Review Article

SUBSOIL ACIDITY AMELIORATION FOR IMPROVED SOIL PRODUCTIVITY

ABSTRACT

Subsoil is the layer (stratum) of earth immediately below the surface soil (below 20 cm), consisting predominantly of minerals and leached materials such as iron and aluminium compounds. A favourable condition of subsoil is important for improved productivity of deep-rooted crops like maize, sorghum, soybean etc. Any physical, chemical or biological characteristic of the soil located below the seedbed that limits the ability of crops or pasture to access water and nutrients is considered as a constraint to the subsoil. Subsoil acidity characterized by low Ca and high Al at depths below the plough layer, constrains crop productivity all over the world, especially in the highly weathered acid soils of the humid tropics. Yield reduction due to subsoil acidity results from high concentrations of soluble Al, Mn etc. or low plant-available calcium or magnesium in the root zone, inhibiting physiological and biological activities, root development and uptake of nutrients as well as water. Aluminium toxicity in the subsoil is the major growth limiting factor associated with subsoil acidity. Research findings suggest that conventional surface liming has very little effect on subsoil acidity. Therefore, successful amelioration of acidity in the subsoil requires specialised management practices involving application of soluble sources of calcium or magnesium or improving the solubility and downward movement of liming materials by the application of organic amendments like biochar. This paper attempts to analyse the impacts of subsoil acidity on soil productivity and its mitigation strategies.

Keywords: subsoil acidity, crop productivity, aluminium toxicity, biochar, amelioration of subsoil acidity

1. INTRODUCTION

Subsoil is the layer (stratum) of earth immediately below the surface soil (below 20 cm), consisting predominantly of minerals and leached materials such as iron and aluminium compounds. Subsoil contributions to plant nutrition range between 10 and 80 per cent and are expected to increase when topsoil is dry or nutrient depleted. Unsurprisingly, several studies have shown no yield increase after fertilization even in nutrient-poor soils, since nutrient availability is typically characterized for the topsoil and potential nutrient delivery from subsoil was not considered. Guaranteeing plant access to the subsoil nutrient and water reservoir greatly increases the resistance of the crop production system, making a greater pool of resources available and allowing the plant to avoid detrimental conditions in the topsoil [1]. A favourable subsoil is important for the production of deep rooted crops like maize, sorghum, soybean etc.

2. SUBSOIL CONSTRAINTS TO CROP PRODUCTION

Any physical, chemical or biological characteristic of the soil located below the seedbed that limits the ability of crops or pasture to access water and nutrients is considered as a constraint to the subsoil. Subsoil constraints can affect plant growth directly and indirectly. Direct chemical effects are attributed to subsoil acidity, sodicity and salinity, presence of phytotoxic concentrations of specific ions such as borate, Cl^-, Na^+, HCO_3^- or Al^{3+}, as well as reduced nutrient solubility induced by alkaline pH (>8.5) that causes nutrient deficiency in the plant, particularly for P, Zn, Cu and Mo. Direct physical effects arise from induced or inherent high soil strength that presents mechanical resistance to root penetration [2],[3]. Indirect effects refer to the secondary problems induced by the presence of subsoil constraints hindering plant growth. Among the various subsoil constraints, subsoil acidity is a major impediment to crop production especially in the humid tropics.

3. SUBSOIL ACIDITY

Subsoil acidity refers to acidification below the plough layer, in general below 20 cm. Surface soil acidity and its effect on crop production has been a research subject for several centuries. Recognition of subsoil acidity and its consequences, however, is quite recent [4],[5]. Subsoil acidity, as characterized by low Ca and high Al at depths below the plough layer, is restricting crop growth and production in many parts of the world, especially in the humid tropics where most soils are highly weathered[6],[7]. It is one among the many soil-related constraints in the hot, humid, tropical climatic regions.

