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Soil Acidity Challenges to Crop Production in Ethiopian Highlands and Management Strategic Options for Mitigating Soil Acidity for Enhancing Crop Productivity

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Abstract: Soil degradation is the primary restriction affecting many developing countries' agricultural systems. Ethiopia is a developing country in horn Africa that is severely challenged by soil degradation issues. The main processes of soil deterioration are acidification and salinization. Furthermore, soil acidity is one of the primary reasons obstructing and preventing lucrative and sustainable agricultural productivity in many African countries as well as many other regions of the world. Soil acidity problems have hampered sustainable agricultural productivity in practically all productive areas in Ethiopia. The main goal of the seminar is to highlight the problems of soil acidity to agricultural production in Ethiopia's highlands, as well as management strategies for alleviating soil acidity and increasing crop output. Soil acidity affects over half of Ethiopia's arable land. Strong acid soils cover more than half of the arable land affected by soil acidity. Researchers discovered two primary reasons that limit acidic soil fertility: the presence of phytotoxicity substances and nutrient shortage. Numerous strategic soil acid management plans have been created to address these issues in the country's highlands.. Several studies have been undertaken on soil management, which influences the physiochemical qualities of the soil and crop productivity in various ways. Thus, the primary goal of this seminar is to emphasize various literatures on the ideas of soil acidity, its causes and extents in highland areas of the country, as well as its impacts on soil and crop productivity through strategic management strategies. Many findings suggested that liming and ISFM improved soil physiochemical parameters such as soil texture, pH, accessible P, exchangeable acidity, organic carbon, exchangeable cation, cation exchange capacity, and crop yield and productivity.

Keywords: Highland, Liming, Physiochemical Properties, Soil Acidity

1. Introduction

Crop management's key soil concerns include deterioration of soil physical qualities, nutritional inadequacies, loss of soil organic carbon, anthropogenic soil erosion and degradation, and a lack of incentives and regulations to adopt improved and ecologically friendly technologies. Because of the enormous range of topography, climate, soil types, and associated vegetation and farming systems, practically all soil-related problems are occurring at an alarming rate throughout Ethiopia's highlands, with noticeable differences in magnitude. The most significant soil chemical degradation is fertility decrease, which manifests itself as excessive nutrient exhaustion, followed by salinization and acidity. This element of soil chemical deterioration is the most important concern in the majority of Ethiopia's farmed soils, negatively impacting crop yields and agricultural output. As a result of this degradation, the national average yield of cereal crops is less than 1 t/ha, even in the country's prolific highlands. This is exacerbated by intense land use and a high population density [43].

Nitrogen and phosphorus are the key nutrients that decrease and so severely limit soil productivity. The somewhat weathered soils are more limited by a lack of phosphorus, whilst the black and poorly drained soils are more limited by nitrogen. Nationwide cereal fertilizer trials have revealed that more than half of the soils are very responsive to nitrogen addition, 25% to phosphorus, and only a handful to potassium. Furthermore, the nutritional level of most soils is declining. Phosphorus deficiency affects between 70% and 75% of Ethiopia's agricultural soils in the highland plateau region. Soil acidity deterioration is mostly an inherent problem produced by the weathering stage of the soil, as opposed to problems induced by humans. However, subsoil acidity caused by erosion of surface soils is most common in warm, humid places where soils are disturbed by humans. According to Ethiopian soil surveys, the soils in extensive regions of western and southwestern Ethiopia are acidic, with pH values below 5.5 [44, 25].

The amount of acid soils is estimated to be 30% of the total land area, with severely acidic soils (with a pH of 5.5) accounting for 13% of the total land area. According to a recent study on the two key plant development limiting elements, nitrogen and phosphorus, acid soils dominate most of the southern and southwestern areas of Ethiopia and have low P content in general. Soils in the south and southwest have high N and low P concentrations, including Sidamo, Illubabor, and Keffa. It is a major issue that requires immediate treatment across much of Ethiopia's highlands because to its influence on crop output and productivity. The chemical and biological qualities of most acidic soils are poor. Its acidity is linked to Al, H, Fe, and Mn toxicity in soil solutions, as well as corresponding deficits in accessible P, Mo, Ca, Mg, and K. Soils in the humid tropics naturally become acidic owing to the leaching of basic cations under excessive rainfall. Al is easily soluble in water at pH below 5, and it becomes the dominating ion in the soil solution. In Ethiopia, soil acidity is increasing in extent and scale, significantly restricting agricultural output. Farmers in the central and southern Ethiopian highlands, for example, have switched from growing barley, wheat, and faba beans to cultivating oats, which is more tolerant to soil acidity than wheat and barley [33, 39].

To recover soil acidity and improve the productivity of extremely acidic soils, several methods have been suggested. Acid-tolerant plants should be grown, organic fertilizers should be used, and liming should be done. The adoption of acid-tolerant plants, liming, and the use of organic fertilizers are thought to be the most effective methods since their benefits last longer. However, the high cost of fertilizers and lime, as well as unsustainable crop production, necessitates the use of locally accessible low-cost organic sources such as manures, green manures, and mineral fertilizers in a balanced mix for long-term productivity and soil quality. Farming in Ethiopia's highlands is characterized by low agricultural production in comparison to industrialized nations due to gradual soil fertility reduction over time and insufficient use of amendments. Acidification occurs in Ethiopia along with other circumstances such as degraded topsoil and reduced organic matter, depleted nutrients, and alternating drought stress and heavy rainfall. Excessive rainfall combined with adverse temperature and precipitation in high rainfall locations is sufficient to drain significant amounts of exchangeable basic cations. Because of the impacts of parent materials, land shape, vegetation, and climatic pattern, its severity varies greatly. Acidification can also be produced in moisture-stressed areas by the continual use of acid-forming chemical fertilizers [23]. Taking into account all of the causes and consequences, Ethiopian land, particularly highland soil, requires strategic approaches to minimize all of the adverse effects of acidic soils. Using aforementioned gap the objective of this paper is to review of soil acidity challenge to crop production in Ethiopian highlands and strategic options for mitigating soil acidity for enhancing crop productivity.

2. Methodology of Review

To ensure the success of this work, many sources such as journals, conferences, thesis works, and reports on the causes, extent, and impact of acid soil in Ethiopia, as well as its influence on crop production and management techniques, were used.

3. Causes of Soil Acidity

Soil acidification is a complicated series of processes that results in the development of acidic soil. In the widest sense, it refers to the total of natural and human activities that reduce the pH of soil solution. It has been shown that numerous factors contribute to soil acidification, including (i) climate, (ii) acidic parent material, (iii) ammonium fertilizer application, (iv) organic matter decomposition, and (v) element removal during crop harvesting.

It has been well documented that a significant supply of bases is generally found in dry area soils since little water flows through the soil. As rainfall increases, the quantity of soluble salts decreases and any calcium carbonate and gypsum present is eliminated. With additional increases in rainfall, the rate of removal of bases surpasses the rate of their release from nonexchangeable forms. Acidic soils are more likely in wet climates. Excessive rainfall leaches the basic elements (Ca, Mg, Na, and K) in the soil profile over time that preventing soil acidification. High rainfall washes away soluble nutrients like Ca and Mg, which are specifically replenished by Al at the exchange sites [22, 47, 18].

