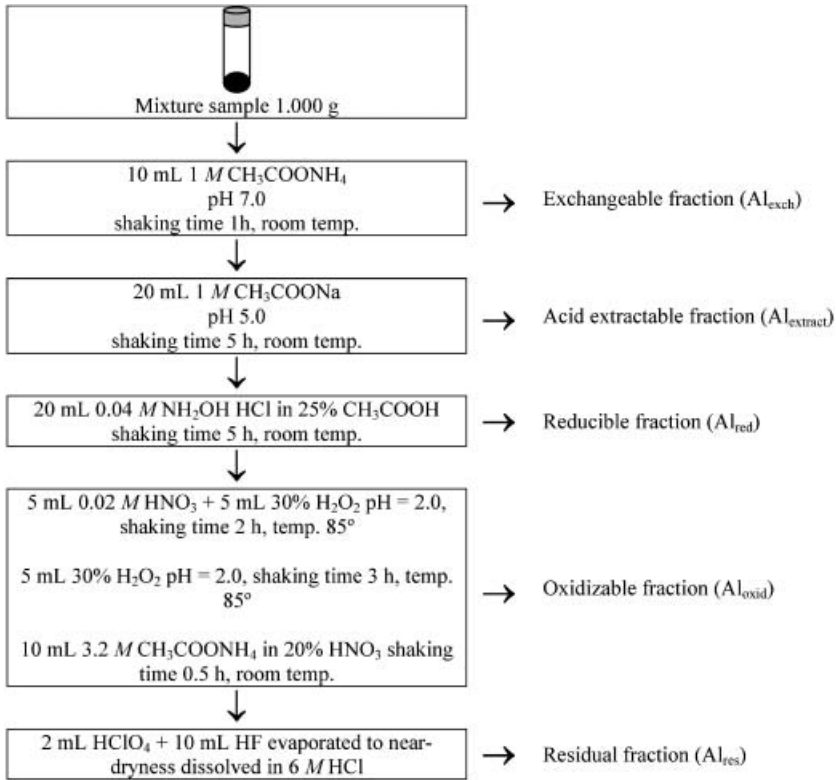


Figure 2. Diagram of the sequential extraction procedure employed for Al fractionation. Adapted from Zerbe et al. (1999) and Walna, Spychalski, and Siepak (2005).

slightly with a glass stick. Composts differed greatly in total Al content, varying from $980 \text{ mg Al kg}^{-1}$ for Y to about $8900 \text{ mg Al kg}^{-1}$ for HA and G. On average, Al contents in HA and G were almost four times higher

Table 1. Results of pH, electric conductivity (EC), total Al, total organic carbon (TOC), and total nitrogen (TN) in organic composts

Compost	pH (H ₂ O)	EC ($\mu\text{S cm}^{-1}$)	Total Al (mg kg^{-1})	TOC ¹ (g kg^{-1})	TN (g kg^{-1})
Yard waste (Y)	6.32 b ^d	3893 b	979.8 c	387.1 a	11.84 b
Co-compost (YM)	6.12 c	4426 b	2360.4 b	339.2 a	19.29 b
Greenedge (G)	5.41 d	8930 a	8829.1 a	229.7 b	65.70 a
Humic acid (HA)	9.56 a	9373 a	8938.4 a	360.2 a	10.51 b

¹Means followed by the same letter in columns do not differ by the Duncan multiple range test at the 5% level.

