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6

Soil Acidification: Processes, Effects on Soil and Plants, and Remediation Strategies

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Apstract: *Soil acidification is an adverse reduction in soil pH and is among the most common soil degradation types. It is primarily caused by the decomposition of soil organic matter (SOM), weathering of minerals, acidic parent material, acid rain impacted by industrial emissions, improper agricultural activities (mono-cropping), and use of acidic fertilizers. Studies show that soil acidification extensively affects its fertility through reducing nutrient availability, disturbing soil structure, shift in microbial community structure, impaired nutrient cycling, increased metal solubility, and subsequent soil and water pollution. Soil acidification also affects crop productivity as low soil pH cause crop roots damage, thereby reduced nutrients absorption which leads to lesser crop yields. Such adverse soil implications due to soil acidification are selectively needed to remedial measures for the management of soil acidification by applying, e.g., liming, acid tolerant crops, addition of SOM, biochar, and ash, crop rotation, and genetic modification of crops to tolerate acidic conditions. In this chapter, authors have comprehensively summarized the causes and processes in the development of acidification in soils, its effect on soil health and crop plants along with the remedial measures.*

Keywords: Soil Acidification, Soil Degradation, Liming, Soil Organic Matter Loss, Nutrient's Availability

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6.1. Introduction

Globally, around 50% of the arable soils are acidic in nature (Wang et al. 2021), posing a notable concern in the soil productivity, mostly resulting from the decomposition of soil organic matter (SOM) (Mockeviciene et al. 2022). This process involves the breakdown of complex organic molecules into simpler compounds by soil micro-organisms, including bacteria, fungi, and actinomycetes. The presence of organic acids, such as acetic acid, citric acid, and oxalic acid, leads to soil acidity by increasing the concentration of hydrogen ions (H^+) in the soil solution (Grenni et al. 2012). The process of nitrification in nitrogen (N) cycle, also cause of soil acidification where it converts organic N molecules into ammonium (NH^{4+}) and nitrate (NO^{3-}), while simultaneously releasing H^+, exacerbating the soil acidification process. Carbon dioxide (CO_2) released into the soil atmosphere is also a contributing factor to soil acidification. Organic matter in the soil affects the soil redox potential, resulting in the formation of compounds with reduced oxidation states, such as methane (CH_4) and organic acids (Gerke 2022). Weathering encompasses the disintegration of rocks and minerals through physical, chemical, or biological mechanisms. During weathering, minerals are exposed to water and atmospheric gases e.g., CO_2, oxygen (O_2), and sulfur dioxide (SO_2) (Qiao et al. 2015). When soil solution comes in contact with CO_2, it forms carbonic acid (H_2CO_3) which is a dilute acid but produces bicarbonate ions (HCO_3^-) and free H^+, which decrease soil pH (Dietzen and Rosing 2023; Stojanović Bjelić et al. 2023a). Biological weathering produces organic acids through plant roots, fungi, and microbes, facilitating the breakdown of minerals and increasing H^+ concentration in soil solution (Altevogt and Jaffé 2005). Anthropogenic activities, such as the burning of fossil fuels, have exacerbated soil acidity by emitting sulfur (S) and nitrogen oxides (NOx) into the atmosphere, resulting in the occurrence of acid rain. Soil acidification is also influenced by the disintegration of acidic parent materials, such as granite, sandstone, shale, and basalt via weathering through hydrolysis, oxidation-reduction, and dissolution (Sun et al. 2023). Industrial emissions, including sulfur dioxide (SO_2) and NO_X, are a primary contributor to the process of soil acidification. Emissions of these gases occur as a result of operations such as the combustion of fossil fuels, the extraction of metal ores, and the production of chemicals (Syed et al. 2022). When the pH of soil decreases, the levels of harmful metals such as aluminum (Al) and manganese (Mn) is increased, leading to more soil acidification and pollution (Ilić et al. 2020, 2022; Stojanović Bjelić et al. 2022, 2023b, Mehmood et al. 2024; Malić et al. 2025; Mihajlović et al. 2025). Soil acidity is also caused through the use of N-based fertilizers, crop farming, organic amendments, and irrigation methods. N-based fertilizers, especially, those containing NH_4^+ by undergoing nitrification and mono-cropping of legumes may speed up the process of soil acidification (Zhang et al. 2022b). This occurs because when N-fixing plants are decomposed, they produce organic acids and remove important cations from the soil. During the decomposition process, organic amendments such as manure and composts may generate organic acids, which, in turn, contribute to a decrease in soil pH. Irrigation with higher HCO_3^- and other salts that displace calcium (Ca) and magnesium (Mg) ions, leading to an increase in H^+ concentration. Acid rain cause accelerated rates of SOM decomposition, leading to soil acidification (Gunasekera and Silva 2020; Farooqi et al. 2023; Pržulj and Tunguz 2022; Pržulj et al. 2022; Farooqi et al. 2024).

As soil acidification cause deleterious effects on soil productivity, crop yield and soil health via impacting microbial community structure, nutrient's cycling and their availability as well as soil structure (Shetty and Prakash 2020). So, the issue of soil acidification should be addressed via suitable measure. The notable measures include liming (lime, gypsum, calcium-based soil conditioners/ amendments), SOM-containing amendments, biochar, ash, and crop and soil management practices. This chapter addresses, firstly, the key issues of soil acidification by reviewing the causes and processes responsible for soil acidity development. Secondly, it discusses the key issues and challenges posed by soil acidity on soil health and plant productivity. Thirdly, it comprehensively discusses numerous remedial measures to combat soil acidification.

6.2. Sources of soil acidification

6.2.1. Natural sources

6.2.1.1. Organic matter decomposition

SOM decomposition results in the formation of simpler constituents from complex organic molecules through soil microbes i.e., bacteria, fungi, and actinomycetes. The formation of organic acids (acetic acid, citric acid, oxalic acid) is a key process by which SOM breakdown causes soil acidification (Prescott and Vesterdal 2021). These acids have the ability to decrease soil pH by directly raising H+ concentration, thereby considerably altering the soil chemical equilibrium. Moreover, during the process of SOM decomposition, organic N molecules undergo mineralization and are converted into NH_4^+ through the process known as ammonification. The NH_4^+ is then converted to NO_3^- by nitrifying bacteria, resulting in the emission of H+ (Anjum and Khan 2020). In addition, NO_3^- may form associations with alkaline cations including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), thereby extracting them from soils and further increasing the soil pH as soil buffering capacity is altered. Furthermore, SOM decomposition also results in CO_2 emissions, which form H2CO3 when dissolved in soil water and dissociates into H^+ and HCO_3^-. This process contributes to the accumulation of H+ in soil, resulting in decreased soil pH (Mohankumar 2018).

