

Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved

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Abstract

High rates of lime and fertilizer-P are characteristically required to obtain high crop yields on highly weathered acid soils. Much of the agriculture in the southern tropical belt, where acid soils predominate, is carried out by resource-poor, semi-subsistence farmers who are unable to purchase large quantities of lime and fertilizer. There are, however, a number of reports that additions of organic residues to acid soils can reduce Al toxicity (thus lowering the lime requirement) and improve P availability. The literature regarding these effects is sparse and disjointed and an integrated overview of the probable mechanisms responsible and their implications is presented and discussed. During decomposition of organic residues, a wide range of organic compounds are released from the residues and/or are synthesized by the decomposer microflora. The two most important groups in relation to Al toxicity and P availability are soluble humic molecules and low molecular weight aliphatic organic acids. Both these groups of substances can complex with phytotoxic monomeric Al in soil solution thus detoxifying it and they can also be adsorbed to Al and Fe oxide surfaces consequently blocking P adsorption sites. During residue decomposition, there is often a transitory increase in soil pH and this induces a decrease in exchangeable and soil solution Al through their precipitation as insoluble hydroxy-Al compounds. It also confers a greater negative charge on oxide surfaces and thus tends to decrease P adsorption. The increase in pH has been attributed to a number of causes including oxidation of organic acid anions present in decomposing residues, ammonification of residue N, specific adsorption of organic molecules produced during decomposition and reduction reactions induced by anaerobiosis. There are also mechanisms specific to either Al detoxification or improved soil P status. For example, regular applications of organic residues will induce a long-term increase in soil organic matter content. Complexation of Al by the newly-formed organic matter will tend to reduce the concentrations of exchangeable and soluble Al present. As organic residues decompose, P is released and this can become adsorbed to oxide surfaces. This will, in turn, reduce the extent of adsorption of subsequently added P thus increasing P availability. The practical implication of the processes discussed is that organic residues could be used as a strategic tool to reduce the rates of lime and fertilizer P required for optimum crop production on acidic, P-fixing soils. Further research is, therefore, warranted to investigate the use of organic residues in the management of acid soils.

Introduction

Acid soil infertility is a major limitation to crop production on highly weathered and leached soils in both tropical and temperate regions of the world (Sanchez, 1976; Von Uexküll & Mutert, 1995). In addition, soil

acidification induced by the activities of mankind has become of increasing concern in recent years. Common anthropogenic causes of acidification include leaching with acid rainfall (the result of industrial pollution) and nitrification following applications of nitrogenous fertilizers (Wild, 1988). Two fundamental

factors limit the fertility of acid soils; nutrient deficiencies e.g. P, Ca and Mg, and the presence of phytotoxic substances e.g. soluble Al and Mn.

In most situations, poor crop growth in acid soils can be correlated directly with Al saturation (the percentage of effective CEC occupied by exchangeable Al) (Abruna-Rodriguez et al., 1982; Sartain & Kamprath, 1977). The practice of liming acid soils, i.e., applying CaCO_3 , in order to raise soil pH and precipitate exchangeable Al as insoluble hydroxy-Al has long been recognized as necessary for optimum crop production (Haynes, 1984). However, in many acid soils large quantities of lime e.g. 2–10 tonne ha^{-1} , are commonly required to achieve adequate growth of many crops.

The low P status of highly weathered acid soils is a particular problem because large amounts of P need to be applied in order to raise concentrations of available soil P to an adequate level (Sanchez & Uehara, 1980). This is because such soils contain large quantities of Al and Fe hydrous oxides which have the ability to adsorb P onto their surfaces. Thus, much of the added P is 'fixed' and is not readily available for crop use.

Acid soils occupy about 30% of the world's ice-free land area and occur in two main global regions; the northern cold temperate belt and the southern tropical belt (Von Uexküll & Mutert, 1995). The latter belt includes southeast Asia, Africa and central South America where much of the agriculture practiced is semi-subsistence farming. Previously, such farmers had the option of abandoning their land temporarily (for fallow periods), or even permanently, but the increasing population pressures are now forcing them to manage soil fertility in order to maintain productivity (Myers & De Pauw, 1995). For both logistic and economic reasons, it is often not practicable for these resource-poor farmers to apply high rates of lime and fertilizer P to their soils. There is, therefore, a need to develop practicable alternatives.

A number of workers have shown that the addition of green manures and animal wastes to acid soils can reduce Al toxicity and increase crop yields (Berek et al., 1995; Hue, 1992). Additions of organic residues have also been shown to increase P uptake and crop growth on P-deficient soils (Hue, 1990; Hue et al., 1994). The application of organic residues to acid soils in order to minimize the need for lime and fertilizer P would be of considerable benefit to resource-poor, semi-subsistence farmers. Indeed, organic residues such as animal manures, composted wastes and grass

and crop residues are usually readily available to such farmers albeit sometimes in limited amounts.

The purpose of this paper is to review the role that applications of organic residues could have in reducing Al toxicity and P deficiency in acid soils. Emphasis is placed on the probable processes and mechanisms that are involved. Literature on the subject is sparse and somewhat disjointed, and this paper sets out to produce an integrated, mechanistic discussion on the topic. The areas where further research is required are highlighted and the practical significance of the findings are discussed.

Al solubility in soils in relation to Al toxicity

In order to understand how organic matter (OM) additions can help ameliorate Al toxicity, an appreciation of the chemistry of Al in acid soils is required. For this reason, the basic principles of Al solubility in soils are briefly outlined below.

Al solubility in soils

Aluminium exists in soils in many mineral forms including hydrous oxides, aluminosilicates, sulphates and phosphates. The processes and factors influencing the dissolution and precipitation of Al-containing minerals in soils have been reviewed in detail elsewhere (Huang, 1988; Ritchie, 1994) and this is not considered in this review.

In acid soils, an appreciable portion of the cation exchange capacity is satisfied by Al ions i.e. the soils have a high Al saturation. Whilst these Al ions are referred to as exchangeable Al^{3+} , they are a mixture of monomeric Al ions [Al^{3+} , AlOH^{2+} , $\text{Al}(\text{OH})_2^+$] with an average charge per Al between 2 and 3, decreasing as pH increases (Wild, 1988). Aluminium is tightly held to exchange sites and, as a result, concentrations in soil solution are characteristically low, often ranging between 10 and 250 μM (Adams & Moore, 1983; Curtin & Smillie, 1983; Kamprath, 1978).

Since the solubility of Al is highly pH-dependent, when an acid soil is limed, exchangeable and soluble Al precipitate as hydroxy-Al species. The positively charged monomeric AlOH^{2+} and $\text{Al}(\text{OH})_2^+$ species can polymerize to form both large and small positively-charged polynuclear complexes which become sorbed to clay mineral and organic matter surfaces (Rengasamy & Oades, 1978; Stole et al., 1976). Thus, liming an acid soil to above about pH 5.5 results in concentrations of soluble and exchangeable Al

being lowered to negligible levels and Al toxicity no longer limits crop growth. In this review, an alternative to liming (i.e. applying organic residues) is examined as a method of reducing the concentration of phytotoxic Al present in soil solution. Such an alternative could reduce the amount of lime required to produce adequate crop yields in acid soils.