Table 2. Soil chemical properties as affected by soil amendments

Treatment	pH (H ₂ O)	EC ^a ($\mu\text{S cm}^{-1}$)	Exchangeable acidity (H + Al) ($\text{cmol}_c \text{ kg}^{-1}$)	DOC (mg L^{-1})	TOC (g kg^{-1})	TN (g kg^{-1})
Soil	4.42 h ^b	17.02 d	0.1299 a	20.31 b	5.95 d	0.24 c
Soil + Y 1%	5.22 g	113.47 d	0.0325 c	66.54 b	9.76 c	0.35 c
Soil + Y 5%	6.69 e	492.23 c	0.0325 c	153.28 b	25.01 a	0.82 bc
Soil + YM 1%	5.74 f	138.67 d	0.0180 cd	74.84 b	9.28 c	0.43 c
Soil + YM 5%	6.63 e	487.87 c	0.0397 c	193.59 b	22.61 a	1.19 b
Soil + G 1%	7.03 d	934.73 b	0.1010 b	477.10 ab	8.19 cd	0.89 bc
Soil + G 5%	8.23 b	2631.33 a	0.0072 d	791.88 a	17.13 b	3.51 a
Soil + HA 1%	7.62 c	778.33 bc	0.0001 d	n.d. ^c	9.49 c	0.34 c
Soil + HA 5%	9.13 a	2497.00 a	0.0001 d	n.d.	23.66 a	0.75 bc

^aEC, electrical conductivity; DOC, dissolved organic carbon; TOC, total organic carbon; TN, total nitrogen.

^bMeans followed by the same letter in columns do not differ by the Duncan multiple range test at the 5% level.

^cn.d., not determined.

than those in YM and about nine times higher than those in Y. For composts, in general, Al concentration is extremely variable, depending on the source material. All the composts had similar concentrations of C and N, with the exception of G, which had the lowest C but highest N. This is due to the enrichment of this compost with mineral N, in addition to the lime and the other nutrients, diluting the C content.

The soil used for the experiment had low organic C (Table 2) and clay content of only 7 g kg^{-1} soil. Because of its low buffering capacity, addition of the organic amendments increased soil pH for all treatments, with the highest level of application (50 g kg^{-1}) resulting in the greatest increase in soil pH. Soils having received 5% HA had the highest pH value, because of the high pH of this material plus its high pH buffer capacity. Similar to pH, organic amendments also increased soil EC. Exchangeable acidity, however, decreased with addition of the composts and subsequent rise in pH, mainly because of the protonation and/or Al complexation in the functional groups of the organic compounds. Organic amendments also contributed to increases in TOC, TN, and DOC, as expected. However, G increased the DOC more than the other composts, suggesting that this compost had a greater amount of labile organic C.

The changes in soil pH, EC, and exchangeable acidity during the incubation period are presented in Figure 3. In general, pH slightly increased during the first week and did not change considerably thereafter. Exceptions were the treatment of G (1 and 5%), which caused a large increase in pH in the first week of incubation, likely because of the dissolution of lime. Results of EC had small variation during the period