6.2.1.2. Weathering of minerals

The weathering of soil minerals is a fundamental process in earth's geochemical cycles and is responsible of contributing to soil acidification. When minerals react with water and CO_2, O_2, and SO_2, the dissolution of CO2 in water forms H2CO3, which comes into contact with mineral surfaces and yield HCO_3^- and H^+ ions which are key players in soil acidification (Dietzen and Rosing 2023) (equation 1).

$$2KAlSiO_3O_8 + 11H_2O + 2H^+ \xrightarrow{Hydrolysis} Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2K^+ \ldots (i)$$

It facilitates the breakdown of feldspar into clay minerals, dissolved silica, K^+, and HCO_3^-. The release of HCO_3^- and H^+ into soil solution lowers the soil pH, contributing to acidification. Another significant pathway for soil acidification through weathering involves the oxidation of sulfide minerals, such as pyrite (FeS_2). When pyrite is exposed to O_2 and water, it undergoes oxidation, producing sulfuric acid (H_2SO_4). The H_2SO_4 formed in this reaction dissociates into sulfate ions (SO_4^{2-}) and H+, significantly lowering the soil pH (Ji-zheng 2002), equation 2-3.

$$FeS_2 + 15/4O_2 + 7/2H_2O \xrightarrow{Oxidation} +Fe(OH)_3(s) + 2H_2SO_4 \ldots (ii)$$

$$H_2SO_4 \rightarrow 2H^+ + S0_4^{2-} \ldots (iii)$$

This process is particularly pronounced in mining areas where sulfide minerals are brought to the surface and exposed to atmospheric conditions. Biological weathering also contributes to soil acidification as plant roots, fungi, and microorganisms produce organic acids which enhance the minerals weathering and chelating metal cations and increasing the availability of H+ in the soil solution. For instance, the exudation of organic acids by plant roots can accelerate the dissolution of Al-bearing minerals, releasing Al^{3+} and H+ into the soil (Huang et al. 2023).

6.2.1.3. Acidic parent materials

Parent materials are the underlying geological formations that give rise to soil through weathering processes. When these materials are inherently acidic, they contribute to the development of acidic soils, which can significantly impact the agricultural soils. Several types of rocks and minerals can be classified as acidic parent materials. Granite, for example, is a common acidic parent material composed mainly of quartz, feldspar, and mica (equation 4-6).

The feldspar and mica in granite contain aluminum silicates (Al_2SiO_5), which release H^+ during weathering, contributing to soil acidity.

$$KAlSi_3O_8 + 4H_2O + 4H^+ \xrightarrow{Hydrolysis} K^+ + Al^{3+} + 3H_4SiO_4 \dots (iv)$$

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \dots (v)$$

$$KAl_2(Si_3AlO_{10})(OH)_2 + H^+ \rightarrow K^+ + 2Al^{3+} + SiO_2 + 2H_2O \dots (vi)$$

Sandstone, particularly when it lacks significant amounts of calcareous cement, can be another source of acidic parent materials (Datta and Adhikari 1973). The sand-sized particles predominantly consist of quartz, which is resistant to weathering but often associated with more acidic conditions.

Shale, formed from compacted clay sediments, often contains significant amounts of iron (Fe) and S, which can oxidize/hydrolyze to produce H_2SO_4 and lowers soil pH (He et al. 2022). Although generally more basic than granite, certain volcanic rocks like basalt can also contribute to soil acidity under specific conditions. The weathering of basalt releases Mg and Ca, but if these elements leach out quickly, the remaining soil can become acidic (Fujii et al. 2020).

The weathering of acidic parent materials involves both physical and chemical processes that release various ions into the soil. Key weathering processes include hydrolysis, oxidation-reduction, and dissolution. The hydrolysis of feldspar in granite can release H+, contributing to soil acidity.

Oxidation-reduction processes, such as the oxidation of S-bearing minerals in shale, produce H_2SO_4, increasing soil acidity (Tabak et al. 2020). Dissolution processes, where minerals dissolve in water, also release H^+ ions (equation 5). For instance, the dissolution of gypsum in the presence of CO_2 forms calcium bicarbonate and releases H+. Climate and vegetation significantly influence the extent to which acidic parent materials contribute to soil acidification.

In humid regions, higher precipitation rates can enhance the leaching of basic cations like Ca^{2+} and Mg^{2+}, leaving behind the acidic ions (Yang et al. 2021). Additionally, organic acids produced by decaying vegetation can further acidify the soil by accelerating the weathering of acidic parent materials (Ji-zheng 2002).

6.2.2. Anthropogenic sources

6.2.2.1. Industrial emissions

Sulfur dioxide (SO_2) and NOx which are released into the atmosphere through burning of fossil fuels, smelting of metal ores, and certain chemical manufacturing processes. When they undergo a series of chemical reactions e.g., SO_2 is oxidized to form sulfur trioxide (SO_3), which then reacts with water vapor to produce H_2SO_4 (equation 7), while NOx form nitric acid (HNO_3), (equation 8) (Liu et al. 2020b).

$$SO_2 + 1/2O_2 + H_2O \rightarrow H_2SO_4 \dots (vii)$$

$$2NO + O_2 + H_2O \rightarrow HNO_3 \dots (viii)$$

These acids are subsequently deposited onto the earth surface through wet deposition (rain, snow, fog) or dry deposition (gases and particles). Wet deposition, commonly known as acid rain, is a primary pathway through which industrial emissions contribute to soil acidification. Soils that are rich in calcium carbonate ($CaCO_3$) or other alkaline materials have a higher buffering capacity and can neutralize acids more effectively (Liu et al. 2020c). However, repeated and prolonged exposure to acid deposition can overwhelm the soil buffering capacity, leading to a gradual decline in pH (Raza et al. 2021).

6.2.2.2. Agricultural practices

Agricultural practices are a significant source of soil acidification, primarily through the application of N-based fertilizers, crop cultivation, excessive application of organic amendments, and irrigation practices. N-based fertilizers, particularly NH4+-based fertilizers contribute to soil acidification through nitrification process, where NH4+ is converted to NO3⁻, releasing H+ into the soil and increasing its acidity (equation 9) (Lin et al. 2021). The repeated cultivation of some crops, especially leguminous crops can accelerate acidification as the decomposition of N-fixing plants releases organic acids and removes essential cations (Ca, Mg, HCO3-) from the soil. Some pesticides and herbicides e.g., organophosphate-containing pesticides contribute to soil acidification through the release of acidic by-products and/or leaching (Qaswar et al. 2020; Trkulja et al. 2023).

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \dots (ix)$$

6.2.2.3. Use of acidic fertilizers

Acidic fertilizers, commonly used in agriculture to enhance crop yields, play a significant role in soil acidification. The primary mechanism through which acidic fertilizers contribute to soil acidification is through their chemical composition (Michael 2021). Acidic fertilizers typically contain ammonium (NH_4^+) or urea (NH_2CONH_2) as their main N source. When these fertilizers are applied to soil, they undergo chemical transformations that release H^+ into the soil solution, thereby decreasing soil pH (Zhang et al. 2022b).

$$NH_2CONH_2 + 2O_2 + 2H_2O \rightarrow 2NO_3^- + 2H^+ + H_2O \ldots (x)$$

NH_4^+-based fertilizers, such as ammonium nitrate (NH_4NO_3) and ammonium sulfate ($(NH_4)_2SO_4$), contribute to soil acidification through a process called nitrification i.e., conversion of NH_4^+ to NO_3^-. During this conversion, H^+ are released as byproducts, leading to increased soil acidity (Wang et al. 2020). Urea, another commonly used N fertilizer, also contributes to soil acidification, though through a slightly different mechanism. When urea is applied to the soil, it is first hydrolyzed by the enzyme urease into ammonium carbonate. This compound then decomposes into ammonium bicarbonate and CO2 (Yao et al. 2021). The ammonium carbonate dissociates into NH_4+ and $HCO3^-$. The NH_4^+ are eventually converted to NO_3^- through nitrification. In addition to NH_4^+ and urea-based fertilizers, superphosphate fertilizers also contribute to soil acidification, though to a lesser extent (Gao et al. 2021). Superphosphate fertilizers, which are derived from phosphate rock, contain H_2SO_4 as a byproduct. When superphosphate fertilizers are applied to soil, the sulfuric acid dissociates into H^+ and SO_4^-, which can contribute to soil acidification (Kubheka et al. 2020) (equation 10, Fig. 6.1).

