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Acid Soil Formation: Causes, Constraints and Reclamation Strategies

Aditi Chourasia and Devendra Kumar Inwati

Department of Soil Science, College of Agriculture, RVSKVV, Gwalior

*Corresponding Author
Aditi Chourasia*

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INTRODUCTION

Soils form the foundation of agricultural productivity and environmental sustainability. Among the various soil constraints affecting crop production worldwide, soil acidity is one of the most serious problems, particularly in tropical and subtropical regions. Acid soils are generally defined as soils having a pH below 6.5, while strongly acidic soils possess a pH below 5.5. In India, acid soils occupy nearly 28% of total geographical area out of which 9.3% are strong to moderately acidic(pH<5.5), while 18.9% are slightly acidic (pH 5.5 to 6.5) , mainly distributed in the northeastern states, eastern India, hilly regions, and high rainfall areas. Acid soils significantly influence nutrient availability, microbial activity, root growth, and crop productivity. Deficiencies of essential nutrients such as phosphorus (P), calcium (Ca), magnesium (Mg), and molybdenum (Mo), along with toxicities of aluminium (Al), iron (Fe), and manganese (Mn), are common in acidic environments. Therefore, understanding the factors responsible for acid soil development and adopting suitable amelioration strategies are essential for sustainable agricultural production.

Characteristics of Acid Soils

Acid soils exhibit several physical, chemical, and biological characteristics:

- Soil pH is generally below 6.5
- High concentration of hydrogen (H^+) and aluminium ions (Al^{3+})
- Low base saturation
- Deficiency of secondary and micronutrients
- Reduced microbial activity
- Poor root development
- Increased phosphorus fixation
- Toxicity of aluminium and manganese

These conditions adversely affect plant growth and reduce crop yield potential.

Factors Responsible for the Development of Acid Soils

1. Precipitation and Leaching

Rainfall continuously adds acid to the soil through the following reaction

$$H_2O + CO_2 \leftrightharpoons H_2CO_3 \leftrightharpoons H^+ + HCO_3^-$$

The industrial emissions containing sulphur dioxide (SO_2) and nitrogen oxides (NO_x) react with atmospheric moisture to form sulfuric and nitric acids, contributing to soil acidification.

$$S0_2 + 1/2O_2 + H_2O \leftrightharpoons SO_4 + 2H^+$$

High rainfall is one of the primary causes of acid soil formation. In humid and sub-humid regions, excessive rainfall results in the transport of water below the root zone, carrying dissolved or soluble ions. As the most soluble ions like NO_3^-, Cl^- and HCO_3^- leach, to maintain the electrical neutrality, most soluble cations, which are Na^+, Ca^{2+}, Mg^{2+}, and K^+ also leaches down, leaving acidic ions, such as hydrogen and aluminium, behind. As these cations are basic cations, it leads to reduction of base saturation and pH which ultimately leads to soil acidification. Regions with annual rainfall above 1000 mm are highly susceptible to acidification.

The process can be represented as:

$$\boldsymbol{Ca^{2+} + 2H^+ \rightarrow 2H^+_{soil} + Ca^{2+}_{leached}}$$

2. Parent Material

The nature of the parent rock greatly influences soil acidity. Soils formed from acidic rocks such as granite, sandstone, and quartzite tend to become acidic because these rocks contain fewer basic minerals. In contrast, soils derived from limestone or basalt usually exhibit neutral to alkaline reactions due to higher calcium and magnesium content.

3. Organic Matter Decomposition

Decomposition of organic matter by the microorganisms and root respiration releases CO2 that quickly reacts with water to produce carbonic acid.

$$CO_2 + H_2O \rightarrow H_2CO_3$$

In addition to this microorganism also produce organic acids, which release H^+ ions into the soil environment.

4. Intensive Use of Acid-Forming Fertilisers / Oxidation of Nitrogen

Ammonium ions (NH_4^+) from organic matter or from continuous application of ammonium-based fertilisers, such as ammonium sulphate, urea, and ammonium chloride are subject to microbial oxidation that converts Nitrogen to Nitrate ions (NO_3^-). This nitrification process releases H^+ ions and increases soil acidity. Long-term indiscriminate fertiliser use without liming accelerates acidification.

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

5. Crop Removal of Basic Cations

Crop removal of substantial quantities of calcium, magnesium, and potassium from soils reduces base saturation and increases soil acidity. Continuous cropping without replenishment depletes these bases and gradually increases acidity.