Phytotoxicity of soil Al

Aluminium toxicity is usually the major growth-limiting factor for crop production in acid soils (Foy, 1988). The initial, and most obvious symptom is inhibition of root growth and injured roots are characteristically stubby with reduced growth of the main axis and inhibited lateral root formation (Foy, 1988). Inhibition of root growth occurs through impedence of both cell elongation and cell division (Kochian, 1995). Since root growth is restricted, the ability of the plant to explore the soil volume for nutrients and water is much reduced. As a result, nutrient and/or water stresses are common in plants suffering from Al toxicity.

Aluminium toxicity also interferes directly with active ion uptake processes functioning across the root-cell plasma membrane (Kochian, 1995; Wright, 1989). In particular, Al-induced reductions in Ca and P uptake have been widely reported (Huang et al., 1992; Mugwira, 1980). The mechanism of the Al/P interaction is thought to be an adsorption - precipitation reaction between Al and P at the root surface or in the root free space i.e. cell walls (McCormick & Borden, 1974; Naidoo et al., 1978). The P may be adsorbed by hydroxy-Al already precipitated in the root free space or the P may be precipitated as insoluble aluminium phosphates; both occurrences are likely. The practical result is that P deficiency symptoms are common in plants suffering from Al toxicity (Foy, 1988; Haynes, 1984). Thus, amelioration of Al toxicity by liming characteristically results in greatly increased P uptake by plants even though the availability of soil P may be unchanged or even decreased (Haynes, 1982).

Whilst both exchangeable Al and Al saturation have been used as measures of potential Al toxicity (McCray & Sumner, 1990; Pearson, 1975), the concentration of Al in soil solution is a more direct measurement of the conditions to which plant roots are subjected to. Indeed, Al concentrations in soil solution have been observed to be closely related to inhibition of plant growth in acid soils (Adams and Moore, 1983; Evans and Kamprath, 1970). However, growth inhib-

ition is not only related to the quantity of Al in soil solution but also the species of soluble Al present.

It is now generally accepted that Al toxicity is reduced in the presence of inorganic and organic complexing ions in soil solution (Cameron et al., 1986; Hue et al., 1986). Indeed, it is the activity of Al^{3+} and/or monomeric hydroxy - Al species that is most negatively correlated with depressed yields due to Al toxicity (Wright, 1989). Blamey et al. (1983) suggested that either Al^{3+} or $Al(OH)_2^+$ might be the predominant ions responsible for decreased root elongation of soybean [*Glycine max* (L.) Merr]. However, both Alva et al. (1986) and Kinraide & Parker (1990) found that growth of plants was more sensitive to $Al(OH)_2^+$ and $Al(OH)_3$ than Al^{3+} . The reason for this is thought to be that at low pH (where Al^{3+} predominates) the presence of H^+ partially alleviates the phytotoxic effect of Al^{3+} by competing with Al^{3+} at the root cell plasma membrane (Kochian, 1995). At higher pH values, where monomeric hydroxy-Al species predominate, the activity of H^+ is much reduced so that its competitive effects are negated.

Aluminium forms stable complexes in soil solution with soluble humic molecules and simple aliphatic organic acids (Ritchie, 1989). The nature of these complexes is discussed in detail in following sections. Aluminium in a form complexed to soluble OM is not toxic to plants (Kinraide, 1991; Suthipradit et al., 1990) and complexation of Al by OM appears to be a very important mechanism of detoxification of soil solution Al (Kochian, 1995; Ritchie, 1989).

Role of organic matter in binding with Al

During the decomposition of plant and animal debris, a whole range of organic compounds are released from the debris and/or synthesized by the decomposer microorganisms. Aluminium can bind strongly to many of these compounds. Soil organic matter complexes with Al and other polyvalent cations can be grouped in two main categories (Stevenson & Vance, 1989). These are: (i) well-defined biochemical compounds such as simple aliphatic organic acids, phenols, phenolic acids, hydroxamate siderophores, sugar acids and polymeric phenols and (ii) complex humic materials. The relative importance of specific biochemical compounds versus humic substances in binding Al is unknown and varies with soil and environmental conditions. It is, however, generally considered that humic substances may be of greater importance in reducing

phytotoxicity of Al in acid soils (Harper et al., 1995; Stevenson and Vance, 1989; Wong et al., 1995).

Reactions with humic materials

Nature of products

Humic substances, which make up 70–80% of the soil organic matter (SOM) content of most mineral soils, are complex systems of high molecular weight organic molecules made up of a core of phenolic polymers produced from the products of biological degradation of plant and animal residues and the synthetic activity of microorganisms (Stevenson, 1994). They exist as heterogeneous, complex, three-dimensional amorphous structures.

Humic substances are able to form complexes with polyvalent metal ions, such as Al, due to their unusually high number of O - containing functional groups, which include COOH, phenolic, enolic, alcoholic OH and C=O. Due to the heterogeneous nature of humic substances, complexation may be regarded as occurring at a large number of reaction sites with binding affinity that ranges from weak forces of attraction (ionic) to formation of stable coordinate linkages (Stevenson & Vance, 1989). As a result, the mechanisms involved in the reactions of Al with organic matter are complex and probably involve simultaneous chelation, complex formation, adsorption and coprecipitation (Haynes, 1984). Because there is little distinction between the various mechanisms in the literature, Al is often described as being 'bound' to organic matter (Ritchie, 1989). Aluminium forms both soluble and insoluble associations with humic material.

Detoxification of soluble Al

Soluble humic material can form associations with Al in soil solution. The result is generally referred to as organically 'complexed soluble Al' although, as noted above, a number of different binding mechanisms occur. Several workers have shown that when monomeric Al becomes bound to soluble humic material it is no longer toxic to plants. For example, in greenhouse experiments in sand culture, Tan & Binger (1986) showed that in the absence of humic acid (HA), growth of maize plants decreased linearly with increasing Al additions. However, addition of humic acid at 100–350 mg kg⁻¹ greatly benefited plant growth and ameliorated the negative effect of increasing Al concentrations.

Similarly, in solution culture experiments, Suthipradit et al. (1990) found that addition of fulvic acid

(FA) dramatically reduced the amount of monomeric Al present in solution and alleviated the toxic effect of Al on growth of soybean, cowpea and green gram. The non-toxic Al-fulvate complex remained in solution. Harper et al. (1995) showed that addition of FA to solution cultures negated the phytotoxic effect of a concentration of 30 μM Al on root growth of maize seedlings (Table 1). Indeed, addition of FA tended to stimulate root growth; where FA had been added, Al was present in solution almost entirely in complexed form and virtually no monomeric Al was detectable.

Reactions with organic acids

Nature of products

Low-molecular-weight organic acids that are commonly identified in soils include formic, acetic, propionic, butyric, %crotonic, lactic, oxalic, succinic, fumaric, tartaric and citric (Stevenson, 1967). The leaves of plants often contain high concentrations of organic acids such as malic and citric and to a lesser extent succinic, fumaric and oxalic (Stevenson & Vance, 1989) which are added to the soil in plant residues. In addition, a wide range of organic acids are produced by the soil microbial biomass (Rovira & McDougall, 1967). Organic acids can form stable chelate complexes with Al³⁺ and other polyvalent cations. Hydroxy acids, such as citric, form stronger complexes than those containing a single COOH group (Stevenson & Vance, 1989).