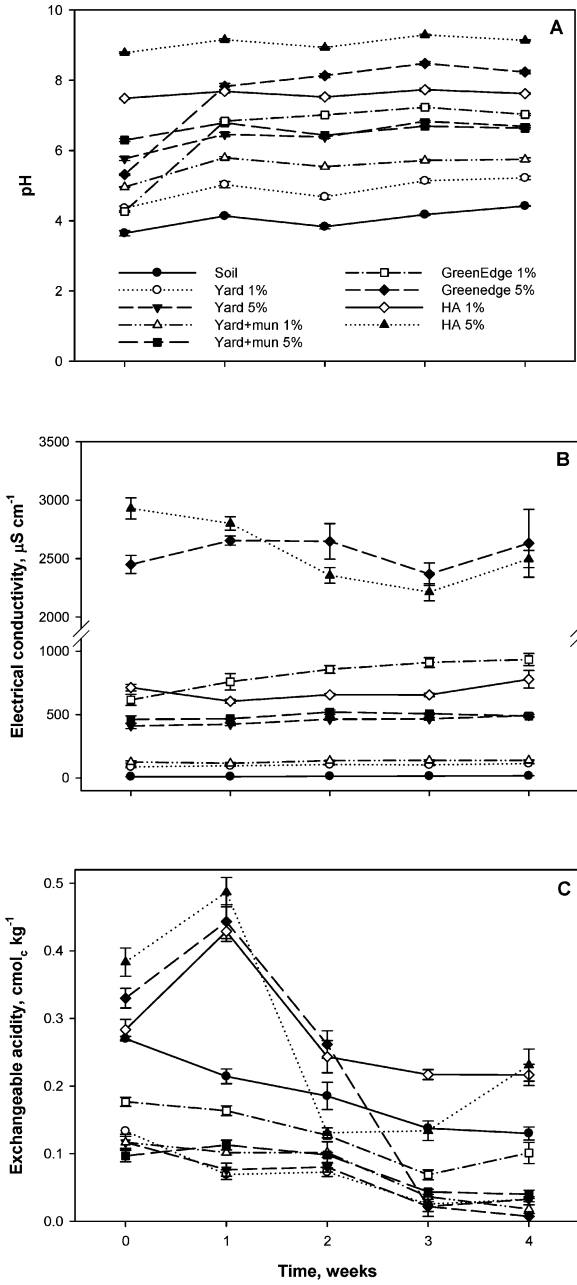


Figure 3. Changes in pH, EC, and exchangeable acidity during the period of incubation of a sandy Alaquod soil and organic amendments.

of incubation. Treatments that received HA and G presented significantly higher values of EC than soil amended with other organic composts during all the period. Exchangeable acidity decreased in all treatments during the incubation. However, the absolute values of exchangeable acidity remained low throughout the incubation period.

Al Fractionation by Single Extractions

The single extraction data (Table 3) demonstrated that, with the exception of HA, all the organic amendments decreased soil exchangeable Al⁺³

Table 3. Aluminum concentrations of fractions obtained with the single-extraction procedure

Treatment	Aluminum fractions (mg kg ⁻¹ , %) ^a				
	Exchangeable ^b (Al _{KCl})	Weakly org. bound ^c (Al _{wkl})	Strongly org. bound + interlayer ^d (Al _{str})	Amorphous ^e (Al _{am})	Free ^f (Al _{DCB})
Soil	2.21bc ^g (2.6)	6.5c (7.3)	13.0c (15.4)	24.9c (29.4)	84.6b (100)
Soil + Y 1%	0.17c (0.2)	10.5c (11.7)	11.3c (12.7)	24.2c (27.0)	89.6b (100)
Soil + Y 5%	0.36c (0.4)	22.8c (27.6)	7.0c (8.5)	30.8c (37.5)	82.2b (100)
Soil + YM 1%	0.15c (0.2)	20.0c (22.0)	12.0c (13.2)	32.0c (35.2)	90.7b (100)
Soil + YM 5%	0.26c (0.2)	53.9b (37.3)	3.4c (2.3)	61.1b (42.1)	144.9b (100)
Soil + G 1%	0.10c (0.1)	54.6b (29.4)	0.0c (0.0)	49.8b (26.7)	186.2b (100)
Soil + G 5%	0.32c (0.1)	122.8a (20.6)	85.8a (14.3)	179.5a (30.0)	598.4a (100)
Soil + HA 1%	4.62b (3.0)	25.6c (17.7)	31.4bc (20.4)	55.9b (36.4)	153.8b (100)
Soil + HA 5%	17.19a (3.7)	109.2a (26.2)	73.9ab (15.8)	185.8a (39.7)	468.3a (100)

^aNumbers in parentheses mean the percentage of Al in relation to “free Al” fraction, which is herein considered as being 100%.

^bKCl-extractable Al.

^cCuCl₂-extractable Al minus KCl-extractable Al.

^dNa₄P₂O₅-extractable Al minus CuCl₂-extractable Al.

^eNH₄-oxalate-extractable Al.

^fDCB-extractable Al.

^gMeans followed by the same letter in columns do not differ by the Duncanis multiple range test at the 5% level.