Acid rocks, such as granite and rhyolite, have an overabundance of quartz or silica in comparison to their concentration of basic minerals or basic elements. When base-deficient rocks are fragmented or decomposed during the process of soil accumulation, the resulting soil material is acidic, despite no loss of base during the process of soil formation. Soils formed from worn granite are more acidic than those formed from shale or limestone. There are vast regions of siliceous and sandy soils formed from acid parent rocks that have always required lime. Most acid soils, on the other hand, have evolved as a result of leaching losses and crop removal of bases [18].

The intrinsic fertility of Ethiopian soils formed under various parent materials and climates varies according to the origin and content of the ingredients. Soils formed from sandstones, for example, are poor sandy soils, but the intrinsic soil fertility formed from fundamental parent materials is rather high. Alluvium becomes rich and fruitful in alluvium plains if it comes from relatively fresh materials, and less fertile if it comes from heavily worn surfaces. The bulk of soils have pH values ranging from 4.5 to 6.5. Soils at high altitude parts of the country are often acidic in response, deficient in exchangeable cations, and base saturation [14, 43].

In the end, continuous use of inorganic fertilizer without soil testing might raise soil acidity. The usage of ammonia-based nitrogen fertilizers contributes to acidification. Acidity is formed when ammonium fertilizers are put to the soil, yet the type of N extracted by the crop is comparable to that found in fertilizer. Hydrogen is supplied to fertilizers in the form of ammonia (NH_4), urea (CO $(NH_2)_2$, and proteins (amino acid) in organic fertilizers. The conversion of such N fertilizers into nitrate (NO_3) releases hydrogen ions (H^+), resulting in soil acidity. In actuality, N fertilizer raises soil acidity by raising crop yields, which increases the quantity of basic elements taken from the soil. As a result, applying NH_4 fertilizers or adding substantial amounts of organic matter to a soil will ultimately increase soil acidity and reduce pH [28].

Organic matter breakdown generates H^+ ions, which are responsible for acidity. In the near term, the growth of soil acidity due to organic matter decomposition is negligible. Soil acidity is caused by large amounts of carbonic acid generated by microbes and higher plants, as well as other physicochemical and biological processes; however the effect of its dissociation is relatively minor because most of it is lost to the atmosphere as CO_2. Organic matter in soil, known as humus, includes reactive carboxylic and phenolic groups that function as weak acids. They emit H^+ ions upon dissociation. In addition, the production of CO_2 and organic acids during decomposition results in the replacement of bases on exchange complexes with H^+ ions [46].

Soil acidity is caused by the removal of elements, particularly from soils with a small reservoir of bases, as a result of the harvest of high-yielding crops. When soils are mechanically worked and crops are produced, the equilibrium is upset and the soils become more acidic. This is due to the removal of base cations by crops, as well as the increase in leaching that occurs when soils are disturbed and worked. The harvest of high-yielding crops has the greatest impact on increasing soil acidity. Crops absorb fundamental minerals such as Ca, Mg, and K throughout growth to meet their nutritional needs. More of these lime-like minerals are taken from the field as crop yields grow. In comparison to the plant's leaf and stem, grain contains just trace levels of these essential elements. As a result, collecting high-yielding forages like Bermuda grass and alfalfa has a greater impact on soil acidity than harvesting grain. Most soil physical, chemical, and biological characteristics are often modified as a result of changes in land use and management techniques, and this is reflected in agricultural production [31, 18, 28].

Previous research has shown that the conversion of native forest and range area to farmed land degrades soil characteristics. Such activities result in an increase in bulk density, a decrease in soil organic matter (SOM) content, and a decrease in CEC, all of which impair the fertility status of a particular soil type. Furthermore, changes in land use such as deforestation, continuous agriculture, overgrazing, and mineral fertilizer can produce major changes in soil characteristics and production reductions [17].

Sand and silt reduced as soil depth rose, while clay increased. Soil pH, total N, organic carbon, available P, exchangeable cations, exchangeable Al, effective cation exchange capacity, and Al saturation all vary considerably among land use regimes. Al saturation increased with soil depth, and top soils had acidity issues while sub soils had Al toxicity. Similarly, Chimdi et al. [23] found that a decrease in total porosity in grazing and cultivated land soils compared to forest land soils was due to a drop in pore size distribution and the amount of SOM loss, which is dependent on the intensity of soil management techniques. Bore and Bedadi [17] also found that the quantity of SOM in grazing and cultivated areas has been reduced by 42.6 and 76.5 percent, respectively, when compared to forest soil.

Contact exchange between exchangeable hydrogen on root surfaces and exchangeable bases on soils is another source of soil acidity. The acid soil lime demand is connected not only to the soil pH but also to the buffer or CEC. The buffering capacity, or CEC, is proportional to the quantity of clay and organic matter present; the more there is, the greater the buffer capacity. If the soil is acidic, soils with a higher buffer capacity have a higher lime need. Coarse-textured soils with little or no organic matter have a limited buffer capacity and, even if acidic, a low lime need. The indiscriminate application of lime to coarse-textured soil may result in over-liming damage. Because a considerably higher base saturation was required to bring the pH to 6 with montmorillonite than with kaolinite, the connection between pH and percentage base saturation is relevant for soils typical of 1:1 and 2:1 clays. Soils with 2:1 clays (fine, mixed, and thermic Vertic (Hapludults), for example, had to be 80% base saturated to achieve the same pH as soils with 1:1 clays (fine, loamy, siliceous thermic Typic Hapludult) at 40% base saturation, as assessed by the sum of cations, pH 8.2 CEC method [46].

The primary hydrous oxides of soils are Al and Fe, which occur as coatings on other mineral particles or as inter-layers in clay mineral structures in amorphous, crystalline, or colloidal forms. When the pH of the soil falls, these oxides dissolve and, by stepwise hydrolysis, release H^+ ions, resulting in additional acidification. Soil acidity restricts plant development not only owing to shortages in P, Mo, Ca, Mg, and other nutrients, but also due to toxicities of Al, Mn, and H ions. These elements' toxicity has been identified as one of the most prevalent causes of yield decline in acid soils. Acid soil toxicity is a set of variables that can influence plant development through several physiological and biochemical processes. Al^{3+}, Mn^{2+}, and low pH (H^+ toxicity) toxicity are significant growth limiting factors linked with acid soil sterility. These toxicity variables may have an independent and/or combined effect on plant development [46].

4. Soil Acidity Challenge to Crop Production in Ethiopian Highlands

4.1. The Extent of Soil Acidity in Ethiopia

Soil acidity is a major agricultural and environmental issue that affects pasture and crop growth in many regions of the world, including Latin America, North America, Asia, Africa, Europe, and Australia. According to the researchers, roughly 43 percent of the world's tropical land area is categorized as acidic, which includes approximately 68 percent of tropical America, 38 percent of tropical Asia, and 27 percent of tropical Africa. In 48 developing nations, acidic soils cover a total of 1.66 billion hectares, whereas the total area impacted by soil acidity is around 4 billion hectares. Soil acidity primarily affects tropical and subtropical regions, as well as places with moderate climatic conditions. Acid soils are expanding and occupying a bigger amount of farmed land in Ethiopia. According to several sources, Ethiopia has substantial soil acidity coverage. Soil acidity is predicted to harm around 40.9 percent of Ethiopia's total arable land, which covers 95 percent of cultivated area and nearly 85 percent of the Ethiopian population. Ethiopia has a total land area of 111.8 million hectares, of which only 79 million hectares are suitable for agriculture. About 27.7 percent of this soil is moderate to weak acid soil (pH in KCl of 4.5-5.5), and about 13.2 percent is severe acid soil (pH in KCl of 4.5 and almost one-third has aluminum toxicity issue) [1, 33].