The concentration of organic acids in soil solution is normally low (about 1–5 mM), but substantially higher concentrations can often be found in the rhizosphere (Stevenson & Vance, 1989). Their concentrations are also significantly higher in soils amended with organic manures (Iyamuremye et al., 1996). Organic acid concentrations can be significantly lower in cultivated soils than in paired sites under native vegetation (Fox and Comerford, 1990; Hue et al., 1986).

Detoxification of soluble Al

The role of organic acids in detoxifying monomeric Al in soil solution is still unclear. Hue et al. (1986) demonstrated that, in nutrient solutions, soluble organic acids (5–50 μM) were effective at detoxifying Al and improving root growth of cotton seedlings. The organic acids that were most effective were citric, oxalic and tartaric acid in that increasing order, while malic, malonic and salicylic acids were less effective in that decreasing order. Similarly, Bartlett & Riego

Table 1. Total and monomeric Al concentrations in nutrient solutions containing increasing concentrations of fulvic acid in the presence of 30 μM Al and relative root lengths of maize plants grown in the nutrient solutions

Fulvic acid (mg C L ⁻¹)	Total Al (μM)	Monomeric Al (μM)	Relative ^a root length (cm)
0	27.3	18.6	0.63
40	27.7	2.7	1.29
120	30.2	ND ^b	1.46
360	32.8	ND	1.10

^aRoot length relative to that where no Al or fulvic acid was added.

^bND = not detected.

Data from Harper et al. (1995).

(1972) found that citric acid could detoxify Al in nutrient solution and thus markedly stimulate root growth of maize seedlings.

Nonetheless, Suthipradit et al. (1990) found, in solution culture, that malic and oxalic acids at 50 μM failed to alleviate Al toxicity in soybean, cowpea and green gram seedlings. By contrast, FA at 65 mg L⁻¹ was extremely effective at complexing and detoxifying Al. Such observations confirm the findings of Ritchie et al. (1982) that HA is more effective than simple carboxylic acids in complexing Al.

It is relevant to consider that many of the organic acids capable of complexing Al may be present in soil solution at high concentrations for relatively short periods of time since they are highly susceptible to microbial degradation (Ritchie, 1994; Wong et al., 1995). It can, therefore, be argued that there will be a need for a regular supply of organic acids into soil solution for Al detoxification to be sustained (Ritchie, 1994). Nevertheless, complexation of organic-acid anions with Al presumably confers some protection against decomposition. The relative biodegradability of organic-acid anions alone compared to those complexed with Al needs to be determined before more definitive statements can be made.

It is interesting to note here that organic acids are involved in detoxification of Al in the rhizosphere (Kochian & Jones, 1996). Malic acid release from root tips appears to be a mechanism of Al resistance for wheat genotypes, whilst citric acid release is apparently related to Al resistance in maize and snapbean genotypes (Delhaize & Ryan, 1995; Miyasaka et al., 1991; Pellet et al., 1994). The release of organic acids protects the root apex by chelating Al in the rhizosphere (Kochian, 1975), thus rendering it non-phytotoxic.

Influence of additions of organic residues on soil Al

The addition of green manures and animal wastes to acid soils can reduce the total concentration of Al in soil solution (Al_T) and/or the concentration of monomeric Al in solution (Al_{Mono}) and thus reduce Al phytotoxicity and increase crop growth (Asghar & Kanehiro, 1980; Hue & Amien, 1989; Hue, 1992; Wong et al., 1995). Controversy surrounds the mechanisms by which such Al detoxification occurs (Hue & Amien, 1989). Proposed mechanisms include an increase in soil pH (Noble et al., 1996), a reduction in exchangeable Al due to complexation of solid-phase organic material (Hoyt & Turner, 1975), and complexation of Al in soil solution by soluble OM thus reducing solution Al^{3+} activity (Hue et al., 1986).

Effect of soil pH

Additions of organic residues to soils can result in an increase in soil pH (Hoyt & Turner, 1975; Hue, 1992; Lungu et al., 1993; Noble et al., 1996). Often, there is an initial increase in pH over the first 1 or 2 months of residue decomposition followed by a decline to above or below the initial pH level (Asghar & Kanehiro, 1980; Hoyt and Turner, 1975; Hue, 1992; Wong et al., 1999). The magnitude of the rise in soil pH varies depending on the type of residue, its rate of application and the buffering capacity of the soil. For additions of about 20 t ha⁻¹, increases in soil pH have generally been in the range of 0.2–0.6 pH unit and, with rates of 40–50 t ha⁻¹, increases of 0.8–1.5 pH units have been recorded (Berek et al., 1995; Iyamuremye et al., 1996; Noble et al., 1996).

Long-term field experiments where organic manures (Schjønning et al., 1994) or crop residues (Van Antwerpen & Meyer, 1998) have been applied to soils

for many decades do not generally show a long-term increase in soil pH. Indeed, there is often a tendency for soil pH to decline slightly due to the accumulation of soil organic matter (Schjønning et al., 1994; Wild, 1994). A long-term increase or decrease in soil pH is dependent on the balance between proton production and consumption in the system (Helyar & Porter, 1989), which can be estimated by calculating proton budgets (Ulrich, 1991). Nevertheless, short-term proton imbalances, such as those which apparently occur during the initial period of decomposition of organic residues may well have considerable practical significance. For example, a rise in soil pH during the initial few months of crop establishment (during decomposition of applied crop residues) could certainly lead to better crop growth and higher yields in acid soils.

There are several different mechanisms that have been suggested to explain the initial rise in soil pH when organic amendments are applied to soils. These include oxidation of organic acid anions present in the decomposing residues, ammonification of residue organic N, specific adsorption of organic molecules produced during residue decomposition and reduction reactions induced by anaerobiosis. These mechanisms are outlined below.

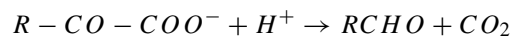
Oxidation of organic acid anions

Plant material generally contains an excess of cations over inorganic anions and the balance is maintained by synthesis of organic acid anions, e.g. oxalate, citrate, malate (De Wit et al., 1963). Oxidation of these organic acid anions, with the consumption of H^+ ions (or the release of OH^-) during decomposition of plant material, is likely to be a major contributor to an increase in pH (Barekzai & Mengel, 1993; Helyar & Porter, 1989; Noble et al., 1996; Ritchie and Dolling, 1985; Tang et al., 1999). Ashing plant material and measuring the alkalinity of ash provides an estimate of the organic acid anion content (Pierre & Banwart, 1973). It can also be calculated by chemical analysis of plant material. The difference between the sum of inorganic cations ($K^+ + Na^+ + Ca^{2+} + Mg^{2+}$) and the sum of inorganic anions ($Cl^- + H_2 PO_4^- + SO_4^{2-} + NO_3^-$) is equivalent to the organic acid anions present (De Wit et al., 1963).