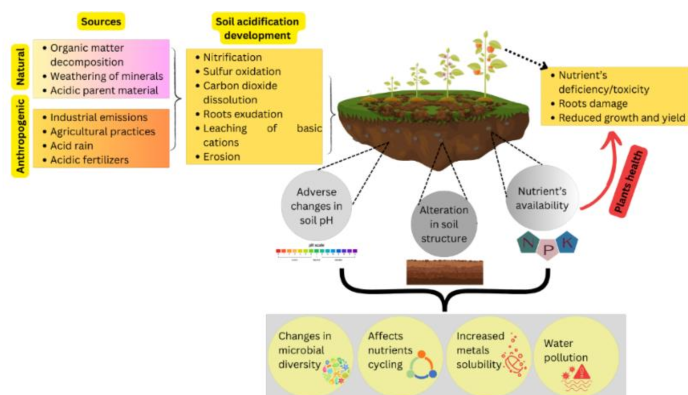

Fig. 6.1. Sources, processes, and effects of soil acidification on soil and plant health

Сл. 6.1. Извори, процеси и ефекти закисељавања земљишта на здравље земљишта и биљака

6.3. Processes in the development of soil acidification

6.3.1. Chemical processes

6.3.1.1. Nitrification

Nitrification is a metabolic process in the N cycle that entails the transformation of NH_3 into NO_3^- through Nitrosomonas and Nitrobacter. NH3-oxidation during nitrification results in the production of NO_3^- and H^+, which immediately leads to a decrease in soil pH (equation 9) (Li et al. 2024). Subsequently, the oxidation of nitrite (NO2⁻) to NO_3^- increase the mobility and subsequent leaching of NO_3^- which have high solubility and leached out of the rhizosphere in regions with abundant precipitation or irrigation. This process results in the transportation of Ca^{2+}, Mg^{2+}, and K^+ which intensifies soil acidification. In addition, NO_3^- have the ability to undergo microbial denitrification in the absence of O_2, resulting in the formation of HNO_3, which dissociates into H^+ and NO_3^- ions, contributing to soil acidification (Zhang et al. 2022a).

6.3.1.2. Sulfur oxidation

The process of S oxidation is of utmost importance in the acidity of soil, exerting a substantial influence on the chemistry of soil and the overall health of ecosystems. The process starts with the existence of S in several forms, including elemental S, sulfides (e.g., pyrite, FeS_2), and organic S compounds. When S-containing chemicals come into contact with air and moisture, some microbes, particularly autotrophic bacteria such as Thiobacillus oxidize them and H_2SO_4 is produced (equation 7). This acid is potent and substantially impacts reducing the pH of the soil. S-oxidation is most widespread in soils abundant in pyrite, which is often found in coal mining regions and naturally sulfide-rich environments. When mining operations or erosion occurs, the pyrite becomes exposed to O_2 and water, resulting in the formation of H_2SO^4 (Ji-zheng 2002).

6.3.1.3. Carbon dioxide dissolution

The dissolution of CO_2 from the atmosphere or soil respiration combines with soil water, it produces H2CO3, which produces HCO3⁻ and H+ (equation 11).

$$CO_2 + 2H_2O \rightarrow H^+ + HCO_3^- \dots (xi)$$

The main sources of CO_2 in soil are microbial respiration, root respiration, and the breakdown of SOM. However, human actions such as burning of fossil fuels and deforestation also contribute to increased levels of atmospheric CO_2, hence increasing soil acidification process (Raza et al. 2021). The elevated concentration of H^+ in soil displace Ca_2^+, Mg_2^+, K^+, and Na^+, from the soil colloids. The cations that have been displaced are removed from the soil by water that percolates through it, resulting in a decrease in nutrients and a decline in soil fertility (Raza et al. 2021).

6.3.2. Biological processes

6.3.2.1. Root exudation

Root exudation release organic acids, H+, and other compounds. These exudates are released in response to nutrient deficiencies, particularly P, making nutrients more available by solubilizing bound forms in the soil. As the organic acids dissociate, they release protons, increasing the H^+ concentration in the soil solution. This release of protons is further augmented by the plant's uptake of cations (e.g., Ca_2^+, Mg_2^+, K^+, and NH_4^+), which must be balanced by an equivalent release of H+ to maintain electrochemical neutrality within the plant. The acidification process is also influenced by root respiration, which produces CO_2. When CO_2 dissolves in water, it forms H_2CO_3. Root exudates not only lower pH directly but also indirectly by stimulating microbial activity as microorganisms decompose SOM, releasing additional organic acids and CO_2, thus exacerbating the acidification process (Wang et al. 2023b). The increased microbial activity also enhances nitrification, the oxidation of NH_4^+ to NO_3^-, which produces H+ ions as a byproduct, further contributing to soil acidification. Additionally, root exudates can chelate metal ions, such as Al, making them more soluble and toxic to plants and soil organisms, which can disrupt nutrient uptake and overall soil health (Cheng et al. 2010; Farooqi et al. 2022).

6.3.3. Physical processes

6.3.3.1. Leaching of basic cations

The leaching of basic cations (Ca, Mg, K, Na) results in reduction of soil pH. Leaching process transport the dissolved basic cations to downward soil, especially regions with high levels of rains, snowfall, or irrigation (Jia et al. 2021). Agricultural activities may worsen the process of cation leaching. N-fertilizers, especially NH_4^+-based fertilizers may cause soil acidity by promoting nitrification. Nitrification is a microbiological process that transforms NH4+ into NO_3^-, while simultaneously releasing H^+ (Yuan et al. 2021).

6.3.3.2. Erosion

The selective loss of soil particles is one of the main ways erosion causes soil acidity. Topsoil, which has a higher concentration of organic matter and vital nutrients, is more prone to erosion. The top fertile soil layer often includes elevated levels of alkaline cations such as Ca, Mg, K, and Na (Horn et al. 2021). Erosion leads to the removal of these cations, exposing underlying soil layers with elevated levels of acidic cations, including Al and H^+ (Babur et al. 2021). As a result, the buffering capacity of the soil is decreased, resulting in an overall rise in soil acidity. Water erosion further intensifies the process of leaking essential ions as water flows through the eroded soil. The depletion of essential nutrients disturbs the equilibrium of the soil, increasing its vulnerability to acidity. Leaching is more pronounced in areas with abundant rainfall or irrigation, where water infiltration occurs often (Jeon and Nam 2019). The soil, which has been worn away, is now deficient in vital nutrients, making it more susceptible to acidification since it is unable to adequately neutralize the presence of acidic substances. In addition, erosion-induced gathering of SOM in downstream or lower elevations in agriculture landscapes cause its decomposition and contribution to soil acidification.