The problem is most severe in the country's northern, western, southern, and central areas. Soils with a pH of 5.5 dominate throughout the western and southern areas of Ethiopia. However, moderately acidic soils (pH 5.5-6.5) are found over most of the rest of the nation. Because of probable Al and Mn toxicity, as well as Ca, Mg, P, and molybdenum (Mo) shortages, strongly acidic soils are typically infertile. In Ethiopia, environmental elements such as rainfall, temperature, and topography all have a role in increasing soil acidity. In Ethiopia, soil acidity frequently develops in areas where heavy rainfall combined with unfavorable temperature and precipitation is high enough to drain significant amounts of exchangeable basic ions including calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) from soil surfaces. In Ethiopia, environmental elements such as rainfall, temperature, and topography all have a role in increasing soil acidity. In Ethiopia, soil acidity frequently develops in areas where heavy rainfall combined with unfavorable temperature and precipitation is high enough to drain significant amounts of exchangeable basic ions including calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) from soil surfaces. Because of the influences of parent materials, land structure, vegetation, and climatic pattern, its severity varies greatly [50, 23, 34].

The clay mineralogy, pH, presence of Fe and Al oxides and hydroxides, and concentration of amorphous components appear to be the most important variables influencing Phosphorous sorption. Phosphorous sorption is high to extremely high in the severely weathered soils of Chenca, Nedjo, and Indibr, where the major minerals include Gibbsite, Goethite, Kaolinite, and disilicated amorphous materials. Several researchers have found high phosphate sorptions by amorphous materials, as well as the presence of iron and aluminum oxides and hydroxides. Phosphate adsorption is thought to occur primarily through the replacement of hydroxyl ions on crystal lattices, as well as hydrated iron and aluminum, by phosphate ions. With rising acidity, phosphorus sorption capacity rises. The soil from Melkassa, which is the least worn, has the least quantity of P sorbed (with a pH value of 7.8). The soil from Chencha has the highest P sorption, with a pH of 4.5 and the largest amount of gibbsite, goethite, and amorphous minerals. Phosphorus deficiency plagues the reddish-brown soils of Ethiopia's highlands. Fertilizer experiments have shown that P application may double, and in some cases quadruple, yields. However, the high prices of high-quality, water-soluble P fertilizers, along with these soils' high P-fixing capacity, provide agronomic and economic limits to crop production [14, 9].

Soil Phosphorous exists in both inorganic and organic forms and their relative distribution is affected by climate, vegetation, parent materials, and soil management techniques. Active forms of inorganic P include Al-P, Fe-P, and calcium bound P (Ca-P), whereas inactive forms include occluded aluminium-iron bound P (occl-Al-Fe-P) and reductant soluble Fe bound P. (reds-Fe-P). Under well-drained conditions, the active inorganic Phosphorous fractions are the most available to plants, with the degree of availability increasing in the sequence of Ca-P, Fe-P, and Al-P. One of the elements influencing available soil P is soil drainage quality. P availability, for example, will be increased in flooded soil because flooding creates reducing conditions that convert previously insoluble ferric phosphate to more soluble ferrous phosphate [28].

4.2. Impacts of Soil Acidity on Crop Production

Acidity causes complicated interactions of plant development limiting variables that involve soil's physical, chemical, and biological qualities. Physical restrictions for producing crops on tropical soils include soil erosion and inadequate water holding capacity. Ca, Mg, and P deficiency or unavailability, as well as aluminum toxicity, are regarded as key chemical restrictions that limit plant development in acidic soils. Soil acidity has a negative impact on the activities of helpful microbes, as well as on the breakdown of organic matter, nutrient mineralization and immobilization, absorption, and usage by plants, and hence on crop yields [28].

The two primary variables that restrict acid soil fertility are nutrient deficits, such as phosphorus, calcium, and magnesium, and the presence of phytotoxicity chemicals, such as soluble aluminium (Al) and manganese (Mn). Aluminium (Al) in acid soil is solubilized into ionic forms, especially when the pH of the soil goes below 5. These ionic forms of Al have been demonstrated to be extremely hazardous to plants, causing root elongation inhibition by damaging the cell structure of the root apex and so disrupting water and nutrient uptake by the roots;

as a result, plant growth and development is severely hampered. Phosphorus, on the other hand, is easily fixed by clay minerals found in acidic soils, such as different iron oxides and kaolinite, making it inaccessible for root absorption. Thus, Al toxicity and P deficit are regarded as the two most significant restrictions to crop yield in acidic soils [13].

Soil acidity has an impact on crop growth because acidic soil contains dangerous amounts of aluminum and manganese and is characterized by a lack of critical plant nutrients such as P, N, K, Ca, Mg, and Mo. Aluminum is soluble in water at pH levels below five (5) and takes control of the soil solution. Excess aluminum mostly damages the root apex and hinders root elongation in acidic soils. Poor root development results in lower water and nutrient uptake, and crops produced on acidic soils face nutrient and water shortages as a result. The total result is decreased crop growth and production. The existence of hazardous amounts of Al and Mn, as well as nutrient deficiencies such as P, Ca, Mg, and Mo, limit the productivity of acid soils. The pH of the soil has a strong influence on the solubility and availability of key nutrients to plants [54, 38, 18].

Furthermore, one of the limits to barley development in Ethiopian highland acidic soils, primarily Nitisols or Oxisols, is soil acidity and related limited nutrient availability. Acid soils are common in Ethiopia's highlands, where rainfall intensity is high and agricultural cultivation has been practiced for many years. The fertility state of these soils is relatively low in terms of nutrient stores available to plants, owing to nutrient removal in harvested products as well as losses through erosion and leaching. Because the pH of the soils is less than 5.5, yields of barley and other crops produced in the highlands are particularly poor when compared to other barley growing soils in the country. In addition to a lack of suitable cultural techniques, low barley yields might be ascribed mostly to nutrient deficit and low soil pH. Farmers' principal crops grown on acidic soils are barley, wheat, teff, rapeseed, faba bean, and field pea [50].

Acid soils impede crop output on 30 to 40% of the world's farmed land and up to 70% of potentially arable area. Various investigations have also suggested that Ethiopia has high soil acidity coverage. As a result, it poses a substantial danger to agricultural production across much of Ethiopia's highlands and is a major crop production limitation for the country's small-scale farmers. The presence of phytotoxic chemicals such as soluble Al and Mn, as well as mineral deficits such as P, Mo, Ca, Mg, and K, are the two primary factors limiting acid soil fertility. The low P status of severely worn acid soils is especially problematic because significant amounts of P must be administered to elevate the concentration of available soil P to an appropriate level. Low P status is caused in part by constantly negative P balances and in part by natural soil features. These soils feature a high concentration of Al and Fe hydrous oxides, which may adsorb P onto their surfaces. As a result, much of the additional P is fixed and not immediately available for crop usage. According to several researchers, the majority of Ethiopia's highland soils are P deficient. Producing various crops is difficult due to the aforementioned issues [45, 33].