There appear to be two mechanisms operative in the organic acid anion-induced increase in soil pH; an immediate chemical reaction followed by a more marked increase associated with the decomposition process (Tang et al., 1999; Yan et al., 1996). The added organic acid anions are able to complex protons

(Ritchie and Dolling, 1985), and this accounts for any immediate rise in soil pH (Tang et al., 1999). That is, if soil pH is less than the dissociation constants (pK_a) for the weak organic acids in the added residues, there will be an increase in soil pH due to association of H^+ from the soil with some of the organic anions. Indeed, this is thought to be a major mechanism involved in the increase in soil pH when relatively stable composted wastes are added. This led Wong et al. (1998) to propose measurement of the proton consumption capacity of such materials by titration of the materials with 0.05 M H_2SO_4 .

However, most of the rise in soil pH when undecomposed plant residues are added is thought to be associated with microbial decomposition and decarboxylation of organic acid anions (Barekzai and Mengel, 1993; Mengel, 1994; Tang et al., 1999; Yan et al., 1996). Decarboxylation of organic-acid anions results in both consumption of protons and release of CO_2 :



Indeed, it has been shown that increases in soil pH following the addition of malate and citrate are highly correlated with CO_2 evolution during the decomposition of these two anions (Yan et al., 1996). Thus, decomposition of organic residues has a liming effect. Indeed, Pocknee & Sumner (1997) showed that addition of calcium oxalate and calcium gluconate to soils had identical effects on final pH to addition of $CaCO_3$ when added in equimolar Ca rates. However, the biological decomposition of the organic molecules (and thus the concomitant rise in soil pH) was markedly slower than for the chemical dissolution of $CaCO_3$.

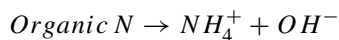
The organic-acid anion content of plant tissue is strongly related to the magnitude of cation accumulation in the plant or plant part (Noble et al., 1996). Thus, it is not surprising that several workers have observed that the increase in soil pH during decomposition of plant material is closely related to the base cation content of the material (Bessho & Bell, 1992; Wong et al., 1998a, b).

Ammonification of residue-N

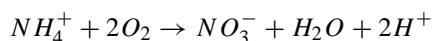
Transformations of N during decomposition of organic residues will also have a large influence on changes in soil pH (Hoyt & Turner, 1975; Pocknee & Sumner, 1997). These effects will be additional to those related to the organic-acid anion content. That is, ash alkalinity measures the excess of base-over-acid-forming elements (excluding N which is volatil-

ized during ignition). Similarly, when the difference between the sum of inorganic cations and anions is used, nitrate accumulated in the plant sample is measured but N incorporated into organic forms (proteins) is not considered.

During decomposition of organic residues, organic N is ammonified. This will cause a rise in pH:



However, when the NH_4^+ is nitrified to NO_3^- there is a release of protons:



The overall transformation of organic N – NO_3^- is, therefore, acidifying with one H^+ being produced per mole of N transformed to NO_3^- . If soil conditions do not favour nitrification then the pH will rise, whilst if nitrification proceeds rapidly the pH will decrease (Haynes & Swift, 1993). Nitrification is thought to be the main reason why a rise in pH following residue addition is often followed by a decline (Hoyt & Turner, 1975). Indeed, Yan et al. (1996) showed that whilst addition of malate to soil resulted in an immediate increase in pH, addition of malate plus NH_4^+ caused an immediate increase in soil pH followed by a decrease associated with nitrification. As noted by Pocknee & Sumner (1997), where rapid decomposition of organic residues leads to an accumulation of NH_4^+ followed by NH_3 volatilization losses, soil pH will remain elevated compared to that if all the N had been nitrified.

Nitrogen mineralization has probably had little influence on pH in short-term incubations (1 or 2 months) where organic materials with a wide C/N ratio are used. For example, Noble et al. (1996) measured increases in pH after incubation of leaf litter residues with a soil for 8 weeks. However, the C/N ratios of litter ranged from about 34 to 120:1 and net N immobilization presumably occurred during this initial period of decomposition. As decomposition continues, the C/N ratio of the residues decreases (due to immobilization of soil mineral N and loss of residue C as CO_2). Once it declines below about 25:1, net mineralization begins to occur (Haynes, 1986) and as organic N is converted to nitrate the pH will decline.

Specific adsorption of organic molecules

Another possible mechanism for the organic residue-induced increase in pH is specific adsorption of humic material and/or organic acids (the products of decomposition of organic residues) onto Al and Fe hydrous

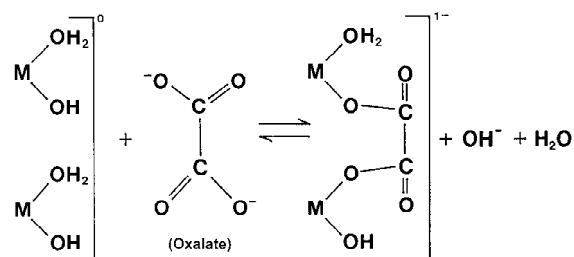
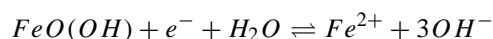
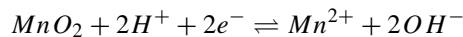


Figure 1. Specific adsorption of oxalate to an Al or Fe (M) hydrous oxide surface. After Hue (1992).

oxides with the consequent release of OH^- ions (Hue et al., 1986; Iyamuremye & Dick, 1996). Such a rise in pH is similar to the 'self-liming effect' when gypsum is added to soils and OH^- ions are released following specific adsorption of SO_4^{2-} (McCray & Sumner, 1990). Specific adsorption of oxalate with the release of OH^- is shown in Figure 1, and the nature of such reactions is discussed in more detail in a following section dealing with the influence of organic molecules on P adsorption.

Reduction reactions

It has also been suggested that the rise in pH could be partially attributable to reduction of higher valence Mn oxides and/or Fe oxides and hydrous oxides in soils (Hoyt & Turner, 1975; Hue, 1992). Such reactions characteristically occur under anaerobic conditions (Ponnamperuma, 1972) and lead to a rise in soil pH:



Hue & Amien (1989) suggested that localized anaerobic conditions could develop around rapidly decomposing pieces of organic residues (due to intense microbial activity), thus promoting reduction reactions and a rise in pH.

Effect on exchangeable Al

Since addition of organic residues to soils often results in an initial increase in soil pH, a decrease in the concentration of exchangeable Al would be expected to occur. Indeed, several workers have measured an increase in soil pH with a concomitant decrease in exchangeable Al and Al saturation during the decomposition of organic residues in soils (Bessho & Bell, 1992; Hoyt & Turner, 1975; Noble et al., 1996; Wong et al., 1998a, b). The decrease in exchangeable Al is not necessarily only a function of the rise in pH.

Adsorption of Al onto decomposing organic residues would also tend to reduce exchangeable Al levels (Hoyt & Turner, 1975). There is little direct evidence for this mechanism. Nonetheless, Patiram (1996) observed that application of farmyard manure, in a field experiment, decreased exchangeable Al during the first 75 days after application but, levels increased with time and were similar to control after 300 and 500 days. Soil pH was, however, unaffected by manure applications.