6.4. Effects of soil acidification on soil ecosystem characteristics

6.4.1. Soil properties

6.4.1.1. Changes in soil pH and structure alteration

Soil acidification due to reduced soil pH cause a range of shifts in physical, chemical, and biological properties. As soil acidification intensifies, it leads to a reduction in soil pH, resulting in increased soil acidity. The change in pH has significant consequences for soil health and its capacity to support plant growth, development, yield, and ecosystem processes (Goulding 2016). Ca and Mg, which are essential for the growth of plant cell walls and enzymatic processes, are more susceptible to leaching under acidic circumstances, resulting in nutritional deficits. On the other hand, some elements have a higher solubility and may become more poisonous as the pH of the soil lowers e.g., Al, Mn, and Fe (Sharpley 1991). Al is liberated from soil minerals and enter the soil solution in acidic soils, causing root damage. This toxicity hinders root development and impairs root function. Mn become too concentrated in acidic soils, leading to harmful impacts on plant physiology and chlorosis, diminished root formation, and stunted plant growth. The pH of soil also has an impact on the activity and diversity of microorganisms, which play a crucial role in maintaining the health and fertility of the soil (Rahman et al. 2018). The pH range of 5.5 – 6.5 is considered optimum for microbes in soil. Acidic circumstances have a detrimental impact on microbial population and diversity, such as bacteria, fungus, and actinomycetes. These microbes are essential for breaking down organic debris, recycling nutrients, and shaping the structure of soil. The presence of very acidic soils greatly diminishes the activity of helpful microorganisms such as nitrifying bacteria, which play a crucial role in converting NH4+ into $NO3^-$ (Ning et al. 2021). This decrease hinders the N cycle, resulting in reduced N availability for plants and worsening nutritional imbalances. pH alterations also impact the biological interactions e.g., symbiotic relationships such as mycorrhizal fungi and plant roots. Mycorrhizal fungi augment the absorption of nutrients by plants, especially P, by expanding the surface area of the roots. The efficacy of these fungi is lowered in acidic soils, hence lowering their symbiotic advantages to plants. In very acidic soils, the activity of earthworms and other soil fauna, which play a crucial role in breaking down SOM and improving soil aeration, is also reduced or diminished, affecting soil health and fertility (Zhang et al. 2022a). Furthermore, the decrease in soil pH affects aggregates formation, affecting soil structure through losing of organo-mineral formation (Gilbert et al. 2007), as well as deposition of soil humic acids at acidic pH 6 (Yang et al. 2024), which is crucial for ensuring optimal soil aeration, water infiltration, and root penetration. Acidic soils exhibit diminished soil structure as a result of heightened solubility and leaching of Ca, which serves as a cohesive agent for soil particles. Ca depletion may cause soil particles to disperse, leading to the formation of compacted and poorly organized soils that are susceptible to erosion and have diminished water retention ability (Horn and Peth 2009).

6.4.1.2. Nutrient availability

The process of soil acidification can restrict or improve the accessibility of essential micro- and macro-nutrients. The macronutrients that mostly influenced by soil pH include N, P, K, Ca, Mg, and S. N, mostly present as NH_4^+ and NO_3^-, becomes less accessible in acidic soils. Under acidic conditions, the transformation of NH_4^+ into NH_3 is promoted, leading to its potential loss into the environment. In acidic soils, the activity of nitrifying bacteria, which convert NH_4^+ to NO_3^- is decreased, resulting in a decrease in its availability (Olego et al. 2022). P availability in acidic soils has a tendency to combine with Al and Fe to create compounds that are not soluble, therefore reducing its availability to plants. Plant roots absorb nutrients in pH range 4.5 – 6.5 but do not easily absorb these chemicals below this range, resulting in P deficiency. Moreover, acidic nature of the soil solution of acidic soils enhance the ability of Al and Fe to dissolve, thereby worsening the problem by further combining with P (Ofoe et al. 2023). Under acidic circumstances, K is leached from the soil exchange complex due to displacement by H^+. The process of leaching diminishes the K concentration in the soil, which, in turn, has a negative impact on plant nutrition and development. H+ and Al ions displace Ca and Mg from soil particles, resulting in leaching and decreased availability. This reduction may lead to their deficiencies, since plants have difficulties in assimilating enough amounts of Ca and Mg for their growth (Han et al. 2018). Sulfur, often found as sulfate (SO_4^{2-}), may not be directly affected by acidification to a great extent. However, the general soil health and crucial microbial activities involved in S-cycling might be adversely impacted, indirectly affecting its availability. Micronutrients, which are needed in lower amounts, also show different reactions to soil acidification. Fe, Mn, Cu, Zn, and boron (B) exhibit increased solubility and accessibility in acidic soils due to instability of organo-mineral complexes under acidic conditions (Gilbert et al. 2007; Zhang et al. 2022a). Nevertheless, the heightened accessibility of these substances may lead to toxic concentrations, causing damage to plants and microbes. The solubility of Fe and Mn is greatly enhanced in acidic soils, resulting in potential poisoning symptoms in plants, including chlorosis and necrosis (Karna et al. 2018). Cu and Zn become more accessible, but excessive amounts can be poisonous and hinder the development and function of plant roots. Boron, although necessary in modest quantities, may become excessive and hazardous in very acidic environments (Cai et al. 2021). On the other hand, several micronutrients have reduced availability as soils grow more acidic. Molybdenum (Mo), which is necessary for N fixation and enzyme activity, becomes less soluble and accessible in acidic soils, possibly resulting in shortages. The decreased accessibility might hinder the process of N fixation in legumes and impact the overall nutritional status of plants (Rahman et al. 2018).

6.4.2. Plant health

6.4.2.1. Nutrient deficiency/toxicity

Soil acidification greatly impedes plant development and yield, since the presence of vital nutrients becomes limited under acidic environments. A direct consequence of soil acidity on plants is the reduced accessibility of macro-nutrients such as N, P, and K. The lower nutrient's availability occurs due to the tendency of P to create insoluble compounds with Al and Fe (Warke and Wakgari 2024). Consequently, the availability of P for plant absorption decreases, resulting in inhibited growth, under-developed roots, and decreased agricultural productivity. Similarly, Ca, Mg, and K are also easily washed away under soil acidity via high solubility of soil fulvic acids and protein-like substances (Yang et al. 2024) which occurs due to instability of organo-minerals under acidic conditions (Gilbert et al. 2007), leading to a decrease in their concentration in the soil. Insufficient Ca may cause blossom-end rot in tomatoes and tip burn in lettuce, whereas inadequate Mg generally leads to interveinal chlorosis, characterized by yellowing of the spaces between leaf veins while the veins themselves stay green (Hodges and Steinegger 1991).