Soil acidity is a key constraint to acid sensitive crop cultivation in highland Ethiopia. The sterility of these acid soils is related to an excess of Al, Fe, or Mn on the one hand and a deficiency of P, K, Ca, and Mg on the other. Acidic soil has a negative impact on crop growth because it includes dangerous amounts of Al, Fe, and Mn and is deficient in critical plant nutrients such as phosphorus (P), calcium (Ca), potassium (K), magnesium (Mg), and molybdenum (Mo). It is one of the chemical soil degradation issues affecting soil production in Ethiopia's highlands. Because of the acidic character of the soil and a lack of P fertilization, most of Ethiopia's highland soils are deficient in their inherent available P levels, posing a barrier to agricultural output [3].

Furthermore, phosphorus is the second most critical element for crop production after nitrogen, with P deficit resulting in lower plant development, delayed crop maturity, and a loss in crop yield quality and quantity. Soil P deficit in tropical locations may be caused by the parent material's poor P status, weathering, long-term human mismanagement through an imbalance between nutrient inputs and exports, and P loss through erosion and surface runoff. Ethiopian soils, like other tropical agricultural soils, are often poor in available P. Several study findings show that most of Ethiopia's highland soils are naturally P deficient, making it one of the limiting nutrient components in agricultural development in the region. Soil acidity affects more than 40.9 percent of Ethiopia's total arable land. It is growing in both extent and scale, significantly reducing crop output. Soil acidity has a significant impact on the highlands of Dawuro, Gamugofa, Sidama, Kembata, Hadya, Siltie, Wolayita Guragie, Kafa, Ilu-ababor, Wallaga, Jima, West Shoa, North Shoa, Asosa, and Gojjam, for example [45, 30, 27, 29, 17].

5. Strategic Options for Mitigating Soil Acidity for Enhancing Crop Productivity

Soil acidity adjustment and maintenance is a critical aspect of crop production soil management. As a result, it is a strategic choice for mitigating several difficulties that impede increasing agricultural output. Crop productivity in tropical acid soils is hampered by Al and Mn toxicity, as well as Ca/Mg deficiency. Acid soil stressors must be addressed in order for agriculture to thrive in these areas. Liming, organic materials, crop mixes, and the use of plant species and cultivars resistant to Al and Mn toxicity are among the agronomic and management alternatives for correcting acid soils, improving nutrient usage efficiency, and increasing crop yield on acidic soils. Similarly, there is substantial evidence in the literature indicating that the application of lime, farm yard manure, compost, biochar, and other mineral fertilizers, particularly mineral P fertilizers, can be utilized to mitigate acidity-related issues and P deficit in acid soils. Liming and the use of phosphate fertilizers in organic or inorganic P forms as organic or inorganic P forms have been proposed for the treatment of P deficiency problems in acid soils. Organic matter plays a significant role in reducing P adsorption and increasing P availability in acid soils with high levels of exchangeable Al due to the cumulative effects of several mechanisms. These include the release of inorganic P from decaying residues, the obstruction of P adsorption sites by organic molecules released from the residues, an increase in soil pH, and the organic molecules' complexation of soluble Al and Fe [26, 41]. The following are some strategic management approaches for increasing crop productivity in acidic soil.

5.1. Liming

Lime is the most important tool for reducing soil acidity since it has a high acid neutralizing ability and can efficiently eliminate existing acid. Liming enhances nutrient absorption, stimulates biological activity, and reduces heavy metal toxicity. It elevates the pH of the soil and causes the aluminum and manganese in the soil solution to return to solid (non-toxic) chemical forms. Because soil acidification is a continual process, many soils require regular lime treatments to keep soil pH in the optimum range. The most frequent substance used to raise soil pH is limestone. However, for the most efficient crop production on acidic soils, both lime and fertilizer must be used. Because lime increases the availability of minerals to plants, liming without the use of fertilizers leads in a decrease in soil fertility, which can lead to major production problems. As a result, it is important to add fertilizer ingredients to correct nutritional restrictions produced by acidity. The relevance of lime and fertilizer management strategies in acid soil management cannot be overstated [15].

Adding lime or other minerals can elevate soil pH to an appropriate range for crop productivity, establish an environment for healthy microorganism function, and boost calcium or magnesium ion levels. Lime neutralizes both active acidity and some reserve acidity. As active acidity is neutralized by lime, reserve acidity is released into the soil solution, hence preserving active acidity or pH. The ability of a soil to tolerate variations in pH is referred to as buffering capacity, and it is mostly determined by reserve acidity. In a strongly buffered soil, more lime is required to counteract acidity than in a less buffered soil. The ability to track pH variations over time is a useful management tool. By comparing historical and contemporary soil testing, it is feasible to determine whether soil acidity is growing over time and whether management practices should be modified to avoid this trend from continuing.

Lime can lessen or eliminate Al toxicity by shifting soil acidity to neutral levels and making nutrients more available to crops. Depending on the soil type and level of acidity, lime doses of 2-5 t ha^{-1} are normally required to neutralize acid soils adequately for crop development. Furthermore, the amount of lime needed to raise soil pH is dictated by the type of lime used, the history of land use, and the pH previous to lime application. Furthermore, the subsurface soil condition should be established before determining the amount of lime that should be applied. Subterranean soils with low pH are the most detrimental to plant root growth, potentially lowering agricultural production considerably. As a result, in areas with low pH soils in the subsurface layer, a small amount of lime may not be enough to eradicate Al toxicity and allow plant growth. To see the effect of surface liming, it may be necessary to treat the subsurface soils with a larger dose of lime application until the desired pH level is obtained. When subsurface soils are not correctly treated, continual surface application of lime, even at large dosages, may not achieve the desired outcome because Ca^{2+} and Mg^{2+} may leach or diffuse below the root zone, and P may remain adsorbed and not be available to plants [20].

In brief, liming acidic soils to a lower pH neutralizes exchangeable Al^{3+} and Mn^{2+} toxicity while also providing calcium and magnesium. This typically promotes plant phosphorus absorption. Liming frequently increases the effective crop rooting depth by lowering Al toxicity in acidic soils, allowing the crop to explore a larger soil volume for nutrients and water. Crushed limestone ($CaCO_3$), dolomatic lime ($CaMgCO_3$), slaked lime (Ca $(OH)_2$), quick lime (CaO), and other liming materials can be used to reduce soil acidity. According to researchers, liming has several other benefits aside from reducing soil acidity by counteracting the effects of excess H^+ and Al^{3+} ions, including its ability to reduce the toxicity effects of some microelements by lowering their concentrations while increasing the availability of plant nutrients such as Ca, P, Mo, and Mg in the soil and reducing the solubility of heavy metals. Crops absorb a large quantity of most of these nutritional elements, notably Ca, P, and Mg, and so increasing their levels in soil can greatly boost crop yields. Liming also boosts microbial activity and improves N fixation and mineralization, thus legumes benefit greatly from it. As a result, liming is a significant and successful strategy for overcoming soil acidity restrictions and improving crop output on acidic soils. In acid soils, lime is known as the "workhorse" or "foundation crop" [28].