(Al_{KCl}), which represents the form most toxic to plant roots (Hargrove and Thomas 1981; Bertsch and Bloom 1996). This Al pool is mainly bound to negatively charged surface of soil colloids and thus can be exchangeable with other cations in the soil system. On average, exchangeable Al^{+3} was reduced by approximately 90%, as compared to the control (2.21 mg Al kg⁻¹ for control and mean of 0.23 mg Al kg⁻¹ for the organic amended soils, excluding HA treatments). Such a decrease is obviously related to the raised pH, as KCl is a nonbuffered solution. Exchangeable Al decreased in soils with pH up to 5.5 and was close to zero at pH \geq 5.5. With the exception of Y, application of only 10 g kg⁻¹ soil was enough to raise pH values to more than 5.5. In HA-amended soil, the high exchangeable Al^{+3} was probably caused by the inefficiency of centrifugation in separating the supernatant from the dissolved HA-Al complexes, which were accounted for in the exchangeable instead of organically bound fraction.

In addition to decreased exchangeable Al^{+3} , organic amendments increased organically bound Al, which is considered to be less toxic to the plants than the exchangeable Al, although it is more reactive than both crystalline and noncrystalline aluminum hydroxide and Al in aluminosilicates (Bloom, McBride, and Weaver 1979; Walker, Cronan, and Bloom 1990; Kinraide 1997). A consistent increase occurred only in the weakly organic bound Al (Al_{wkl}), both in absolute and relative values. However, the effect of organic amendments on strongly organic bound Al (Al_{str}) was not clear. According to the results, Al-organic complexes tended to be stronger in HA-amended than in Y- and YM-amended soils, but this strongly organic bound Al can originate from the structure of HA. The copper chloride ($CuCl_2$) is supposed to extract the exchangeable plus the weakly organic bound Al (Juo and Kamprath 1979), whereas the sodium pyrophosphate is supposed to extract exchangeable Al, Al weakly and strongly bound to organic matter, and also a part of Al present in the interlayer of 2:1 silicate minerals (Bascomb and Thanigasalam 1978). Considering that the used soil had basically quartz in its mineral composition and a high percentage of sand in its texture, it is possible to claim that no relevant quantity of Al from interlayer was extracted, which indicates that Al extracted by pyrophosphate represents exclusively the sum of weakly and strongly organic bound plus the exchangeable Al. The Al_{wkl} and Al_{str} did not have significant correlation with total organic C of the incubated mixtures ($r^2 = 0.25$ and 0.11 , respectively), but were correlated with dissolved organic carbon ($r^2 = 0.75$ and 0.51 , respectively, both with $P < 0.05$). On the average, 22 and 12% of the free Al oxides (Al_{DCB}) were either weakly or strongly bound to organic materials.

The ammonium (NH_4)-oxalate is supposed to extract the amorphous (noncrystalline) Al fraction (Al_{am} , Blackmore 1978). Subtracting the Al-pyrophosphate from the Al_{am} gives an estimation of the inorganic

portion of the total amorphous Al (Alvarez, Monterroso, and Fernandez Marcos 2002). The results suggest the amorphous Al fraction, in the present study, is basically composed of organically bound Al, because the results are very similar to those extracted by pyrophosphate, indicating no significant concentration of inorganic amorphous Al in the samples. This fact is positive, considering that when Al^{+3} activity is controlled by inorganic amorphous Al rather than gibbsite, for example, the activity tends to be much higher (Lindsay 1979). In this study, amorphous Al constituted about 30–40% of the free Al oxides.

The Al_{DCB} was attributed to be 100% by convention merely to facilitate the comparison among Al from each single extraction, though it does not mean that DCB extracted all Al present in the sample because it does not digest all mineral constituents in the sample. The Al_{DCB} had a significant correlation with the Al amount that was added to the mixtures from the composts (Figure 4). By observing the slope of the graph, one can see that Al_{DCB} is basically Al from the composts, with only a small portion native from the soil (64 mg kg^{-1} soil, equivalent to the intercept of the axe). The used soil has quartz as the vastly predominant mineral and, consequently, is constituted essentially of silica, having a very low