6.4.2.2. Root damage

Acidic soils put harmful effects to plant roots. As the pH of acidic soils decreases below 5.5, the concentration of Al increases, exerting severe toxicity towards plant roots, impeding their elongation and inflicting harm onto the root tips (Ahmad et al. 2019). Similarly, Mn poisoning disrupt many physiological processes in plant roots, such as enzyme activity and metabolic functions. An excess amount of Mn result in oxidative stress, which can harm root cell membranes and contribute to the development of lesions (Zhou et al. 2022). These lesions weaken the root's structural integrity and hinder their capacity to efficiently absorb water and nutrients. Soil acidity also impacts the accessibility of vital nutrients, resulting in shortages that harm plant roots (Wang et al. 2023a).

6.4.2.3. Reduced crop growth and yield

As soil acidity negatively affects nutrient accessibility and roots growth, it results in decreased plant strength and poor agricultural output. Plants in acidic soils have reduced uptake of N, P, and K, while enhanced ability of Al and Mn to dissolve and higher mobility (Olego et al. 2022). Elevated levels of Al also have detrimental effects on plant roots, impeding their development and impairing their function as Al toxicity hinders the process of root cell division and elongation, resulting in the growth of under-developed root systems. This compromised roots growth has reduced efficiency in the absorption of water and nutrients, leading to a direct impact on the plant's general development and health. Mn poisoning may also arise in acidic soils, resulting in chlorosis and necrosis in plant tissues, hence reducing plant vigor and yield (Ofoe et al. 2023). Moreover, soil acidification has an impact on microbial activity and soil biodiversity, both of which play a critical role in preserving soil fertility and structure. Beneficial microorganisms, such as N-fixing bacteria and mycorrhizal fungi, flourish in environments that are neither too acidic nor too alkaline. When the pH of the soil decreases, the activity and number of these microorganisms decrease, which, in turn, reduces their capacity to promote plant development (Choma et al. 2020).

6.4.3. Microbial communities

6.4.3.1. Changes in microbial diversity

Microbial diversity is greatly impacted by soil acidification as they can survive in a narrow range of acidic pH (5.5 – 6.5), apart from microbes having adapt to acidic conditions. Soil acidification primarily reduces the population and diversity of microorganisms, resulting in a decrease in microbial diversity. Various soil microorganisms, such as bacteria, fungi, and archaea, exhibit optimal pH ranges for their growth and development (Song et al. 2023). Acidification may cause the soil pH to exceed the optimum ranges, resulting in a decrease in their populations that are sensitive to acidity. Acidophilic bacteria, namely Actinobacteria and Proteobacteria, tend to decline in population with increasing soil acidity. On the other hand, microorganisms that are able to tolerate or thrive in acidic conditions, such as Acidobacteria and fungus, may become more prevalent (Choma et al. 2020). This change in community structure lead to a decrease in the total microbial diversity, as a smaller variety of species becomes dominant in the environment. Reduced microbial diversity may negatively impact essential soil functioning as microorganisms responsible for SOM may be shifted from acidic soil. For example, several N-fixing bacteria are susceptible to lower pH levels. As the population of these bacteria declines, the amount of N in the soil also drops, which has a negative impact on both plant development and soil fertility. Likewise, the breakdown of organic matter decelerates, resulting in the buildup of unprocessed organic remains and a reduction in the accessibility of nutrients. Soil acidification has an impact on microbial interactions and the dynamics of the community. Within a robust soil ecosystem, microorganisms engage in intricate interactions, establishing networks of mutualistic, antagonistic, and competitive partnerships (Gowda et al. 2017). Acidification may disturb these interactions, specifically restraining some bacteria groups. For example, mycorrhizal fungi, which establish mutually beneficial associations with plant roots and improve nutrient absorption, are often adversely impacted by acidic environments. The decrease in these fungi may diminish the efficiency of nutrient interchange between plants and soil, hence exacerbating the health of plants and the structure of soil. In addition, soil acidity may modify the generation and functioning of microbial enzymes, leading to a decrease in the efficiency of certain activities (Hu et al. 2022). For instance, the functioning of enzymes responsible for P mineralization, such as phosphatases, might decrease in acidic soils, resulting in a decrease in the amount of P that is accessible to plants. Higher Al mobility may hinder the establishment of helpful bacteria and fungi, worsening the decrease in microbial diversity and disturbing soil processes (Kamran et al. 2018).

6.4.3.2. Impact on decomposition and nutrient cycling

Decomposition and nutrient cycling processes are facilitated by a diverse variety of microorganisms, such as bacteria, fungi, and actinomycetes. These organisms have a high level of sensitivity to changes in soil pH and are often hindered in their activity and variety by acidic environments (Xiao et al. 2020). For example, bacterial populations, which flourish in circumstances that are neither acidic nor alkaline, see a substantial decline when the soil gets more acidic (Sánchez-Galindo et al. 2022). The decrease in bacterial activity hinders the breakdown process, resulting in the buildup of organic materials in the soil, particularly occurrence of deposition of soil humic acids at acidic pH 6 (Yang et al. 2021). In contrast, fungi exhibit greater tolerance towards acidic environments and often assume the role of primary decomposers in soils that have been acidified. Although fungi are capable of ongoing decomposition of organic materials, their metabolic pathways vary from those of bacteria. Fungal decomposition exhibits a longer and less effective process in breaking down intricate organic molecules, including lignin, which is a significant component of plant cell walls (Khomutovska et al. 2024). Consequently, the pace at which organic matter breaks down diminishes, leading to the accumulation of partly digested organic wastes. The gradual accumulation of soil humic acids may result in the formation of organic acids (Yang et al. 2021; Pržulj et al. 2024), specifically the remaining soil fulvic acids and protein-like substances (Gao et al. 2018; Mohinuzzaman et al. 2020), as well as their high solubility under acidic conditions (Tadini et al. 2018), which in turn acidify the soil matrix. The modified decomposition dynamics in acidified soils have a direct impact on nutrient cycling, which is the process of releasing, transforming, and making nutrients accessible for plant uptake. Soil acidification has a significant impact on the availability of N, which is a crucial nutrient for plant development (Soong et al. 2020). Microbial activities, such as ammonification and nitrification, facilitate the transformation of organic N into inorganic forms, namely NH4+ and NO3‾. Under acidic circumstances, the activity of nitrifying bacteria is suppressed, leading to a decrease in the conversion of NH4+ to NO3‾. This inhibition results in the buildup of NH4+, which may be harmful to plants when present at high levels and can also be released as NH3 volatilization, particularly in soils with inadequate buffering capacity. Soil acidification has an impact on the availability of P in the nutrient cycle (Mpanga et al. 2019). P in acidic soils has a tendency to combine with Al and Fe to create insoluble compounds, hence reducing its accessibility to plants. The decreased accessibility may restrict the development of plants and impact the overall efficiency of the ecosystem. In addition, the immobilization of P may disturb the equilibrium of nutrient ratios in the soil, so complicating nutrient management even more. Soil acidification also impacts the process of micronutrient cycling, including elements like Fe, Mn, Zn, and Cu, which may affect due to instability of organo-mineral complexes (Gilbert et al. 2007). While many micronutrients exhibit increased solubility and accessibility in acidic conditions, which may result in toxicities, others have reduced availability, leading to shortages (Antoniadis et al. 2015). Fe and Mn toxicity may manifest in very acidic soils, leading to hindered root development and functionality. On the other hand, when there is a decrease in the amount of Zn and Cu available, it may result in deficiencies that have a negative impact on plant metabolism and development. In addition, soil acidity may impact the physical characteristics of soil, including its structure and porosity, which subsequently affect the processes of decomposition and nutrient cycling (Faria et al. 2021). Soils that have been acidified often exhibit deteriorated structure and less aggregate stability, resulting in lower levels of aeration and water penetration. These physical alterations provide an inhospitable setting for soil microbes and roots, hence impeding breakdown and the absorption of nutrients (Pierzynski and Hettiarachchi 2018).