Also, absorption of cations by plant roots results in the extrusion of H^+ ions or organic acids to maintain electrical neutrality, which results in lowering the pH of the soil.

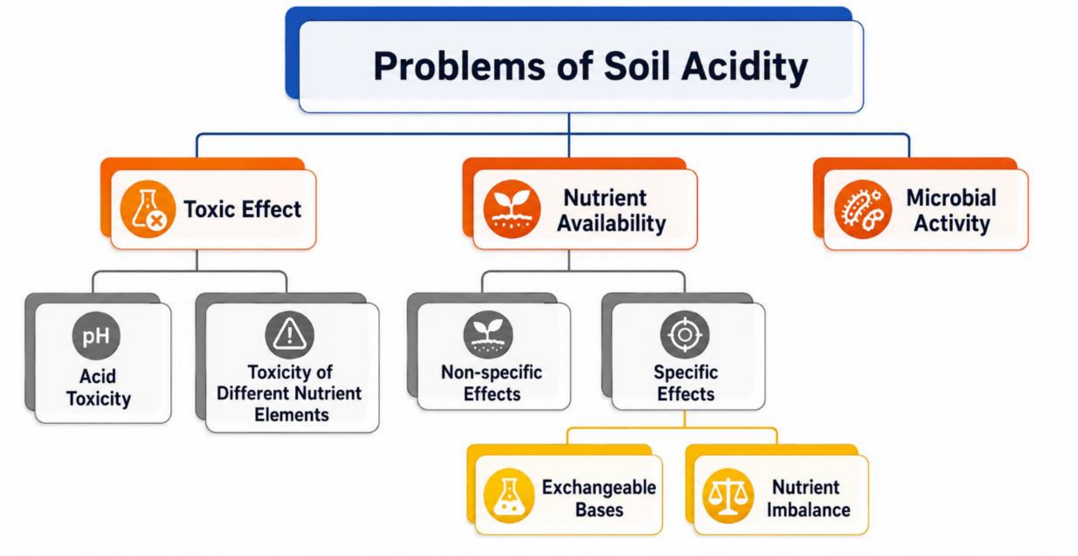
6. Weathering of Minerals

In tropical regions, intense weathering removes silica and bases from soils, leaving iron and aluminium oxides behind. Such highly weathered soils are naturally acidic. Examples include: Ultisols, Oxisols.

At low pH aluminium is present as hydrated Al^{3+} which undergoes hydrolysis and produces H^+ ion in soil solution. The process can be represented as:

$$Al^{3+} + H_2O \leftrightharpoons Al(OH)^{2+} + H^+$$
$$Al(OH)^{2+} + H_2O \leftrightharpoons Al(OH)_2{}^+ + H^+$$
$$Al(OH)_2{}^+ + H_2O \leftrightharpoons Al(OH)_3{}^0 + H^+$$
$$Al(OH)_3{}^0 + H_2O \leftrightharpoons Al(OH)_4{}^- + H^+$$

Problems Associated with Acid Soils



1. **Toxic Effects:**

a. Acid toxicity: Low solution pH, higher H^+ ion concentration results in the following toxicity symptoms

- Stunted top growth,
- Reduced lateral root growth
- Brownish discolouration of roots (very similar to Al^{+3} toxicity).
- Deteriorates root membrane structure and function, increasing root permeability and loss of organic substrates, and
- Reducing nutrient uptake
- Root growth decreases substantially

b. Fe^{2+}, Mn^{2+} and Al^{3+} toxicity: The concentration of $Fe^{2+}$and Mn^{2+} in soil solution depends upon the soil reaction, organic matter and intensity of soil reduction. Increase in organic matter results in the increased microbial population which increases the oxygen uptake. Due to the decreasing oxygen reduction of soil occurs. As a result $Fe^{2+}$and Mn^{2+} concentration increasese to very high leading to its toxicity.

$$MnO_2 + 4H^+ + 2e^- \leftrightharpoons Mn^{2+} + H_2O$$

A substantial increase in soluble Al^{3+} below pH 5 results in the following symptoms:

- Rapid inhibition of root growth
- Discoloured roots indicate the deterioration of cells in the root cap, root apex and vascular elements.
- Inhibition of root cell division resulting in a reduction and/or cessation in tap and lateral root growth, with subsequent inhibition of root elongation.
- Decreased root membrane permeability to water and nutrients, which reduces both root and top growth.