5.1.1. Effects of Lime on Some Properties of Acid Soils

The solubility and availability of key nutrients to plants is directly tied to soil pH, which is defined in terms of pH and indicates whether the soil is acidic, alkaline, or neutral. It determines the concentration of hydrogen ions in soil solution. Liming makes other nutrients more accessible by raising soil pH and preventing Al and Mn from becoming poisonous to plant development. Aluminum or iron, as well as any exchangeable H that may be present in the exchange sites, constitute exchangeable acidity. Soil exchangeable acidity is nearly completely attributable to Al^{3+} ions. This is due to the fact that in moderately to extremely acidic soils, only Al^{3+} is a frequent exchangeable cation. Only at soil pH levels below roughly 5.5 does exchangeable Al exist in large concentrations. The exchangeable acidity decreases when the pH of the soil solution rises due to liming. Furthermore, phosphorus shortage issues are exacerbated by acid soils' ubiquitous high phosphorus fixation capacity. Because elemental P is very reactive chemically, it is not found in nature in its pure state. It can only be found in chemical combinations with other elements. The degree of inorganic P fixation is determined by a variety of parameters, the most important of which is soil pH. In acidic soils, inorganic P precipitates as Fe/Al-P secondary minerals or is adsorbed to the surfaces of Fe/Al oxides and clay minerals as Fe/Al-P secondary minerals. In acid soils, up to 98 percent of applied phosphate was transformed into inaccessible forms in relatively short periods of time, according to researchers. Lime is commonly attributed with enhancing the availability of P in acidic soils [16, 38].

The use of lime raised soil pH and phosphorus availability dramatically, according to tests done by several researchers. Lime treatment, according to other researchers, reduced exchangeable acidity. This might be attributed to a decrease in the concentration of exchangeable aluminum and hydrogen. The proportion of acid saturation is also reduced as a result of these events. The results of several trials on soil acidity control done in various highland areas of Ethiopia revealed that liming and combined/integrated organic and inorganic fertilizers increased soil pH, P availability, exchangeable bases (K, Ca, and Mg), OC/OM, TN, and CEC. According to several researches, the use of lime and P fertilizer caused a pH alteration. When compared to the control, the application of mineral P fertilizer had no influence on the pH. Similarly, others discovered that the application of various lime enhanced soil pH when compared to the control. The presence of basic cations (Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}) in lime that are capable of exchanging H^+ from exchange sites to create $H_2O + CO_2$ is connected with the rise in pH and reduction in soil exchangeable acidity. Cations fill the space left by H^+ during the exchange, causing the pH to increase. Other researchers observed that soil pH increased after lime treatment as a result of Ca^{2+} ions displacing H^+ and Al^{3+} ions from soil adsorption sites. Liming acid soils elevates soil pH, which releases phosphate ions precipitated with Al and Fe ions, allowing P to be taken up by plants (Table 1) [12, 23, 39, 24, 40].

The investigations done by Ayalew [12] and Desalegn et al. [24] reveal that the application of lime on acidic soil with an inherent trait of high P fixation greatly reduced exchangeable acidity (EA). This reduction can be attributed to enhanced Al replacement by Ca at the exchange site and subsequent precipitation of Al as Al $(OH)_3$ when the soil was limed. Furthermore, increasing soil pH causes the precipitation of exchangeable and soluble Al as insoluble Al hydroxides, lowering the concentration of Al in soil solution. Melese and Yli-Halla [39] further demonstrate that the application of lime and P fertilizer changed the exchangeable acidity. When compared to the control, the application of mineral P fertilizer had no effect on exchangeable acidity. Dessalegn et al. [24] found that using various lime splits considerably lowered exchangeable acidity to a minimal level. Lime application, regardless of rate, dramatically reduced exchangeable acidity when compared to the control. This is to be expected because lime is known to raise soil pH, causing Al to precipitate as $Al(OH)_3$.

According to Buni [19], the application of 3.75 t ha^{-1} lime improved the pH of the soil from 5.03 to 6.72 (Table 1). Another study, done by Moges et al. [40], found that the application of lime and P fertilizer changed the pH. When compared to the control, the application of mineral P fertilizer had no influence on the pH. Similarly, Dessalegn et al. [24] and Abdissa et al. [2] discovered that the application of various lime enhanced soil pH when compared to the control (Table 1). The presence of basic cations (Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}) in lime that are capable of exchanging H^+ from exchange sites to create H_2O plus CO_2 is connected with the rise in pH and reduction in soil exchangeable acidity. Cations fill the space left by H^+ during the exchange, causing the pH to increase. Melese Yli-Halla [39] also showed that soil pH increased after lime treatment due to H^+ and Al^{3+} ions displacement from soil adsorption sites by Ca^{2+} ions in lime. Liming acid soils elevates the pH of the soil, which releases phosphate ions precipitated with Al and Fe ions, making P accessible for plant uptake [23].

Furthermore, Ayalew [12] observed significant impact of liming on soil chemical characteristics in Areka (highland portion of Southern Ethiopia). The same author also observed that lime treatment increased soil pH, available phosphorus, cation exchange capacity, and calcium in three consecutive cropping seasons. Similarly, Abdissa et al. [2] found that lime enhanced pH, OM, TN, and available P in the Ebentu district of Ethiopia's western highlands. However, when application increased, exchangeable aluminium, exchangeable acidity, and acidic saturation (AS) declined. Kidanemariam [35] reported on the residual impacts of lime on the chemical characteristics of soils in Tsegede District, Northern Ethiopia, for two consecutive years. Furthermore, the OM, pH, Av. P, and exchangeable Ca of the respective study soil were consistently raised. Soil exchangeable Ca, for example, showed evident fluctuation in both cropping seasons (first and second year cropping seasons) (Tables 1 & 2), whereas OM showed inconsistency with the shift in the major impacts of lime. However, there was an increase in OM in the residual soils of the year two cropping season compared to the year one cropping season. This increase might be attributed to agricultural residue accumulations. Liming, according to Ayalew [12], might boost crop yields and organic matter returns in acidic soils.

CEC is commonly related with the cations Al^{3+}, H^+, Ca^{2+}, Mg^{2+}, K^+, NH_4^+, and Na^+. With the exception of Al^{3+}, the majority of the exchangeable cations are plant nutrients. The elimination of basic cations, particularly Ca and Mg, through leaching and erosion results in their replacement by acidic cations such as H, Al, and Fe at exchange sites and in the soil solution. When compared to a control, Tigist [52] discovered an increase in exchangeable bases with rising lime rates (Table 2). Similarly, Abdissa et al. [2] stated that higher soil exchangeable bases as a result of lime treatment might be ascribed to an elevation in soil pH, which may have boosted exchangeable base availability in the soil (Table 2). Lime treatment of soil in the Ebentu area of Ethiopia's western highlands dramatically influenced extractable micronutrients

(Fe, Mn, Zn, and Cu) (Table 2). According to the same author, the extractability of Fe, Mn, Zn, and Cu decreases when soil pH rises. The precise processes responsible for limiting availability vary depending on the nutrient, but can include the creation of low solubility compounds, increased retention by soil colloids when lime is applied and increased retention by soil colloids when lime is applied. The decrease in extractable Fe might be attributed to the pH shift generated by the amendments (lime application), because the bioavailability of DTPA extractable Fe reduced as the pH of the soil rose [2]. Buni [19] observed that extractable micronutrients such as Fe, Zn, and Mn reduced at pH values near neutral or higher.

In general, increasing lime rate increased soil pH, Av. P, OC, OM, ECEC, base saturation, and Ex. Ca in a linear pattern. The growth was greatest when the maximum rate of lime was applied. Lime dissociates into Ca^{+2} and OH^{-} ions when applied to acid soils with high Al^{3+} and H^{+} concentrations. The hydroxyl ions will combine with the hydrogen and Al^{3+} ions to generate Al^{3+} hydroxide and water, raising the pH of the soil solution. Meanwhile, applications of the highest rate of lime appreciably reduced soil exchangeable Al^{3+}, exchangeable acidity, and extractable micronutrients such as Fe, Mn, Zn and Cu.