Research using unamended soils suggests that increases in OM caused by additions of organic residues to soils tends to decrease exchangeable Al through complexation by the newly added or formed OM. Thomas (1975), for instance, found that with increasing soil depth there was a strong negative correlation between OM content and exchangeable Al. He found the effect of OM was greater at lower pH values; at pH 3.5 an increase in OM content from 1 to 2% lowered exchangeable Al from 6.0 to 4.2 meq 100 g⁻¹. Similarly, Evans & Kamprath (1970) observed less exchangeable Al in organic than mineral soils even when the pH of the organic soils was lower.

The use of sequential extraction procedures for exchangeable (1 M KCl-extractable) followed by organically bound (1 N CuCl₂-extractable) Al (Soon, 1993) from soils amended and unamended with organic residues would allow further investigation of this mechanism.

Effect on soluble Al

Several workers have shown that additions of decomposing organic residues to soils can reduce both Al_T and Al_{Mono} in soil solution (Bessho & Bell, 1992; Kretzschmar et al., 1991; Nobble et al., 1996; Wong et al., 1995). The decrease in exchangeable Al and Al saturation caused by increased pH and/or complexation of Al by solid-phase organic matter will favour a reduction in Al concentrations in soil solution. Sorption of humic substances, formed during the decomposition process, onto soil mineral surfaces may be another important factor regulating Al_{Mono} (Wong et al., 1995). Wong & Swift (1995), for example, found that treatment of acid soils with HA resulted in a reduced solubility of Al-containing clay minerals and also increased selectivity for exchangeable Al. Both factors interacted and lowered Al_{Mono} activities in soil solution. In addition, soluble organic molecules (organic acids and phenolic, humic - type substances) produced during decomposition of

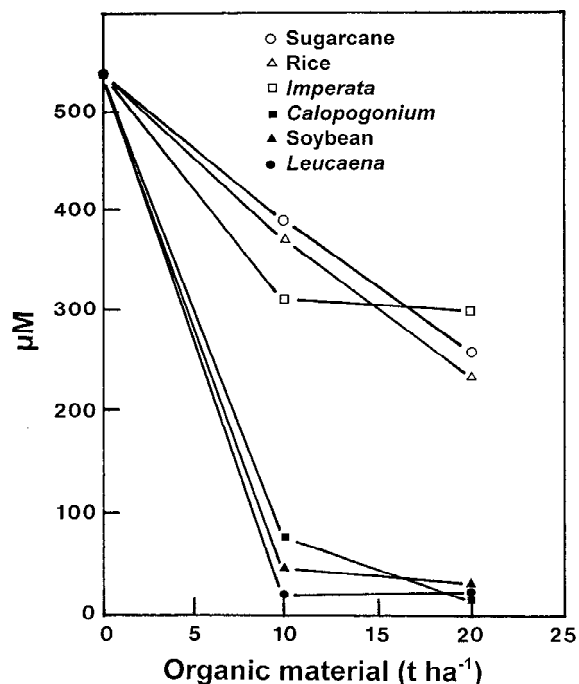


Figure 2. The concentration of monomeric Al in soil solution of a Podzolic soil as affected by source and rate of applied organic material. Redrawn from Berek et al. (1995).

organic residues will complex with monomeric Al in soil solution thus greatly reducing the proportion of Al_T present in phytotoxic monomeric forms.

The complexation of Al by soluble organic materials produced during residue decomposition is a particularly important mechanism of detoxification of Al. Indeed, addition of organic residues to soils typically decreases the proportion of Al_T present in soil solution as Al_{Mono} regardless of whether soil pH has been increased or not (Bessho & Bell, 1992; Berek et al., 1995; Kretzschmar et al., 1991); in greenhouse studies, the growth-promoting effect of adding organic residues to acid soils is often closely related to the magnitude of the reduction in Al_{Mono} in soil solution.

The data (Figure 2) of Berek et al. (1995), show that incubation of the residues of six plant species at increasing rates with an Indonesian red-yellow podzolic soil resulted in marked reductions in Al_{Mono} in soil solution even though there were no significant changes in soil pH. Leguminous residues (*Calopogonium*, soybean and *Leucaena*) were more effective than non-leguminous residues (*Imperata*, sugarcane and rice) at reducing Al_{Mono} (Figure 4) possibly because of their more rapid rate of decomposition. Growth of soybean in the residue-amended soils

was greater than that in unamended soil and growth was generally better for legume-than non-legume-amended treatments.

Whilst the amount of Al_{Mono} is generally reduced, in some cases, Al_T in soil solution is unaffected or is even increased during organic residue decomposition (Berek et al., 1995; Slattery & Morrison, 1995). In such cases, it is thought that the large amounts of soluble organic matter present, originating from the decomposition of residues, complex with Al and maintain it in the solution phase. Indeed, Wong & Swift (1995) pointed out that a decrease in Al_{Mono} activity in soil solution due to complexation by soluble organic matter would result in more dissolution of Al-containing minerals e.g., gibbsite or amorphous hydroxy-Al oxides, and thus an increase in Al_T in soil solution.

Applications of organic residues to soils under field conditions have been shown to influence speciation of Al in soil solution in several studies. Slattery & Morrison (1995) compared stubble retention with stubble burning on an acid soil, and they found that soil pH was not significantly altered, whilst exchangeable Al and Al_T in soil solution tended to be higher under stubble retention. Nevertheless, in the stubble retention plots there was a higher concentration of soluble, low molecular weight organic acids present in the soil and as a result Al_{Mono} as a proportion Al_T in solution was decreased markedly. In a field experiment on a tropical Oxisol in Burundi, Wong et al. (1995) showed that additions of the prunings of various trees and farmyard manure all greatly decreased the concentration of monomeric Al in soil solution. Grain yields of maize and beans in these soils were correspondingly increased due to alleviation of Al toxicity.

Perspective

It is evident that a major effect of adding organic residues to soils is an increase in soil pH. This may be a short-term effect lasting several months or it may be more long-term in nature. Nonetheless, such an effect creates a short-term window of opportunity for crop production on acid soils.

As noted by Pocknee & Sumner (1997), it is interesting to consider that although addition of organic residues can increase soil pH it only transfers alkalinity from one place to another and does not independently synthesize alkalinity. That is, one locality benefits from the addition of residues only at the expense of the place from which the material came. In

this regard, it is relevant to consider that, in fact, most plants growing in soil using NO_3^- as their major N source (the usual situation) actually raise their rhizosphere pH due to excess anion uptake (Haynes, 1990). Thus, the transfer of their residues results in net transfer of the equivalent amount of acidity to another site. This does not, however, preclude there being a transient rise in pH during the initial stage of decomposition due to decarboxylation of organic acid anions.

By contrast, leguminous plants, when using biologically-fixed N_2 as their main N source, acidify their rhizosphere due to excess cation uptake (Haynes, 1983), and therefore result in the net transfer of alkalinity when their residues are transferred to another site (Haynes & Williams, 1999). Indeed, even in short-term incubation experiments, application of leguminous residues tend to cause in a greater rise in soil pH than non-leguminous ones (Bessho & Bell, 1992; Iyamuremye et al., 1996).