6.4.4. Soil and water quality

As soil acidification has a substantial effect on the solubility of metals and soil humic substances, therefore it leads to soil and water pollution (Ilić et al. 2021a, 2021b, 2021c, 2021d, 2023, 2024a, 2024b). With the decrease in soil pH, the characteristics of metals in the soil change, resulting in higher solubility and movement of potentially toxic metal ions. This phenomena have significant ramifications for the soil health, and productivity of agriculture (Boechat et al. 2016). As soil pH decreases, the concentration of H^{+} rises, leading to their interactions with metal ions present in the soil. Under acidic circumstances, organo-mineral complexes, for instance, metal oxide and hydroxides, e.g. Al, Fe, and Mn (Hemingway et al. 2019; Kirsten et al. 2021; Zhang et al. 2024a) which undergo dissolution (Malik et al. 2018), transforming into more soluble compounds. The enhanced solubility of these metals in the soil solution results in their higher concentration, which makes them more easily accessible for absorption by plants (Faria et al. 2021). For example, Al is liberated from mineral complexes and rendered soluble in acidified soils. Acidic soils also cause increased solubility of many other metals e.g., lead (Pb), cadmium (Cd), and copper (Cu) and transported to edible plant parts or drinking water and pose hazard to human and plant life (Kleber et al. 2021; Porębska and Mulder 1996).

6.5. Remedial measures for soil acidification

6.5.1. Addition of organic matter

Soil organic matter is generally known as an effective solution for soil acidity. It is essential for developing soil structure, increasing nutrient availability, and boosting the ability of soil to resist acidification through soil buffering capacity. An important advantage of incorporating SOM is its capacity to enhance soil pH via several ways e.g., soil humic substances, composing of humic acids, fulvic acids and protein-like substances found in decaying plant matter and compost may initially decrease the pH of the soil (Mohinuzzaman et al. 2020; Tadini et al. 2018). However, as decomposition continues, these acids are broken down, resulting in the creation of more stable molecules that assist in regulating the soil pH (Hayashi et al. 2023). In addition, SOM includes organic bases that have the ability to counteract H+ in the soil, hence raising the soil pH and decreasing acidity. Incorporating SOM in the form of manure and composts improves the ability of the soil to resist changes in pH i.e., soil pH buffering capacity. Organic matter, particularly soil humic acids, stimulates the soil aggregates formation in degraded soil structures due to acidity as these aggregates improve the permeability and water retention of the soil as well as decreasing soil erosion (Hussain et al. 2021). Enhanced soil structure also helps in the prevention of the leaching of Ca and Mg, which are crucial for counteracting soil acidity. Moreover, addition SOM ensures a safe habitat of microorganisms, hence stimulating their development and productivity. Microbial communities that are actively engaged in metabolic processes play a crucial role in decomposing organic waste and transforming it into humic substances. These stable organic compounds have the ability to improve soil fertility and regulate pH levels (Hussain et al. 2021).

6.5.1.1. Crop rotation

Crop rotation entails the practice of rotating several crops in the same field throughout the different growing seasons, instead of mono-cropping. Farmers may mitigate the impacts of soil acidity by diversifying their crops, since this might have an effect on different soil qualities and processes. Crop rotation effectively mitigates soil acidification by altering the soil pH through various crops (Zhang et al. 2024b). As various crops have diverse impacts on soil pH owing to their root systems, N absorption behavior, and breakdown of crop residues (Bossolani et al. 2021). For example, legumes such as clover or beans with cereals or cover crops are very advantageous because this rotation can convert atmospheric N into the soil, resulting in enhanced soil fertility and a balanced acid-base equilibrium. In addition, the decomposed remains of legumes may improve the ability of soil to resist changes in pH, helping to neutralize acidic situations. The root systems of various crops also contribute to the overall soil health i.e., perennial plants with extensive root systems facilitate the movement of essential nutrients and organic substances from lower layers of soil, which may have an impact on the acidity level of the soil (Bangash et al. 2023). Crops with extensive root systems or tubers e.g., maize and potato have the ability to obtain nutrients and minerals that are less readily available to plants with shallow root systems. When these nutrients are transported to the upper layers of soil by extensive root systems, they have the ability to interact with the top soil, which may influence its acidity. Additionally, crop rotation aids in the management of SOM. Various crops provide different kinds and quantities of organic wastes to the soil, their breakdown impacts the pH level of the soil. For example, the residues of some crops may break down into compounds that assist in neutralizing the acidity of the soil (Dane et al. 2017). Various crop's organic matter may have specific impacts on the pH of the soil, and the diversity brought via rotation can help create a more harmonious soil ecosystem. Crop rotation has an impact on soil microbial populations, in addition to the contributions of organic matter. Various crops harbor distinct microorganisms, and these microbial communities are essential for soil functions such as organic matter breakdown and N cycling (Breza et al. 2023). Crop rotation promotes a wide range of microbial species, which in turn improves soil quality and influences soil acidity levels. Specific crops may have microbial mechanisms that might help neutralize acidic environments (Guerra et al. 2022). Crop rotation may mitigate soil erosion, so indirectly addressing soil acidity. Through the practice of crop rotation, farmers may enhance soil composition and mitigate erosion rates. Erosion often results in the depletion of topsoil, which contains abundant nutrients and organic matter that aid in maintaining soil pH stability (Shehrawat et al. 2023).

6.5.1.2. Liming

As soil acidity is due to higher H+ ions, it can be countered by basic ions (OH^-). Liming is treatment is a proven method used to address soil acidification, hence promoting plant development and enhancing agricultural production. Lime is mostly comprised of calcium carbonate ($CaCO_3$), calcium hydroxide ($Ca(OH)_2$), gypsum ($CaSO_4 \cdot 2H_2O$), and calcium oxide (CaO) (Nogaroli and Fonseca 2020). When lime is added to acidic soils, it chemically reacts with soil acids, causing the H^+ to be neutralized and resulting in the production of water and CO_2. This technique efficiently elevates the pH of the soil, mitigating the detrimental consequences of soil acidity. Lime treatment enhances soil structure via the promotion of aggregation and the reduction of soil erosion. Acidic soils often exhibit inadequate structure, resulting in problems such as compaction and diminished water infiltration (Bolan et al. 2023). Liming enhances soil aggregation through neutralizing acidity, leading to improved soil aeration, root penetration, and moisture retention. Soil that is well-organized promotes plant development and decreases the likelihood of erosion, so enhancing soil health (Bolan et al. 2023). The use of lime also affects the availability of nutrients in the soil. Soils with high acidity often have reduced levels of vital elements such P, K, Ca, and Mg. Lime treatment enhances the availability of essential nutrients by modifying the soil pH and improving the solubility of certain minerals (Gurmessa 2021). P availability to plant roots is enhanced by increasing soil pH and enhances nutrients availability, hence optimizing plant development and increasing agricultural yields. Liming not only neutralizes soil acidity, but it also provides secondary advantages for soil health and fertility i.e., the use of lime may augment the activity of soil microbes, which are crucial in facilitating nutrient cycling and the breakdown of organic wastes (Bakari et al. 2020; Nešković Markić et al. 2021, 2024; Ilić et al. 2024).