3.1 Impacts of subsoil acidity

Subsoil acidity causes significant yield reduction in tropical acid soils because of high content of soluble Al and Mn or low plant-available calcium, inhibiting physiological and biological activities, root development and uptake of nutrients such as P, Ca, Mg, K and Mo as well as water [8]. It is the main chemical impediment for most deep-rooted and perennial crops which require uptake of nutrients and water from subsoil layers [9]. The major negative effects of subsoil acidity are aluminium iron and manganese toxicities, deficiencies of Ca, Mg, K, P etc and impeded microbial activity.

3.1.1 Aluminium toxicity

Toxic level of aluminium in the subsoil is a major factor impeding crop production in humid tropics. Aluminium ions regenerate soil acidity and maintain an acidic soil reaction. Toxicity of aluminium associated with subsoil acidity interferes with the availability, uptake, transport and utilization of essential nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), molybdenum (Mo) and boron (B) by the plant and inhibits physiological and biological activities of plants, root development and uptake of water [10],[11].

3.1.2 Manganese and iron toxicity

Manganese toxicity is associated with both pH and redox reactions of manganese oxides in soil. However, similar to Al, toxicity of manganese can be lowered by raising soil pH above 5.5 [12]. Iron becomes toxic on submergence of soil due to solubility of iron oxides. Soluble iron competes with other essential nutrient cations for crop uptake and induces their deficiencies [13].

3.1.3 Nutrient deficiencies

Inadequate levels of Ca, Mg, K, P etc impede crop growth in acid soils. The high rainfall and subsequent leaching loss of basic cations like Ca, Mg and K from the root zone in the humid tropics induce nutrient deficiencies in crops. Phosphorus deficiency, a major constraint to crop production after nitrogen deficiency occurs primarily due the specific adsorption of P by Al and Fe oxides in acid soils. Due to the high weathering and eluviation in Ultisols with lower clay, oxides and crystalline silicates, P is not a major limiting factor for crop productivity due to reduced adsorption [13].

3.1.4 Impeded microbial activity

Soil acidity also constrains beneficial microbial activity and impedes nutrient availability creating a stressed environment for plant growth. Aluminium (Al) toxicity and soil acidity suppress the activities of soil enzymes such as β-D-glucosidase, polyphenol oxidase, L-asparaginase, and acid phosphatase, which are crucial for microbe-mediated nutrient cycling processes [14]. When the pH of the soil falls below 6.0, soil microbial activity is negatively impacted, leading to reduced nitrogen fixation and slower mineralization of organic residues. This, in turn, causes a delay in the mineralization of nitrogen, sulphur, and phosphorus [15].

4. AMELIORATION OF SUBSOIL ACIDITY

Soil reaction determines nutrient availability to plants. Neutral to near neutral soil pH is optimum for the availability of adequate quantities of most nutrients. Therefore, soil acidity amelioration aims at raising pH to this optimum range through the application of inorganic and organic amendments.

4.1 Effects of inorganic liming materials on subsoil acidity

Surface application of lime is a common practice to combat soil acidity. But, this will have little effect on ameliorating subsoil acidity since the downward movement of lime is very slow due to low solubility of conventional lime, consumption of OH^- ions released from lime by exchangeable H^+ and Al^{3+}, reactions of OH^- ions with Fe and Al oxides abundant in highly weathered soils etc. On the other hand, deep incorporation of lime by physical means is costly and often undesirable due to exposure of the infertile subsoil. Thus specialized management strategies which include surface incorporation of gypsum, phosphogypsum or organic manures have to be adopted for managing subsoil acidity [16].

Phosphogypsum is the gypsum by-product of wet-acid production of phosphoric acid from rock phosphate. Surface-applied gypsum or phosphogypsum ameliorates subsoil Al toxicity, acidity and infertility in shorter time periods than surface-applied lime materials like burnt lime. The application of phosphosypsum has a significant influence on acidity components of soil except exchangeable H^+. Application of phosphogypsum at full lime requirement resulted in the lowest values for exchangeable acidity and Al and highest uptake of N, P, K, Ca and S in laterite soils of Kerala [17]. A soil incubation experiment using three Ca sources - $CaCO_3$, $Ca(OH)_2$ and phosphogypsum in laterite soils found that while lime is more effective in increasing pH, phosphogypsum is effective in reducing the exchangeable Al in soils [18].