In many cases, the increase in soil pH following the addition of organic residues to soils is the major factor contributing to a decrease in the concentration of Al_{Mono} in soil solution. Other factors also contribute to the decrease. The release of soluble OM into soil solution during residue decomposition results in complexation of Al and a reduction in the concentration of soluble Al_{Mono} . The relative importance of soluble humic material versus that of specific biochemical compounds, such as organic acid anions, in reducing Al_{Mono} is as yet unknown, but soluble humic material has been a more effective agent in laboratory studies.

In the longer term, repeated additions of organic residues will result in an accumulation of humic material in the soil which will complex Al from soil solution and also increase CEC, thus decreasing Al_{Mono} in soil solution. Humic substances may also coat the surfaces of Al-containing minerals thus decreasing their solubility. There seems no doubt that additions of organic residues to acid soils have both short- and long-term effects in reducing Al_{Mono} activity in soil solution. The agronomic challenge is to use these effects as management tools as part of integrated nutrient management systems. The vast majority of studies conducted so far have been in the laboratory or greenhouse, and work needs to be extended into the field.

Phosphate availability in soils

Phosphate sorption (the loss of orthophosphate from soil solution to solid phases) occurs by both specific adsorption and precipitation reactions (Sample et al., 1980; Sanchez & Uehara, 1980). Specific adsorption (ligand exchange) occurs when P anions replace the hydroxyl groups on the surface of Al and Fe oxides and hydrous oxides (Parfitt, 1978). Precipitation reactions occur when insoluble P compounds form and precipitate. At low soil pH, i.e. <4.5–5.0 additions, of P to soils can result in precipitation of Al and Fe phosphates, whilst at high pH (>6.0–6.5) insoluble calcium phosphates can form (Haynes, 1984). In many situations, however, specific adsorption reactions are the main regulators of soil solution P concentrations (Parfitt, 1978). Specific adsorption of P is effected by many factors including pH, ionic strength of the background electrolyte and anion competition (Bowden et al., 1980; Barrow, 1984).

Highly weathered acid soils often have low levels of extractable 'available' P and also contain large quantities of Al and Fe hydrous oxides, and therefore have the ability to adsorb large amounts of added P. For these reasons, large quantities of P fertilizer are often required for optimum crop production. In this review, the strategy of using the additions of organic residues to soils as a method of reducing P adsorption, and thus reducing P fertilizer requirements, is discussed.

Influence of organic matter on P adsorption and availability

Humic substances

Negatively charged, high-molecular-weight, humic polymers can form strong bonds with metal hydrous oxide surfaces through both electrostatic bonding (anion exchange) and specific adsorption i.e. ligand exchange (Stevenson, 1994). Anion exchange is possible because positive sites exist on the amphoteric Fe and Al oxide surfaces. Ligand exchange occurs through displacement of $\text{OH}_2^{0.5+}$ and $\text{OH}^{0.5-}$ groups at the oxide surface by OH and COOH groups on the humic molecules and results in strong binding of the humic material to hydrous oxides. Parfitt et al. (1977) demonstrated that sorption of FA on oxide surfaces was accompanied by displacement of OH^- groups by COO^- ions indicating ligand exchange. Physical (Van der

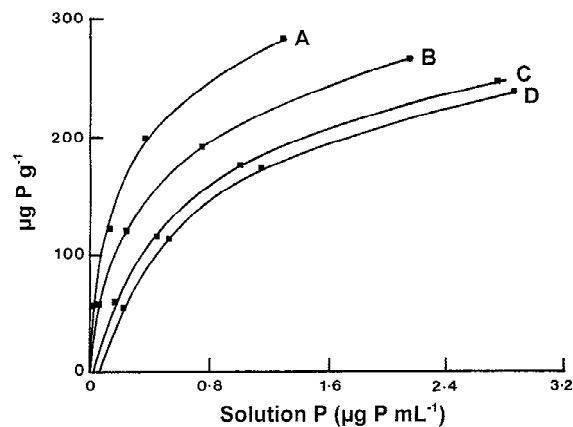


Figure 3. Phosphate adsorption isotherms for an acid soil previously treated with three levels of humic acid (HA). Rates of HA are: A = 0; B = 0.4%; C = 1.6% and D = 3.0%. Redrawn from Sibanda & Young (1986).

Waals) forces will also be involved in the interaction of humic molecules with oxide surfaces (Stevenson, 1994).

Since humic molecules are specifically adsorbed onto oxide surfaces they have a competitive effect on P adsorption. Moshi et al. (1974), for example, reported that adsorption of OM by soils increased the negative charge on surfaces and electrostatic competition resulted in a decrease in adsorption of P. Similarly, Perrott (1978) found that treatment of aluminosilicates with humified clover extracts caused the surface charge to become more negative and P adsorption was consequently decreased. The data of Sibanda & Young (1986) demonstrate the inhibitory effect of adsorption of humic acid onto a soil on subsequent adsorption of P (Figure 3); the presence of HA and FA on soil and oxide surfaces restricted subsequent P adsorption, yet when P adsorption was increased (by increasing P additions) there was virtually no release of humic or fulvic acid into solution. The reason for this is that the competitive ability of humic molecules with P does not exclusively lie in the occupation of adsorption sites by humic OH and COOH groups. The unfavourable electrostatic field generated around the adsorbed humic molecule is also important in preventing P adsorption. In addition, part of the adsorption mechanism for HA is physical (Van der Waals forces) and is not involved in competition for P.

The effect of OM on P adsorption is not, however, clear-cut. Yuan (1980), for example, found that pretreatment of soils with hot water-extractable soil organic materials had no effect on P adsorption by one

soil, a slight effect in another and a large effect in a third. Borggaard et al. (1990) found that removal of OM did not alter P adsorption by soils and concluded that organic matter did not compete with P for adsorption sites in the soils they studied. Appelt et al. (1975) reported that HA and FA did not decrease P sorption by volcanic ash-derived soils. They concluded that addition of humic and fulvic acid to these soils resulted in the formation of organic matter-hydroxy Al complexes which constituted new P adsorption surfaces. Thus, whilst some of the newly-added humic material may be adsorbed to oxide surfaces thus reducing P adsorption, some of it may react with soluble and exchangeable Al with the formation of new P adsorption sites.

Organic acids

Low-molecular-weight organic acids such as citrate, malate and oxalate are specifically adsorbed to Fe and Al hydrous oxide surfaces by ligand exchange reactions (Earl et al., 1979; Jones & Brassington, 1998; Violante and Gianfreda, 1993). An example of specific adsorption of oxalate onto an Al hydrous oxide surface was shown in Figure 1. Adsorption reactions for organic acids are concentration - dependent and generally increase with decreasing pH (Jones & Brassington, 1998).