2. **Nutrient Availability:**

a. Non-specific effects: Inhibition of root growth affects the nutrient availability.

b. Specific effects:

Exchangeable Bases: The uptake and release of bases from the exchangeable form are adversely affected by acidity. High levels of soluble or exchangeable Al^{3+} result in potential Ca and Mg deficiency.

Nutrient Imbalances:

- Fe, Al and Mn present in higher concentration
- Phosphorus reacts with these ions and produces insoluble phosphatic compounds, rendering phosphorus unavailable to plants
- Fe, Mn, Cu and Zn are abundant
- Mo is very limited and unavailable to plants
- Availability of Boron decreases at very low pH due to adsorption on sesquioxides
- Nitrogen, Potassium and Sulphur are also less available at pH below 5.5

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3. Reduced Microbial Activity:

- Bacteria and actinomycetes function better in soils having moderate to high pH values. Beneficial microorganisms such as nitrifying bacteria and phosphate-solubilising microbes perform poorly under acidic conditions.
- Fungi grow well under very acidic conditions and cause diseases like root rot of tobacco, blights of potato etc.

Amelioration Strategies for Acid Soils

1. Liming

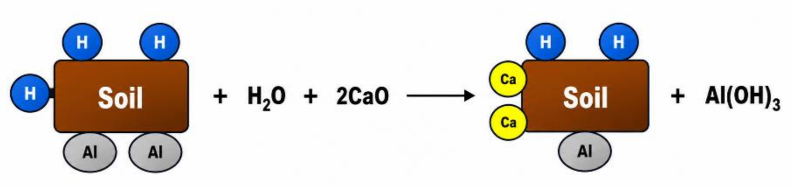
Liming is the most effective and widely adopted method for reclaiming acid soils. Liming materials neutralise soil acidity and improve nutrient availability. Common liming materials include Calcite ($CaCO_3$), Dolomite ($CaMg(CO_3)_2$), Quick lime (CaO) and Slaked lime ($Ca(OH)_2$).

a. Oxides of Lime:

- Normally known as burned lime or quick lime.
- Oxides of lime are more caustic than limestones and are produced as follows:

$$CaCO_3 + Heat \rightarrow CaO + CO_2$$
$$CaMg(CO_3)_2 + Heat \rightarrow CaO + MgO + 2CO_2$$

- Chemical reaction between oxides of lime and acid soil during amelioration is as follows:



b. Hydroxides of Lime:

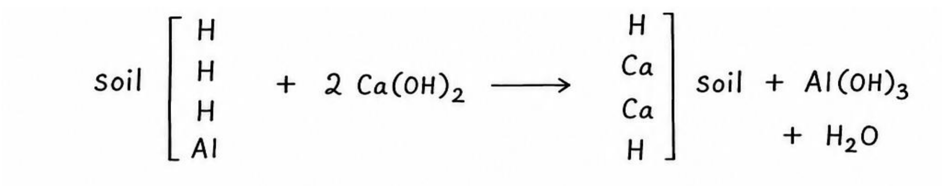
- Normally known as slaked lime
- Produced by adding water to burned lime.

$$CaO + H_2O \rightarrow Ca(OH)_2$$

- It is more caustic than burned lime. If it is kept open in moist air following reaction will take place:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$ and
$$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$$

- Chemical reaction between hydroxides of lime and acid soil during amelioration is as follows:



c. Carbonates of lime: Calcite and Dolomite are generally used.

d. Slags: Blast furnace slag, Basic slag and electric furnace slag generally behaves as calcium silicate are also used as liming materials.

e. Other Liming materials: Coral shell, chalk, wood ash, pressmud, by product material of paper mill, sugar factories, fly ashand sludge etc. can also be used as liming materials.

Benefits of Liming

- Increases soil pH
- Reduces aluminum toxicity
- Enhances microbial activity
- Improves nutrient availability
- Increases fertilizer use efficiency

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2. Application of Organic Matter

Organic amendments such as: Farmyard manure (FYM), Compost, Green manure, Crop residues, Vermicompost etc. help improve soil buffering capacity and microbial activity. Organic matter also complexes toxic aluminium ions and enhances nutrient availability.

3. Balanced Fertilizer Management

Balanced nutrient application helps maintain soil health. Excessive use of nitrogenous fertilizers should be avoided.