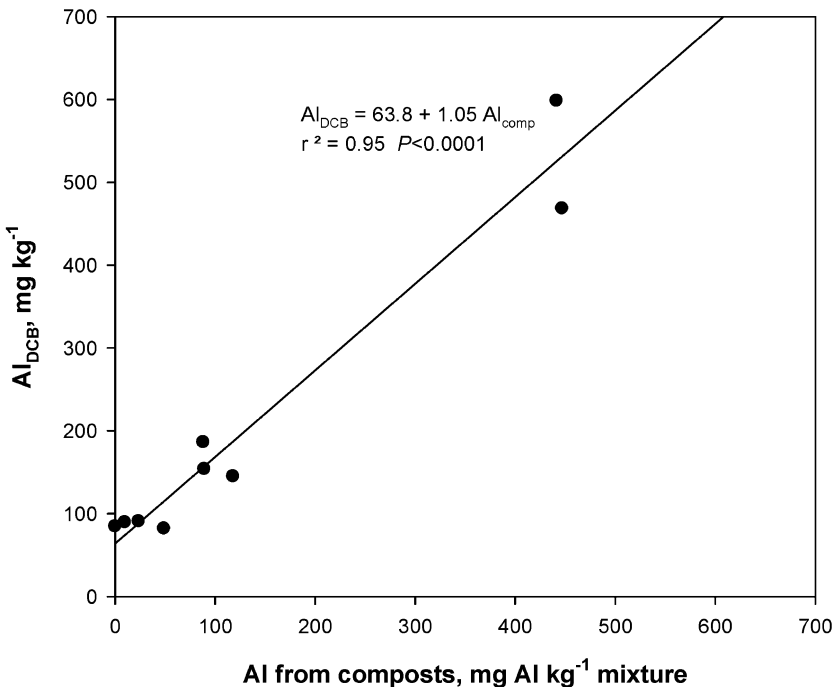


Figure 4. Relationship between Al added to a sandy Alaquod soil by organic amendments and Al extracted from a mixture of soil + compost by DCB solution.

Table 4. Aluminum concentration in fractions obtained from the sequential extraction procedure

Treatment	Aluminum fractions (mg kg ⁻¹)				
	Exchangeable ^a (Al _{exch})	Acid extractable ^b (Al _{extract})	Reducible ^c (Al _{red})	Oxidizable ^d (Al _{oxid})	Residual ^e (Al _{res})
Soil	7.71d ^f	6.93c	13.22e	14.33bc	1860.75b
Soil + Y 1%	11.06cd	5.34d	12.07e	9.35c	2409.91ab
Soil + Y 5%	14.87cd	6.44cd	22.98d	41.82bc	2129.03ab
Soil + YM 1%	8.27d	6.95c	18.23de	16.49bc	2114.77ab
Soil + YM 5%	22.35c	9.75b	44.73c	29.48bc	2193.78ab
Soil + G 1%	16.94cd	9.18b	43.34c	32.63bc	1991.73ab
Soil + G 5%	53.67b	18.26a	120.67a	49.42b	2850.73a
Soil + HA 1%	54.14b	6.48cd	18.26de	13.43bc	2116.22ab
Soil + HA 5%	114.12a	19.21a	68.91b	97.58a	2305.13ab

^aNH₄-acetate pH 7.0-extractable Al.

^bNa-acetate pH 5.0-extractable Al.

^cNH₂OH HCl in acetic acid-extractable Al.

^dHNO₃ + H₂O₂ - H₂O₂ - NH₄ acetate in HNO₃-extractable Al.

^eHClO₄ + HF-extractable Al.

^fMeans followed by the same letter in the column do not differ by the Duncan multiple range test at the 5% level.

original Al content (see also the results of residual Al fraction in the sequential extraction, Table 4). As the Al content in the mixtures is highly dependent on Al from composts, the fraction of Al organically bound had a close correlation with both organic C and Al_{DCB} content (Figure 5).