6.5.1.3. Improved fertilization practices

Enhanced fertilization techniques are essential for reducing soil acidity and revitalizing soil health. Efficient fertilization methods strive to mitigate these impacts by preserving or re-instating soil pH to the ideal values for promoting plant development. Balanced fertilization techniques through precision agriculture practices entails the use of fertilizers that provide vital nutrients in appropriate amounts and right time to prevent over application (Zhang et al. 2024a). Fertilizers, i.e., manures or chemical fertilizers enhance the ratios and arrangement of soil particles and augment its ability to resist changes in pH, hence aiding in the maintenance of pH levels. Conversely, inorganic fertilizers are designed to provide precise nutrients like as N, P, and K (Zhang et al. 2024b). These fertilizers may be customized to match the specific nutrient requirements and pH levels of the soil, hence minimizing the chances of acidification. Slow-release fertilizers are another option for this purpose as they release the N at slower pace and at the time when it is required (Hussain et al. 2021).

6.5.1.4. Use of acid-tolerant crops

Utilizing acid-tolerant crops such as soybean, oat, millet, and alfalfa etc. provides another strategic method for effectively regulating soil acidification and tackling the difficulties presented by the growing acidity of soils (Agegnehu et al. 2021). These specialty varieties are specifically developed or chosen for their capacity to flourish in settings when the soil pH is lower than the usual optimal level for most crops. Their use is a pragmatic solution to soil acidity, a factor that might otherwise impede agricultural output. The creation and acceptance of acid-tolerant crop varieties are based on both conventional breeding methods and contemporary genetic engineering (Shetty et al. 2021).

6.5.1.5. Biochar

Biochar is produced through pyrolysis of biomaterials and recognized as a potentially effective solution for combating soil acidity. The use of it in soil management arises from its distinct characteristics and the many advantages it provides for soil health and fertility. Biochar is characterized by its significant surface area and porous structure, which provide an ample home for microbial organisms and enhance the soil capacity to hold nutrients and water (Xia et al. 2020). Biochar effectively counteracts soil acidification by modifying soil pH as biochar synthesis process yields a material that is often alkaline, particularly when generated from substances such as wood. Biochar, when used on acidic soils, may raise the soil pH, reducing the level of soil acidification. The rise in pH is a result of the alkaline properties of biochar, which counteracts the surplus of H^+ in the soil, so decreasing its acidity (Liu et al. 2020a). In addition, biochar enhances the cation exchange capacity (CEC) of the soil, enabling it to effectively retain and exchange important cations including Ca, Mg, and K. Acidic soils often have poor CEC, resulting in a diminished capacity to retain essential nutrients. Biochar improves it by offering more locations for the exchange of positively charged ions, thanks to its porous structure and surface charge characteristics (Geng et al. 2022). The elevated CEC not only aids in balancing soil acidity but also enhances the accessibility of vital nutrients for plant absorption. The capacity of biochar to enhance soil structure is an additional noteworthy aspect of its function as a restorative treatment. The incorporation of this substance into the soil enhances soil aggregation and porosity. Enhanced soil structure improves the process of aeration and water infiltration, hence decreasing the likelihood of erosion and runoff (KedirJemal 2021). Biochar indirectly enhances the soil ability to resist acidification by fostering improved soil structure, which creates a stable environment that is favorable for plant development and microbial activity. Another benefit is the enduring stability of biochar in the soil over an extended period of time (Bolan et al. 2023). Unlike other organic additions, biochar exhibits exceptional resistance to degradation as a result of its inherently stable carbon structure. Once biochar is applied, it stays in the soil for long periods of time, resulting in long-lasting benefits. The extended lifespan of this solution contributes to the maintenance of an alkaline pH and the enhancement of soil health, making it a resilient method for regulating soil acidification (Huang et al. 2023). Moreover, biochar has the ability to impact soil microbial populations as its porous structure serves as a home for advantageous microorganisms, which contribute to the process of nutrient cycling and the overall soil health. These bacteria facilitate the breakdown of organic materials, hence influencing soil acidity levels. Biochar may augment microbial activity, so bolstering the general well-being and resilience of the soil ecosystem. When combined with other soil management strategies, biochar may provide significant benefits in agricultural settings. The use of this may enhance the effects of lime or other soil amendments by offering further advantages including enhanced nutrient retention and better soil structure (Shiyal et al. 2022).

6.5.1.6. Microbial inoculants

Microbial inoculants e.g., rhizobium, azospirillum, Pseudomonas spp., and mycorrhizal fungi are becoming more widely acknowledged as a feasible method for reducing soil acidity, due to their ability to improve soil health and promote sustainable agriculture practices (O'Callaghan et al. 2022b). Inoculants are composed of helpful microorganisms, including bacteria, fungus, and actinomycetes, which are added to the soil to enhance different biological processes. They have the capacity to play a substantial part in tackling the difficulties presented by soil acidification via their influence on soil pH, nutrient accessibility, and dynamics of microbial communities (Lopes et al. 2021). Microbial inoculants play a crucial role in remedying soil acidification by improving the soil's inherent ability to resist changes in pH. Specific bacteria, especially those with the ability to generate organic acids, may assist in counteracting acidic environments. For example, several bacteria and fungi generate alkaline compounds like NH3 or $CO3^{-}$ that neutralize soil acidity (O'Callaghan et al. 2022b). The activity of these microorganisms contributes to the equilibrium of soil pH, resulting in a reduction of acidity and an enhancement of conditions for plant development. Microbial inoculants help enhance the process of making vital nutrients more soluble in acidic soils. Under acidic circumstances, nutrients like P and Ca tend to precipitate, making them unavailable to plants. Phosphate-solubilizing bacteria and mycorrhizal fungi have the ability to convert these nutrients into forms that plants can easily take up (Daraz et al. 2021). Microbial inoculants indirectly alleviate the negative impacts of soil acidity by enhancing nutrient availability, enabling plants to more effectively get the necessary minerals for their growth and development. Microbial inoculants have the ability to improve soil structure and aggregation, in addition to their function in nutrient solubilization. Some specific types of fungus and bacteria secrete extracellular polysaccharides that bind soil particles, resulting in the formation of solid aggregates (Chen et al. 2021). Enhanced soil structure promotes water penetration and decreases erosion, hence contributing to the maintenance of a more stable pH environment. The enhanced stability of soil aggregates also decreases the likelihood of nutrient leakage, which may otherwise worsen soil acidity. Moreover, microbial inoculants have the ability to impact the dynamics of the microbial population in the soil (Wahid et al. 2020). The acidity of soil may modify the makeup and functioning of soil microbial communities, often promoting acid-tolerant microbes while inhibiting beneficial ones. Through the introduction of targeted microbial inoculants, it is feasible to reinstate a more harmonized and efficient microbial community (O'Callaghan et al. 2022a). This equilibrium may enhance soil vitality and resistance, therefore facilitating mechanisms that counteract soil acidification. Microbial inoculants also facilitate the biological processes associated with the breakdown of organic materials. Highly proficient decomposer microorganisms have the ability to successfully break down organic wastes, resulting in the release of nutrients and buffering agents that may counterbalance soil acidity. The accelerated breakdown of organic matter leads to the creation of humic compounds, which possess buffering qualities and may also counteract soil acidity. Microbial inoculants may also be used into several soil management strategies in agricultural systems to combat soil acidity (Ewubare et al. 2023).