As a result of specific adsorption reactions, organic acids can compete with P for adsorption sites on synthetic metal oxide and soil surfaces (Earl et al., 1979; Lopez-Hernandez et al., 1986; Violante & Gianfreda, 1993). Nagarajah et al. (1970), for example, in a study of the effect of a wide range of organic acid anions on P adsorption by oxide surfaces found that they reduced P adsorption in the order: citrate = oxalate > malonate = tartrate > acetate = succinate. Similarly, Earl et al. (1979) found that, in both soils and synthetic Al and Fe oxides, citrate caused a larger reduction in P adsorption than did tartrate, whereas acetate had little or no effect. Maximum reduction in P adsorption occurs when organic acids are added before P, and their effectiveness in inhibiting P adsorption generally increases with decreasing pH (Nagarajah et al., 1970; Violante et al., 1991; Violante & Gianfreda, 1993).

Violante & Gianfreda (1993) suggested that on the surfaces of hydroxy Al-montmorillonite complexes, P and oxalate may compete for some adsorption sites but not others. Of the sites on the clay minerals, that were available for adsorption by both anions, 51 – 79% of the sites were occupied by P. Many sites were highly

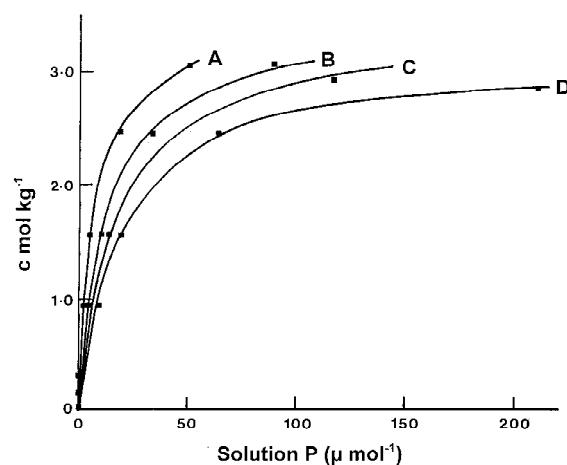


Figure 4. Phosphate adsorption isotherms for a soil previously treated with animal manure at rates of: A, 0; B, 1%; C, 2.5% and D, 5% w/w. Redrawn from Iyamuremye et al. (1996).

specific for P, whereas others were common to both oxalate and P, but these sites still had greater affinity of P than oxalate. Yet other sites were specific for oxalate.

Addition of organic residues

A number of studies have demonstrated that addition of organic amendments to soils can significantly increase the availability of P to plants and decrease the P adsorption capacity of soils (Easterwood & Sartain, 1990; Hue et al., 1994; Iyamuremye et al., 1996). A marked reduction in P adsorption capacity of a soil previously treated with increasing rates of animal manure is shown in Figure 4. The reduced P adsorption and increased P availability following applications of organic amendments to soils is thought to be the cumulative result of several mechanisms (Iyamuremye & Dick, 1996). These include release of inorganic P from decaying residues, blockage of P adsorption sites by organic molecules released from the residues, a rise in soil pH during decomposition and complexation of soluble Al and Fe by organic molecules.

Release of inorganic P

Organic materials generally contain significant quantities of P which is mineralized during decomposition of the organic residues and orthophosphate is released into the soil solution. Indeed, a large proportion of P in plant residues is soluble in water and, therefore, is readily released during decomposition (Bromfield & Jones, 1972). Nonetheless, in some circumstances,

much of this P may be immobilized by the microbial biomass decomposing the residue (McLaughlin & Alston, 1986). In general, a residue C:P ratio < 100 leads to net P mineralization, whilst a C:P ratio > 300 leads to net immobilization (Iyamuremye & Dick, 1996).

Where net release of P occurs during decomposition of the residue, the P is then rapidly adsorbed onto soil surfaces, thus increasing the proportion of adsorption sites occupied by P. As a result, the phosphate adsorption capacity of the soil is decreased with respect to subsequently-applied P. This seems to be the main mechanism by which addition of organic residues decrease the P adsorption capacity and increase P availability in soils (Iyamuremye et al., 1996; Li et al., 1990; Reddy et al., 1980; Singh and Jones, 1976). For example, Singh and Jones (1976) found that when residues with a P content less than 0.3% (sawdust, wheat straw and maize stalks) were incubated with soil, subsequent P adsorption by the soil was actually increased because previously-adsorbed P had been depleted during P immobilization as the residues decomposed. By contrast, for residues with a P content greater than 0.3%, lucerne, barley and bean residues and poultry manure, the P adsorption capacity of the soil was significantly decreased due to net P mineralization and adsorption of the released P. Similar results were recorded by Iyamuremye et al. (1996).

Occupation of P adsorption sites by organic molecules

Humic substances and organic acids, produced during the decomposition of organic residues, can be adsorbed onto soil surfaces. This blocks potential P adsorption sites and tends to increase the availability of P originating from both the organic materials and subsequently-added fertilizer P. Indeed, several workers have suggested that the release of soluble humic material and/or organic acids from decomposing organic residues and manures contributes greatly to the decrease in P adsorption capacity and increased P availability that occurs in soils following their application (Easterwood & Sartain, 1990; Hue, 1990, 1992). Iyamuremye et al. (1996), for example, found that incorporation of wheat straw, with a low P content, decreased the P adsorption capacity of most soils studied. Since little inorganic P was released from the straw, they reasoned that blockage of P adsorption sites by organic molecules was the probable cause.

It is difficult to separate the simultaneous effects of addition of inorganic P and addition of soluble organic compounds during the decomposition of organic

residues as factors reducing subsequent P adsorption by soils. Consideration of the charge characteristics of the soil may help disentangle these two effects. Easterwood & Sartain (1990) used potentiometric titrations relating to surface charge when inorganic P or clover residues were added to a soil. They found that, as expected, addition of inorganic P altered charge characteristics due to adsorption of phosphate. However, addition of clover residues altered surface charge, but in a different way to P, suggesting adsorption of organic compounds originating from the clover residue.

Increase in soil pH

As noted in the sections dealing with additions of organic residues to soils on Al toxicity, there is commonly a transient increase in soil pH during the first few months of residue decomposition. An increase in pH confers a greater negative charge on adsorption surfaces and thus tends to reduce P adsorption. Thus a decrease in P adsorption during this period may be partially attributable to the increased soil pH (Iyamuremye et al., 1996; Mkeni and MacKenzie, 1985).

Complexation and precipitation of soluble Al

The concentration of monomeric Al in soil solution is usually greatly decreased by additions of organic residues due mainly to complexation of Al by organic ligands and/or increased pH. There are two possible ways in which a reduction in the activity of monomeric Al in soil solution could increase P availability. Firstly, a common symptom of Al toxicity is P deficiency. Phosphate is precipitated in and around plant roots and translocation of P to stems and leaves is greatly inhibited (Haynes, 1984). Alleviation of Al toxicity will, therefore, greatly stimulate uptake and translocation of P. This mechanism has not received the attention it deserves since it is a major mechanism by which liming increases P uptake by crops (Haynes, 1982).

Secondly, in acid soils (<pH 5.0), P availability can be partially controlled by precipitation reactions. Added P can precipitate as insoluble Al (and Fe) phosphates thus reducing its plant-availability. A reduction in Al^{3+} activity in soil solution will decrease the likelihood of precipitation of Al phosphates (Iyamuremye & Dick, 1996). There is little evidence that this mechanism has a significant effect in residue-amended soils and Iyamuremye et al. (1996) considered it to be of minor importance, even in soils of pH less than 5.0.