Aluminum Fractionation by Sequential Extraction

Aluminum concentrations in the fractions of the sequential extraction are presented in Table 4. In contrast to the exchangeable Al from the single extraction, extracted with 1 M KCl solution (Table 3), results of sequential extraction did not have a decrease in exchangeable Al due to addition of organic amendments. It is mainly because of the effect of the buffered pH in the extracting solutions, which masked the intrinsic pH differences in the samples and changed the original pH values to 7.0 (NH₄-acetate) or 5.0 (Na-acetate), in addition to the nature of the displacing cation, implying a different capacity of extracting Al than KCl. Aluminum contents extracted with KCl were smaller than the exchangeable and acid-extractable Al from the sequential method, indicating a possible overestimation of these fractions, mainly in the extraction with NH₄-acetate (pH 7.0) solution. In spite of the difference in magnitude, Al_{KCl} had a significant relation with Al_{NH₄-acet.} ($r^2 = 0.80$,

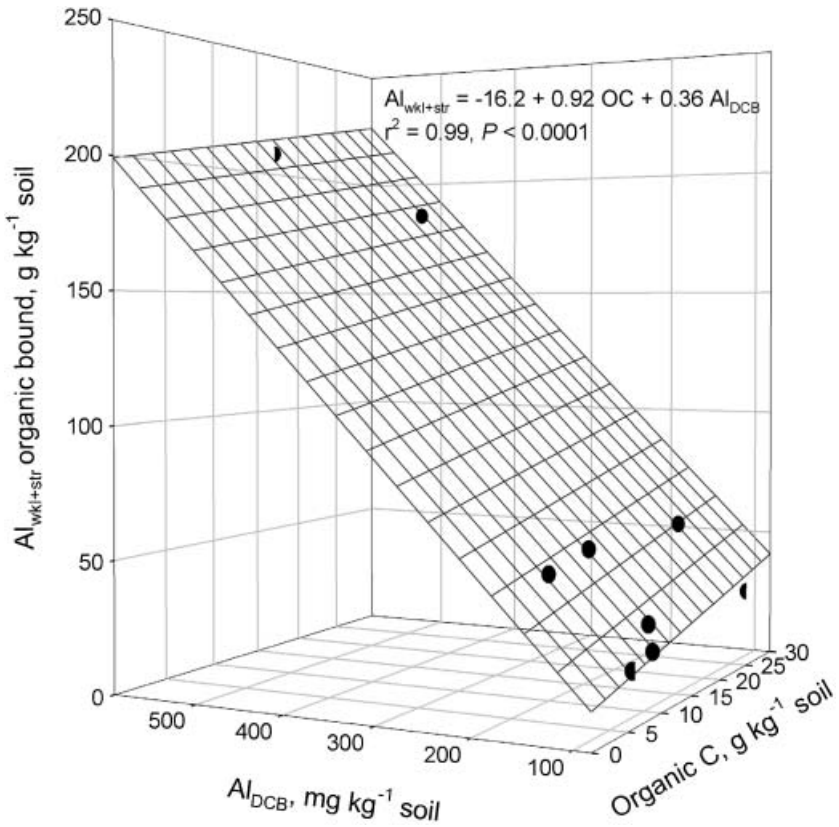


Figure 5. Relationship among total organic carbon, Al extracted by DCB solution, and Al organically bound (sum of weakly plus strongly organic bound) in a sandy Alaquod soil amended with organic composts.

$P < 0.01$) but had a poor relation with $Al_{Na-acet.}$ ($r^2 = 0.35$). Soils amended with HA and GreenEdge[®] had the highest $Al_{NH_4-acet.}$ concentration, and similar to the single extraction, the high Al content in HA-amended soil can be due to the presence of soluble HA-Al complexes in the supernatant after centrifugation. The use of micro-filtration after centrifugation could solve this doubt (Swift 1999; Senesi and Loffredo 1999), but it would be difficult to recuperate the retained Al-HA bound in the filter. In the Na-acetate extraction, the high Al content in the soil amended with G is probably due to the dissolution of carbonates by the buffered pH 5.0 solution, releasing the coprecipitated or adsorbed ions and increasing the amount of Al extracted at this stage of the sequential procedure.