Application of gypsum as an amendment alone or in combination with burnt lime and dolomite in acid soils reduces both surface and subsoil acidity and increases the available nutrient status of the surface as well as sub surface soil layers, resulting in better root proliferation and vigorous plant growth and development [19]. Simultaneously, the incorporation of ground limestone and gypsum to surface soil was identified as an appropriate strategy for amelioration of both surface and subsoil acidity [20]. While incorporating lime into the soil helps in decreasing soil acidity and increasing the availability of calcium and magnesium within the surface layer of Oxisols, the application of phosphogypsum increase the availability of sulphur and calcium in the deeper soil layers [21].

It is also desirable to use dolomitic limestone containing Ca and Mg for mitigating acidity, since heavy loading of Ca through lime and gypsum inputs is likely to deplete surface soil reserves of Mg and affect plant growth. Apart from lime, dolomite and gypsum, alkaline slag, fly ash, calcium silicates and magnesium sulphate have demonstrated the ability of successful mitigation of the ill effects of surface and subsoil acidity.

4.2 Effects of organic amendments on subsoil acidity

Organic amendments can be used to reduce subsoil acidity because the decarboxylation reactions that they promote have the potential to increase soil pH, decrease Al toxicity and improve the conditions for root growth [22]. The effectiveness of organic amendments to ameliorate soil acidity depends on their nutrient retention capacity and ability to minimise the toxicities of aluminium and other cationic micronutrients [23].

Mobile organic ligands produced by organic amendments can move to subsoil and produce alkalinity through ligand displacement of OH^- [24]. The alkalinity produced by organic amendments like biochar can allay aluminium toxicity by complexing Al ions and upgrade subsoil pH [25]. Among organic amendments biochar has been found to have greater potential in ameliorating subsoil acidity.

Biochar is a carbon-rich product produced by slow pyrolysis of organic matter. It contains alkaline substances and has high pH [26], [27], and thence can be used as an alternative amendment for the correction of soil acidity [28]. Biochar can also improve soil productivity by increasing soil pH, CEC and decreasing the availability of toxic metals in highly weathered acidic soils. It reduces soil exchangeable acidity by replacing the exchangeable Al^{3+} and H^+ on the soil exchange complex with basic cations [29]. In addition to its liming effect, biochars can prevent re-acidification of ameliorated acidic soils by improving soil pH buffering capacity [30].

Application of biochar can alleviate soil Al toxicity in multiple ways through adsorption and exchange reactions. The basic cations present in biochar replace monomeric Al in soil exchange sites and form neutral Al hydroxides [31]. Biochar adsorbs Al by complexation with the help of organic hydroxyl and carboxyl groups through esterification reactions. It also brings about surface adsorption and co-precipitation of Al with silicate particles forming compounds such as $KAlSi_3O_8$ [32]. The high alkalinity and good ash content of biochar produced from lignin-rich recalcitrant biomass residues of coconut palms viz. mature coconut husk, tender (immature or green) coconut husk, coconut leaf petiole and coir-pith alone or in combination with coconut leaf vermicompost can remediate the problems encountered in acid soils [33]. Similarly, wood biochar was found to have high potential to decrease soluble and exchangeable Al in soils indicating its higher ameliorating capacity [34]. Application of rice husk and coconut frond biochars exhibited an increasing trend in soil pH in laterite and sandy soils upto 180 days of incubation and a decline thereafter whereas pH declined after 90 days in control and FYM treated soils after an initial increase upto 90 days [35].