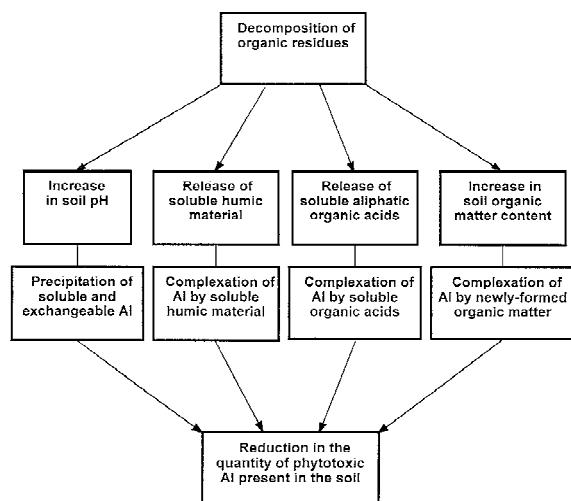


Figure 5. A conceptual model of the major processes that lead to detoxification of soil Al when organic residues are applied to soils.

Perspective

It is evident that in relation to P adsorption and P availability, the major effect of applying organic residues to soils is the addition of P in the residues. The added P increases P availability directly and is specifically adsorbed onto soil colloid surfaces and, as a result, the availability of subsequently added P is raised. As a consequence, residues with a high P content (and low C:P ratio) have the largest effect since net mineralization of P occurs and inorganic P is released onto soil solution. Secondary effects also occur. Adsorption of organic compounds produced during residue decomposition also decreases adsorption of subsequently added P and increases its availability. In addition, the rise in soil pH that occurs during residue decomposition increases surface negative charge and decreases P adsorption.

From a practical viewpoint, the effect of adding organic residues on P availability is principally a function of the P content of the residues. The extent to which an increase in pH and adsorption of organic molecules amplifies this increased P availability is still unclear. In addition, a reduction in Al phytotoxicity due to residue additions is likely to allow a crop to use available P more effectively. Further research is warranted to examine the extent and practical significance of these latter effects.

Summary and conclusions

A conceptual model of the main processes that occur during decomposition of organic residues in soils that could result in alleviation of Al toxicity is presented in Figure 5. Complexation of phytotoxic monomeric Al in soil solution by both soluble humic material and aliphatic organic acids occurs, whilst a reduction in exchangeable and soluble Al may occur through either increased pH or complexation of Al in the solid phase by newly-accumulated organic matter. At present, the relative importance of these various processes is unknown; it presumably differs in specific situations depending on factors such as the nature of the residues, frequency of residue application, soil properties and environmental conditions that influence residue decomposition.

Both short- and long-term effects are likely. For example, organic acids are subject to rapid microbial degradation in soils. Thus, it has been suggested that their concentrations in soil solution are likely to increase during the initial period of residue decomposition but then decline, whereas humic molecules are less susceptible to degradation and, therefore, may provide for a more permanent amelioration of Al toxicity. Even so, the situation is not clear-cut since formation of complexes with Al could greatly increase the resistance of organic acid anions to microbial degradation. This aspect needs further study. Complexation of Al by the newly-formed organic matter, in turn, leads to a reduction in concentrations of exchangeable and soluble Al.

An increase in soil pH during the first few months of residue decomposition is often observed. The main reason for this rise in pH is decarboxylation of organic-acid anions during residue decomposition. The fact that plants normally raise their rhizosphere pH when growing with NO_3^- as their main N-source suggests that transfer of their residues to another site will have an acidifying effect on the soil pH at that site in the long-term. Thus, short- and long-term effects of residue additions of soil pH may be conflicting and longer term experiments are required to disentangle these effects. Nonetheless, short-term Al-detoxifying effects in the first few months after residue application could have considerable significance in relation to the establishment and early growth (and thus final yields) of crops. Thus, a reduction in exchangeable and soil solution Al induced by an increase in pH, and a reduction in the proportion of soil solution Al present in monomeric form due to complexation by organic

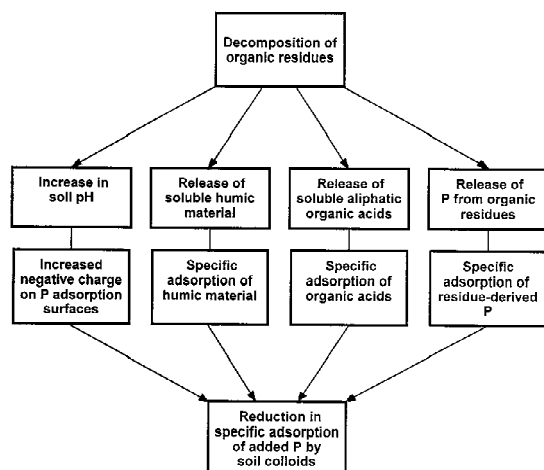


Figure 6. A conceptual model of the major processes that lead to a reduction in P adsorption and increased P availability when organic residues are applied to soils.

acids, are likely to be of great practical importance. They provide a window of opportunity for crop establishment and early growth in acid soils. In the longer term, regular applications of organic residues leads to an increase in soil organic matter content.

A model of the processes that can induce a reduction in P adsorption and increased P availability when organic residues are added to soils is shown in Figure 6. It is interesting to note that three of the pathways shown are closely related to those in Figure 5. That is, a rise in pH causes an increase in net negative charge on Fe and Al oxide surfaces, thus reducing P adsorption, whilst both soluble humic material and organic-acid anions can be adsorbed onto oxide surfaces, thus inhibiting subsequent P adsorption. The presence of P in organic residues is, however, an additional and apparently often dominant factor affecting P adsorption. Phosphate released from decomposing residues will be adsorbed onto oxide surfaces, thus increasing the proportion of adsorption sites occupied by P. As a result, less subsequently-added P is adsorbed and P availability is, therefore, increased. Nevertheless, the relative importance of factors shown in Figure 6 is still unknown and further research will be required to disentangle these effects.

A number of studies have investigated one or more of the mechanisms shown in Figures 5 and 6 and a few field experiments have demonstrated reduced Al phytotoxicity and/or increased P availability following applications of organic residues to soils. There is great scope for future research both in relation to the mechanisms that are involved and their relative importance

and also the practical significance of using organic residues in the management of acid soils. The latter consideration is of particular relevance in relation to the management of soil fertility by resource-poor, semi-subsistence farmers in South East Asia, central South America and Africa where acid soil infertility is often a major limitation to crop production. The regular use of organic residues such as animal manures, crop and grass residues and composts is a practical alternative for such farmers, whilst lime and fertilizer P are expensive commodities. Knowledge of the extent to which application of organic residues can reduce lime and fertilizer P requirements is needed so that integrated soil fertility management programmes can be devised. Such programmes would greatly benefit resource-poor farmers who are currently struggling to produce crops on acidic, P-deficient soils. The relative effects of various types of residues, the most appropriate timing of their application and methods of quantifying their potential benefits are all important practical considerations requiring further research.

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