Table 1. *Effects of liming and its residual on selected chemical properties of the soil.*

Treatment	Rate	pH	Ex. Ac cmolckg^{-1}	Ex. Al cmolckg^{-1}	AS (%)	OM %	TN %	P mg/kg	Reference
control	0	4.83	2.38	1.70	30	2.13	0.20	4.5	[2]
Lime (tons ha^{-1})	2	5.20	2.13	1.28	23	2.17	0.21	5.6	
	4	5.44	1.15	1.12	12	2.21	0.21	6.3	
	6	6.01	0.171	0.33	1.62	2.28	0.23	6.2	
Lime (tons ha^{-1})	0	4.89	2.22	1.28	-	-	-	5.7	[39]
	3.5	5.15	0.85	0.13	-	-	-	5.8	
	7.0	5.43	0.35	0.09	-	-	-	6.3	
	9.2	5.63	0.23	0.07	-	-	-	6.5	
	11.2	6.03	0.14	0.07	-	-	-	6.8	
Residual Lime Effects of first cropping season	Control	4.46	2.91	-	-	6.28	-	2.71	[35]
	Half LRR	4.49	2.63	-	-	7.27	-	3.47	
	Full LRR	4.94	1.27	-	-	7.35	-	4.17	
Residual Lime Effects of second cropping season	Control	4.37	5.78	-	-	9.78		1.95	
	Half LRR	4.41	4.43	-	-	9.39		2.09	
	Full LRR	4.75	3.28	-	-	9.13		2.50	
Lime application (kg/ha)	0	5.03	0.97	0.68	-	-	-	5.36	[19]
	1250	5.64	0.75	0.56	-	-	-	6.70	
	2500	6.14	0.51	0.33	-	-	-	7.04	
	3750	6.72	0.36	0.24	-	-	-	6.67	
Lime application (t/ha)	control	5.04	0.96	-	-	-	-	8.95	[40]
	4	5.51	0.35	-	-	-	-	15.66	
	6	5.64	0.19	-	-	-	-	16.77	

Table 2. *The effects of liming and it residual on Ex. Bases, ECEC and selected micronutrients of acidic soil.*

Treatment	Rate	Ca	Mg	K	Na	ECEC	Fe	Mn	Zn	Cu	References
		cmolckg^{-1}					ppm				
control	0	3.5	1.52	0.25	0.16	7.85	40	36	3.06	3.65	[2]
Lime (tons ha^{-1})	2	4.5	1.65	0.31	0.78	9.37	24.1	31	2.96	3.43	
	4	5.2	1.88	0.41	0.90	9.57	16.6	25	2.41	3.15	
	6	5.9	3.09	0.42	0.97	10.49	14.3	17	2.23	2.86	
Lime (tons ha^{-1})	0	4.80	0.84	0.74	0.10	-	-	-	-	-	[52]
	1.62	5.20	3.10	1.18	0.30	-	-	-	-	-	
	3.26	5.20	5.19	1.18	0.26	-	-	-	-	-	
	4.90	6.24	3.94	1.18	0.17	-	-	-	-	-	
Residual Lime Effects of 1st CS	Control	8.14	2.68	-	-	-	-	-	-	-	[35]
	Half LRR	22.84	2.34	-	-	-	-	-	-	-	
	Full LRR	32.97	1.95	-	-	-	-	-	-	-	
Residual Lime Effects of 2nd CS	Control	5.21	2.03	-	-	-	-	-	-	-	
	Half LRR	16.48	1.74	-	-	-	-	-	-	-	
	Full LRR	23.36	1.58	-	-	-	-	-	-	-	
Lime t/ha	0	-	-	-	-	19.18	41.96	70.3	11.67	0.37	[19]
	1.25	-	-	-	-	25.21	33.77	58.4	0.19	0.77	
	2.50	-	-	-	-	31.49	25.04	46.0	9.78	0.99	
	3.75	-	-	-	-	33.34	19.01	34.5	9.75	0.65	

Table 3. *Chemical properties of soil as influenced by application of lime in three consecutive cropping seasons.*

Treatment	pH	P ppm	% OC	% OM	CEC meq/100g soil	% N	Ca cmol/kg	K cmol/kg	Ex. A, meq/100g soil
First cropping season									
Control	5.2	1.6	3.06	5.27	16.0	0.14	7.0	0.41	1.36
900 kg lime/ha	5.4	1.6	3.12	5.38	18.2	0.168	7.0	0.37	0.80
1800 kg lime/ha	5.5	2.00	3.25	5.60	23.4	0.140	10.0	0.33	1.04
Second cropping season									
Control	5.2	2.60	2.80	4.82	22.0	0.168	8.0	0.40	9.0
900 kg lime/ha	5.2	3.00	2.80	4.82	23.2	0.238	9.0	0.37	8.0
1800 kg lime/ha	5.4	6.40	2.73	4.71	24.4	0.07	10.0	0.35	10.0
Third cropping season									
Control	-	4.11	4.34	-	20	0.2	7.4	0.56	-
900 kg lime/ha	-	6.44	4.5	-	21	0.21	9.2	0.70	-
1800 kg lime/ha	-	6.72	4.53	-	23	0.21	10.2	0.64	-

Source: [12].

5.1.2. Effects of Lime on Enhancing Crop Productivity of Acid Soils

Soil acidity restricts or lowers agricultural output primarily by affecting root development, resulting in reduced nutrient and water intake. Soil acidity changes available soil nutrients into inaccessible forms, and soils impacted by soil acidity are deficient in basic cations such as Ca, K, Mg, and certain micronutrients, all of which are required for crop growth and development. The level of soil acidity's harm varies based on numerous conditions, and there have been cases where total crop loss has occurred as a result of soil acidity. Thus, the major impacts of liming are increased available P by inactivation or precipitation of exchangeable and soluble Al and Fe hydroxides, increased pH, available P, exchangeable cations, and percent base saturation, and improved root hair growth density and length for P absorption [54, 38]. As a result, liming has a decisive influence on crop productivity in acidic soil. Agegnehu et al. [7] found that applying lime at rates of 1, 3, and 5 t ha^{-1} resulted in a strong linear response with mean faba bean seed production advantages of 45, 77, and 81% over the control.

One of the effects of treated acid soils is an increase in crop output. In Ethiopia, the effect of liming on agricultural output has been researched for a few crops. Table 4 summarizes these findings. Furthermore, the yield increase by applying lime to different locations and crops is in the range of 3.6-5.3, 2.1-2.5, 1.6-3.3, and 2.8-4.5 for common bean, soybean, faba bean, and barley, respectively (Table 4). According to Ayalew [12], the reaction of a crop to lime treatment varies by lime rate, and the influence on production might continue longer than the season in which it is administered. According to an experiment done in Ethiopia, after applying lime for two years, the effect on barley harvest output rose by a similar amount in the following two years. According to Desalegn et al. [24], combining 1.65 t lime ha^{-1} and 30 kg P ha^{-1} resulted in 133 percent higher barley grain yields than the control (Table 4). Lime applications of 0.55, 1.1, 1.65, and 2.2 tons per hectare enhanced barley output by 0.795, 1.041, 1.444, and 1.677 tons per hectare, respectively. Yield increments had a direct association with soil pH values and an inverse relationship with exchangeable acidity, which means that as the pH grew, so did the yield, but as the exchangeable acidity fell, so did the yield of faba bean, and vice versa [10].