Co-composted biochar obtained by composting biochar - biowaste mixture was found to enhance surface reactivity, increase nutrient content, stimulate microbial colonization and degrade harmful substances in biochar [36]. Co-composting also developed an organic coating over biochar molecules thereby eliminating its hydrophobicity and improving the nutrient retention capacity [37]. A study on the effect of biochar, composts and co-composted biochar on soil pH found that biochar improved soil pH by 0.3 units accompanied by an increase in CEC. Compost and co-composted biochar also improved soil pH compared to the initial values [38].

Composts have been observed to lower surface and subsoil aluminium toxicity when applied along with lime. Combined application of composts with lime improved calcium in the subsoil compared to the application of composts or lime alone [39]. Chicken manure and sewage sludge has been reported to be effective in allaying aluminium saturation and improving soil solution pH below the 15 cm layer [40]. Poultry manure when applied to soils results in conversion of NH_4^+-N to NO_3^--N takes place within the surface soil and result in surface soil acidification. However, this conversion aids the leaching and subsequent accumulation of $Ca(NO_3)_2$ in the subsoil thereby raising subsoil pH [26].

A study evaluating the efficacy of thirteen organic amendments (manures, composts, biochars and plant residues) against four inorganic amendments (lime, dolomite, gypsum, and KH_2PO_4) in assuaging soil acidity and resultant crop growth in two soils *viz.,* Dermosol and Sodosol with different pH buffering capacity revealed that poultry manure, poultry litter biochar and biosolids displayed higher shoot response in wheat compared to lime. The application of organic amendments improved the soil pH measured with $CaCl_2$ by up to 0.32 and 0.62 units for the two soils studied, respectively [23].

4.3 Integration of inorganic and organic amendments for subsoil acidity amelioration

Combination of inorganic and organic amendments is a promising strategy to improve soil pH in acidic soils. Organic amendments enhance the efficacy of inorganic amendments through the improvement of soil physicochemical properties and nutrient availability and also aid the movement of inorganic ameliorants to deeper layers of soil ensuring amelioration of subsoil acidity.

The application of phosphogypsum-flyash combination blended at 20:1 ratio was found to increase yield and number of spikes as well as number of berries per spike in black pepper grown in acid lateritic soils. P, K and Ca contents of berries increased and iron and manganese toxicity was reduced by this phosphogypsum-flyash treatment. Mixing the blends with vermicompost was found to further enhance its superiority in ameliorating both surface and subsoil acidity. Phosphogypsum-flyash blend was found to lower exchangeable acidity and Al, alleviate iron and manganese toxicities and improve Zn uptake [41].

Combined application of organic amendments and lime showed greater pH increases than lime alone in the 10–12-cm and the 12–15-cm layers at three months in a soil incubation study. Soil monomeric Al (Al^{3+}) was also significantly reduced under organic amendments or lime alone, and in combination, in the 0–10-cm and 10–12-cm layers at 1 month of the experiment [42]. Surface application of chicken manure and sewage sludge in combination with lime and gypsum followed by periodic leaching with deionised water in 50 cm soil columns prepared using highly weathered Ultisol soil was found to increase pH and calcium and decrease in aluminium and aluminium saturation in the soil solution of the subsoil, particularly below 15 cm depth compared to the application of lime or gypsum alone [40].

Similarly, a laboratory incubation study to investigate the effect of combined application of alkaline slag and crop residues with different C/N ratios and ash alkalinity revealed that the addition of amendments could reduce soil exchangeable acidity and Al saturation and increase exchangeable base cations, but the effect of alkaline slag on soil pH adjustment was reduced when added along with a high amount of residue with a low C/N ratio [43].

Conclusion

Subsoil acidification is a major threat to the productivity of crops especially the deep rooted ones. Many researchers have reported that the currently prevalent practice of surface liming is not adequate for mitigating the negative impacts of subsoil acidity. An integrated approach involving inorganic and organic ameliorants can effectively minimise the ill effects of surface and subsoil acidity and enhance crop productivity.

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