6.5.1.7. Genetic modification of crops

Genetic engineering offers a novel method for tackling soil acidity by improving crop resilience. Genetic modification mostly tackles soil acidification by creating crops that have improved ability to withstand low pH conditions (Kumar et al. 2020). Conventional breeding techniques often encounter constraints when it comes to generating crops that possess the ability to endure harsh soil conditions. These approaches enable the incorporation of certain genes, e.g., ALMT (aluminum-activated malate transporter) and STOP1 (sensitive to proton rhizotoxicity1) genes that are known to provide acid tolerance (Abdul Aziz et al. 2022). Genes responsible for encoding proteins involved in pH control or stress response may be introduced into the genomes of crops, as an example. These alterations may enhance a crop’s tolerance in acidic soils, hence mitigating the adverse effects of soil acidification on production and quality (Rafeeq et al. 2023).

6.5.1.8. Controlled environment agriculture (CEA)

Controlled environment agriculture (CEA) is an advanced agricultural method that effectively deals with soil acidity by maintaining strict regulations in contained systems such as greenhouses. CEA mitigates soil acidification by effectively manipulating environmental parameters such as light, temperature, humidity, and fertilizers delivery. An important advantage of CEA is its capacity to mitigate soil erosion, which is a significant contributor to soil acidity (R'him et al. 2022). By cultivating crops in enclosed or semi-enclosed systems, the risk of soil erosion caused by wind and water is significantly reduced. Vertical farms and greenhouses use buildings to shield the soil and plants from external climatic conditions which guarantees the minimized erosion and its consequential impact on soil acidity. Under regulated settings, water and nutrient solutions are administered with accuracy and effectiveness, hence minimizing the risk of nutritional depletion (Xu et al. 2020). By balancing micro- and macro-nutrients, the risk of soil acidification is minimized, as these nutrients are not bound or washed away (Fan et al. 2020). The use of soil-less growth medium in various CEA methods also reduces the hazards linked to soil acidification. These systems depend on nutritional solutions that are directly supplied to plant roots, bypassing the need for conventional soil (Kalkhajeh et al. 2021). CEA systems completely exclude the possibility of soil-based acidification processes by not using soil. Finally, a summary of different methods used to prevent/combat soil acidification are enlisted in the Figure 6.2.

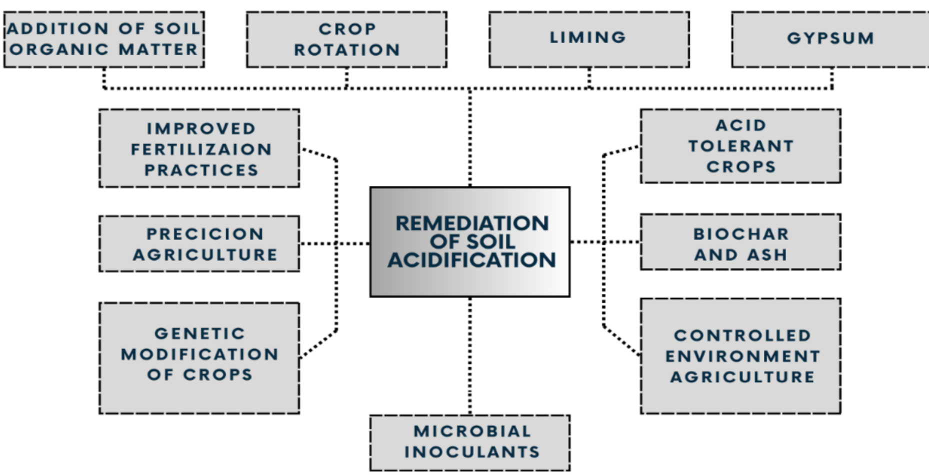

Fig. 6.2. Methods of combating/prevention of soil acidification
Сл. 6.2. Методе сузбијања/превенције закисељавања земљишта

6.6. Conclusion and future research directions

Soil acidification plays a crucial role in agriculture settings, reducing the capacity of soils to neutralize acids and raises its overall acidity. Erosion also speeds up this process through the breakdown of soil organic matter, producing organic acids that further intensifying the acidity of soils. This, in turn, poses challenges for land management and agricultural activities, reducing food crop's yield. Use of recommended methods such as liming, biochar, addition of organic matter, and genetic modifications in crop plants has been effectively applied in combating soil acidification. Controlled environment agriculture also a viable strategy for reducing adverse effects of soil acidity. But due to the lack of evidences on the effectiveness of the existing technologies, future research direction should focus to screen out and prioritize the optimization of different technologies to produce food crops from acidic soils. Furthermore, it is imperative to do research on the enduring impacts of different technologies on getting higher yields with good soil health, as well as its capacity to be expanded for wider agricultural uses.

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Закисељавање земљишта: процеси, ефекти на земљиште и биљке и стратегије ремедијације

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Сажетак

Закисељавање земљишта представља неповољно смањење pH вриједности земљишта и спада међу најчешће типове деградације земљишта. Примарно је узроковано разградњом органске материје у земљишту (ОМЗ), временским утицајима на минерале, киселим матичним материјалом, киселим кишама под утицајем индустријских емисија, неправилним пољопривредним активностима (монокултурама) и употребом киселих ђубрива. Истраживања показују да закисељавање земљишта значајно утиче на његову плодност смањењем доступности хранљивих материја, нарушавањем структуре земљишта, промјеном микробиолошке заједнице, нарушеним циклусом хранљивих материја, повећаном растворљивошћу метала и посљедичним загађењем земљишта и воде. Закисељавање земљишта такође утиче на продуктивност усјева, јер ниска pH вриједност оштећује коријенове усјева, смањујући апсорпцију хранљивих материја, што доводи до мањих приноса. Овакве неповољне посљедице за земљиште усљед закисељавања захтијевају селективне мјере санације, као што су кречење, узгој кисело-отпорних усјева, додавање органске материје, биоугља и пепела, ротација усјева и генетска модификација усјева за толеранцију на киселе услове. У овом поглављу аутори су свеобухватно сажели узроке и процесе развоја закисељавања у земљиштима, његов утицај на здравље земљишта и усјеве, као и мјере санације.

Кључне ријечи: закисељавање земљишта, деградација земљишта, кречење, губитак органске материје земљишта, доступност хранљивих материја