Recommended practices:

- Integrated Nutrient Management (INM)
- Split nitrogen application
- Use of nitrate-based fertilisers where appropriate

4. Use of Acid-Tolerant Crops and Varieties

Certain crops perform better in acidic conditions. Some acid tolerant crops are Tea, Potato, Pineapple, Rice, Oats.

The development and adoption of acid-tolerant cultivars help sustain productivity in affected regions.

5. Integrated Nutrient Management (INM)

This approach improves soil fertility and minimizes acidification.

INM combines:

- Chemical fertilizers
- Organic manures
- Biofertilizers
- Crop residue recycling

6. Biochar Application

Biochar acts as a soil conditioner and helps:

- Raise soil pH
- Improve cation exchange capacity
- Enhance moisture retention
- Reduce aluminum toxicity

6. Proper Water Management

Controlled irrigation and drainage management reduce nutrient leaching and maintain soil health.

7. Conservation Agriculture

Conservation agricultural practices help to conserve soil organic matter and reduce acidification. These practices include:

- Minimum tillage
- Mulching
- Cover cropping
- Crop rotation

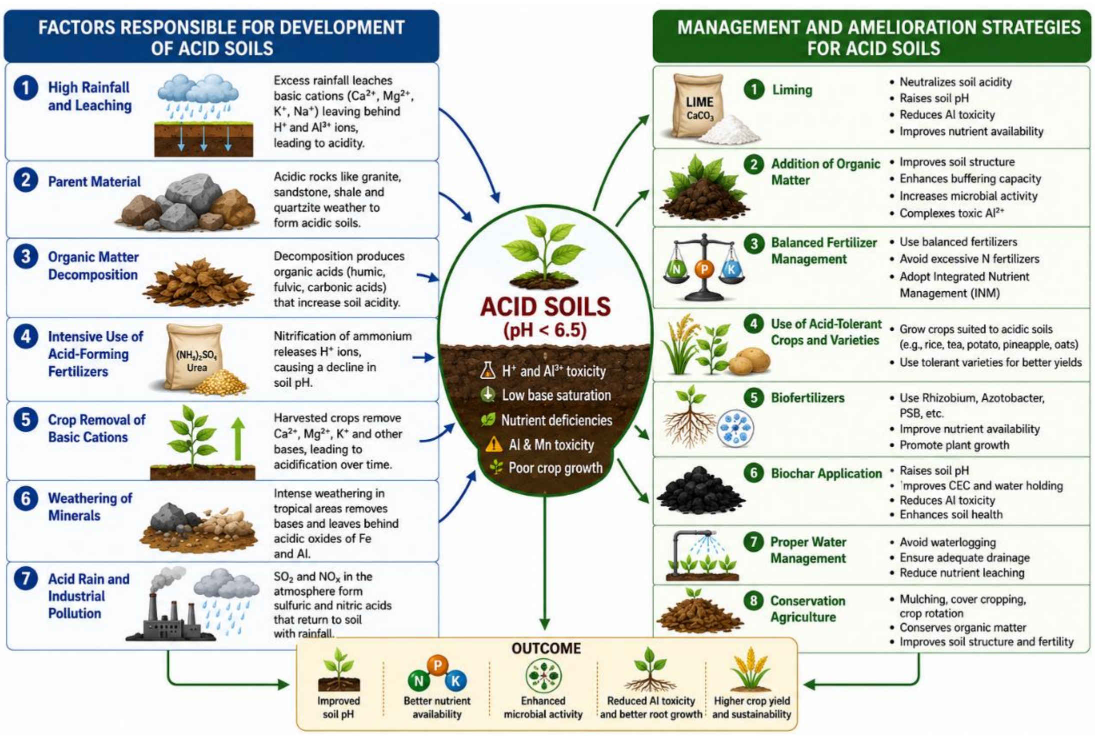

Figure: Development of acid soils and their management strategies

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CONCLUSION

Acid soils pose a serious challenge to sustainable agriculture due to nutrient deficiencies, aluminium toxicity, and poor biological activity. Their development is influenced by natural factors such as rainfall, parent material, and weathering, as well as anthropogenic activities like intensive fertilizer use and industrial pollution. Effective management of acid soils requires an integrated approach involving liming, organic matter addition, balanced fertilization, biofertilizer application, and adoption of acid-tolerant crops. Sustainable amelioration strategies not only improve crop productivity but also enhance soil health and environmental quality.

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