Abewa et al. [4] discovered that using biochar and lime as a soil amendment enhanced yield considerably even in the absence of fertilizer. In grain yield, for example, application of 12 t ha^{-1} charcoal and 2 t ha^{-1} limes without fertilizer exceeds the whole fertilizer rate without amendment. However, boosting soil pH by the same amount would necessitate the use of more biochar than lime [4]. Liming's effects will not be as long-lasting as biochars, especially if the underlying soil layer acidity had not previously sufficiently corrected [54]. As a result, combining lime treatment with biochar might be advantageous. For example, a research in Tigray found that combining moderate biochar application rates with DAP and UREA might considerably enhance soil quality and boost wheat grain and biomass output [32]. Although the effect of acidity varies by crop type, liming can boost soil productivity by lowering Al^{3+} and Mn^{2+} levels, hence alleviating Ca and/or Mg shortage, which is otherwise only modestly available to crops in the soil solution of acidic soils. Liming also boosts phosphorus desorption from soil solutions and increases crop responsiveness to P fertilizers [24]. In Ethiopia, the effects of liming on agricultural output have been researched for a variety of crops. In general, the amount of lime required to achieve optimum soil pH is determined by the soil's original qualities. Table 4 indicates the proportional yield advantage of lime treatment of soils. The yield increase by applying lime above the control (no liming) ranges from 2.8-4.5, 3.01-3.09, 2.01-2.55, 1.6-3.3, 1.9-2.6, and 2.1-2.5 t ha^{-1} for barley, maize, malt barley, faba bean, common bean, and soybean, respectively (Table 4). The response of a particular crop to lime treatment varies from site to site, owing mostly to changes in soil pH.

Table 4. *Grain yield and biomass yield as affected by different levels of lime application on acid soils.*

Lime rate (tha^{-1})	GY (kg ha^{-1}) 2011	Biomass yield (kg ha^{-1})			crop type	References
		2010	2011			
0	2895.8	7641	7598.3		Barley	[24]
0.55	3691.9	9850.5	8990.0			
1.10	3937.5	11947.5	10062.5			
1.65	4340.0	12790.9	11122.5			
2.20	4572.8	13196.7	11454.2			
		1st yr (2007)	2nd yr (2008)	3rd yr (2009)	Maize	[12]
0	3015.5	7812.5	8267	10087		
0.9	2851.1	7118.1	7491	12333		
1.8	3094.8	8159.7	8503	8083		
0	20.2	11.96			Malt barley	[40]
4	25.18	13.71				
6	25.6	14.56				
0	1620	3084			Faba bean	[10]
1.5	2031	3413				
3	3326	33.26				
unlimed	1900	3600			Common bean	[37]
limed	2600	5300				
0	2124				Soybean	[51]
4.6	2522					

5.2. Effect of Inorganic Fertilizers, Organic and Biochar on Some Selected Soil Acidity Properties and Enhancing Crop Productivity

The addition of organic fertilizers to acidic soils has been successful in lowering phytotoxic levels of Al, resulting in increased yield. The main processes responsible for these benefits are assumed to be the development of organo-Al complexes that make Al less poisonous or direct neutralization of Al from the rise in pH generated by organic materials. Organic materials such as agricultural wastes, manures, compost, and biochar might be used as lime alternatives. Furthermore, the use of biochar decreases exchangeable acidity while improving CEC, available phosphorus and pH in Ethiopia's central highland soil [4,]. The same author reported the positive response of biochar on soil pH, CEC and Av. P of the soil which result for the increment of grain and biomass yield of teff in central high land of Ethiopia (Table 7).

Organic fertilizers such as vermicompost, manure, and biochar are important in modifying soil chemical characteristics, which boost crop output in acidic soil. Numerous researches have reported the beneficial effects of the aforementioned fertilizers on the acidic soils of the Ethiopian highlands. They also clearly show the decrease in exchangeable acidity and aluminium as a function of the amount of acid saturation (Table 5).

Even if P treatment alone did not result in long-term gains in grain yield, its application is critical in enhancing available P in the soil by fulfilling sorption sites. Abdissa et al., [2] and Dessalegn et al., [24], for example, found an increase in maize and barley output in diverse acidic soils in Ethiopia's highlands (Table 6). Furthermore, the use of mixed mineral fertilizers is particularly efficient in improving various chemical features of the soil and increasing crop production in acidic soil. According to Ayalew [12], utilizing 69 kg N + 20 kg P enhances maize grain production and biomass by 150.88 and 136.88 percent, respectively, above the control (Table 6). In-short through application of high rate of P fertilizers, soil sorption sites are satisfied and P level increase to sufficiency for crop production.

In addition to the application of lime, a significant effort must be made to repair lost soil fertility. ISFM techniques that mix the use of manure with residue and inorganic fertilizers, as an alternative to liming, can boost crop output on acid soils. Acid soils, in addition to being deficient in many plant nutrients, bind key ones like P and make them inaccessible to crops. The fertilizer application schedule for acid soils varies from that of more neutral soils in that large amounts of P must be administered to prevent the nutrient's fixation/binding. This must be accompanied by a significant increase in the amount of organic materials introduced into the production system. This may be achieved by using leguminous cover crops, which increase biological activity in the soil while also enhancing soil nutrients. When exposed to acidic circumstances, al becomes soluble and can be hazardous to crops. Ca levels are frequently low in these soils. Because lime is absorbed into the topsoil, it has little effect on Al toxicity in the subsurface. Lime treatment along with ISFM and optimum agronomic practices is required to address both soil nutrient depletion and acidity issues and sustainably increase crop output [22, 48, 53].

Several studies have clearly shown that it is feasible to grow teff, maize, barley, wheat, and several types of legumes equitably by using an integrated nutrient application technique rather than providing nutrition from a single source. Ayalew [12] and Assefa et al. [11], for example, found that teff showed a significant response to integrated soil fertility management treatments containing both organic and inorganic forms under farmers' field conditions, implying that they could be considered as alternative options for sustainable soil and crop productivity in Ethiopia's degraded highlands. Chala et al., [21], Melese and Yli-Halla [39], and Abdissa et al., [2] discovered that mixed organic and inorganic fertilizers had a favorable influence on chickpea, barley, and maize production, respectively. Furthermore, crops have responded differentially to N and P treatment on diverse soil types.