The reducible Al is supposed to be the Al in oxihydroxide forms and Al bound to Fe and Mn oxides. In general, Al content in this fraction was

higher than in exchangeable and acid-extractable fractions. The soil that received G had the highest reducible Al fraction, reaching 120 mg Al kg⁻¹ soil. The solubility and formation of the Al oxides and hydroxides are pH dependent, in addition to other factors (Lindsay 1979; Schulze 2002). The results of the reducible Al had a significant correlation with soil pH at the end of the incubation ($r^2 = 0.50$, $P < 0.03$).

The oxidizable fraction is supposed to extract the Al bound to organic matter in a form that is not extractable to the three predecessor extraction steps. The hydrogen peroxide and nitric acid in high temperatures decompose organic matter and may also cause partial decomposition of aluminosilicates. Aluminum content in this fraction ranged from 9 to 98 mg Al kg⁻¹ of soil. The oxidizable fraction, in contrast with the weakly and strongly organically bound Al from the single extraction, had a significant correlation with total organic C (TOC; $r^2 = 0.48$, $P < 0.04$) but did not significantly correlate with dissolved organic C (DOC). These results suggest that in the sequential extraction, the predecessor steps may have either extracted Al from the DOC or, more probably, removed the entire Al-DOC as complexed form. The observation that oxidizable Al was significantly smaller than the sum of weakly + strongly organically bound Al reinforces the hypothesis that sequential extraction underestimated the organically bound Al. Despite the differences in magnitude, both Al_{wkl} and Al_{str} had significant relationships with Al_{oxid}, with Al_{wkl} being the closest (Figure 6). It is important to consider that, like all sequential extraction methods, a systematic error occurring in any point of the process in this method can affect the subsequent stages, representing a drawback as compared with the single extraction method.

Future studies should be conducted to monitor the Al dynamic in soils amended with organic composts in long-term periods, highlighting the effect of organic-matter mineralization and soil acidification on labile Al fractions.

CONCLUSIONS

Amendment of organic composts can be an important and effective management practice for alleviating Al toxicity in acid soils. This claim is supported by the facts that the application of composts, though they contributed to the increase in total Al, significantly increased soil pH and reduced exchangeable Al, as measured by the KCl extraction, converting it to less active forms of Al, such as organically bound Al and other noncrystalline fractions. Single extraction appears to be more reliable than sequential extraction for exchangeable Al, particularly for soils recently amended with organic matter.

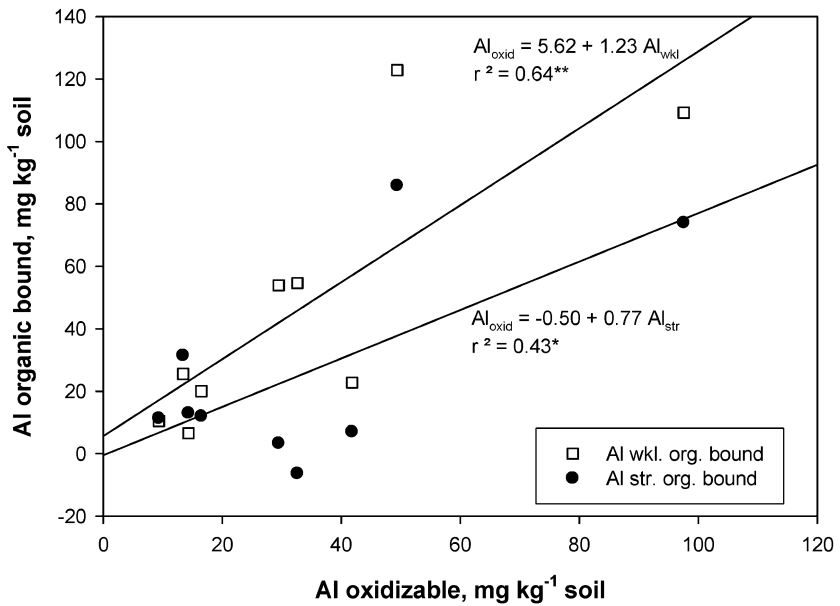


Figure 6. Relationship between Al weakly (wkl) and strongly (str) organic bound obtained from single extraction method and oxidizable Al, obtained from the sequential extraction method, in a sandy Alaquod soil amended with organic composts.

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