Table 5. *Effects of organic and mineral P fertilizers on selected chemical properties of soil.*

Treatment	rate	pH	ExAc	ExAl	CEC	P	PAcs	OC	TN	Ref.
			cmolckg $^{-1}$			mg/kg		%		
VC t/ha	0	4.68	2.57	1.37	22.05	8.77	11.76	-	-	[8]
	5	4.79	2.15	0.33	23.42	9.39	9.85	-	-	
	10	4.99	1.99	0.31	24.02	10.36	9.14	-	-	
VC t/ha	0	4.83	2.38	1.70	7.85	4.5	30	1.24	0.20	[2]
	2.5	5.18	2.18	1.63	10.96	5.8	20	1.58	0.21	
	5	5.19	2.05	1.57	12.15	6.0	17	1.86	0.23	
	7.5	5.46	1.99	1.31	12.59	6.3	16	2.34	0.23	
P (kg ha^{-1})	0	4.83	2.38	1.70	7.85	4.5	30	1.24	0.20	[2]
	20	5.17	2.36	1.70	9.00	5.7	27	1.26	0.21	
	40	4.97	2.34	1.71	7.80	6.0	30	1.24	0.20	
	60	4.95	2.38	1.71	7.96	6.2	30	1.25	0.19	
Fertilizer N/P_2O_5 (kg ha^{-1})	0	5.73	-	-	-	14.70	-	-	-	[4]
	23/30	5.77	-	-	-	16.35	-	-	-	
	46/60	5.75	-	-	-	17.40	-	-	-	
Biochar t/ha	0	-	-	-	-	-	-	1.66	0.17	[4]
	4	-	-	-	-	-	-	1.70	0.17	
	8	-	-	-	-	-	-	1.77	0.18	
	12	-	-	-	-	-	-	1.84	0.18	

Table 6. *Grain yield and biomass yield as affected by different levels of fertilizers application on acid soils.*

Type fertilizer	rate	Grain yield (kg ha^{-1}) 2007	2008	2009	Crop type	References
NPK fertilizer (kg ha^{-1})	0	2847.2	3015.5	2661	Maize	[12]
	69 kg N + 20 kg P	3802.1	4722.0	4015		
	69 kg N + 75 kg K	2517.4	2815.5	2995		
	20 kg P + 75 kg K	3576.4	3679.5	3333		
	69 kg N + 20 kg P + 75 kg K	3750.0	3862.9	3625		
	rate	Biomass yield (kg ha^{-1})				
	0	7812.5	8267	10087		
	69 kg N + 20 kg P	10763.9	11316	10394		
	69 kg N + 75 kg K	6805.6	7742	12011		
	20 kg P + 75 kg K	9895.8	10180	9185		
	69 kg N + 20 kg P + 75 kg K	9618.1	9902	12705		
	rate	GY (kg ha^{-1}) 2011	BY (kg ha^{-1}) 2010	BY (kg ha^{-1}) 2011		
Phosphorus (kg ha^{-1})	0	3132.1	8111.8	7113.3	Barley	[24]
	10	3710.1	10462.7	9855.3		
	20	4258.1	12254.4	10982		
	30	4449.6	13512.3	11431.3		
Chemical P fertilizer (kg ha^{-1})	0	2180	16100		Maize	[2]
	20	2360	16500			
	40	3050	16800			

Table 7. *Effects of organic amendments on the grain and biomass yield on different crops of acidic soil of Ethiopia highland.*

Treatments	Rate	GY (th^{-1})	BY (th^{-1})	Crop	Reference
Vermi-Compost (VC)	0	2.18	16.1	Maize	[2]
	2.5	3.03	17.0		
	5	4.03	18.7		
Biochar	0	1.437	11.55	Teff	[4]
	4	1.724	13.15		
	8	1.980	13.67		
	12	2.668	17.77		
Manure (t/ha)	0	1.343	2.873	Faba- Bean	[10]
	2.5	1.528	3.243		
	5	1.759	3.700		

In brief ISFM is one method for managing and improving soil health and fertility. ISFM is one of the components of acid soil management. Organic plant nutrition sources such as farmyard manure (FYM) and crop leftovers may improve the physical and chemical qualities of soils. In acid soils where P fixation is an issue, FYM treatment releases a variety of organic acids that can form stable complexes with Al and Fe, so blocking the P retention sites and improving P availability and usage efficiency. The addition of organic fertilizers to acidic soils has been successful in lowering phytotoxic levels of Al, resulting in increased yield. The main processes responsible for these benefits are assumed to be the development of organo-Al complexes that make Al less poisonous or direct neutralization of Al from the rise in pH generated by organic materials. Organic materials such as agricultural residues, manures, compost, and biochar can be used as lime alternatives [6, 49, 53].

Table 8. *Effect of biochar combined with chemical fertilizer on yield of Teff.*

Amendments	Fertilizer rate N/P_2O_5 (kg ha-1)	Grain yield (t ha^{-1})	Dry biomass yield (t ha^{-1})
	0	0.817h	9.22f
No Amend	20/30	1.623gf	11.54def
	40/60	1.870ef	13.89cde
	0	0.959h	9.37f
4 t ha^{-1} biochar	20/30	1.860f	14.33cd
	40/60	2.354cde	15.76bc
	0	1.266gh	10.40ef
8 t ha^{-1} biochar	20/30	1.999def	13.59cde
	40/60	2.676abc	17.03bc
	0	2.413bcd	16.15bc
12 t ha^{-1} biochar	20/30	2.462bcd	16.14bc
	40/60	3.129a	21.04a
	0	2.182cde	13.36cde
2 t ha^{-1} Lime	20/30	2.296cde	13.59cde
	40/60	2.877ab	18.16ab
Probability (0.05)		**	**
CV		12.87	12.35

Source: [4].

The authors found that organic sources elevate pH and precipitate Al in direct proportion to their basic cation or ash alkalinity, after accounting for the acidity created by the oxidation of the N in the substance. For example, Abewa et al. [4] discovered that combining high pH biochar with lime and mineral fertilizers increases OC, TN, pH, av. P, and CEC while decreasing exchangeable acidity, percentage acidic saturation, and exchangeable aluminium in acidic soil in northern Ethiopia highland. According to the same authors, employing appropriate combination fertilizers raises teff grain yield from 0.8 t/ha (no amend) to 3.12 t/ha (amend with 12t/ha biochar and 40/60 N/P_2O_5 mineral fertilizers) and increases dry biomass output from 9.22 to 21.04t/ha in the same treatments (table 8). Other researchers have shown that combining organic and inorganic fertilizers has a favorable effect on acidic soil (Tables 9, 10 and 11). Additionally Haile and Boke [33] reported that the combined application of NP fertilizer and FYM on acid soil of Chencha, southern Ethiopia significantly increased potato tuber yield and several studies have been conducted on the use of mixed applications of wood ash manure P, mineral P, and lime for addressing nutrient deficits or imbalances caused by acid deposition and leaching in highland soils, or as a liming agent in various agricultural soils. The application of the appropriate fertilizer mixture to soil is a practical technique of recycling some nutrients, such as Ca, K, Mg, Na, and P and N. As a consequence, the presence of those nutrients improves the physical and chemical qualities of the soil, resulting in increased agricultural yield in Ethiopia's highland acid soil. Furthermore, Melese and Yli-Halla [39] found that combining lime, mineral P, manure P, and wood ash increases pH, CEC, and accessible P while decreasing exchangeable acidity, percentage of acid saturation, and exchangeable aluminium (table 9). According to the same authors, combining the aforementioned fertilizers increases grain production and dry biomass output of barley in acidic soil in Ethiopian highland.

In acid soils where P fixation is an issue, applying manure alone releases a spectrum of organic acids that can form stable complexes with Al and Fe, so blocking the P retention sites and improving P availability and usage efficiency [6]. According to Melese and Yli-Halla [39], applying manure to acidic soil raises the pH and available phosphorus levels from 4.97 to 5.03 and 7.1 to 9.9 mg/kg, respectively. The same authors also observed that supplementing acidic soil with manure reduced exchangeable aluminum and exchangeable acidity (table 9). The positive effects of manure on crop yields have been explained on the basis of cation exchange between root surfaces and soil colloids. The addition of organic fertilizers to acidic soils has been successful in lowering phytotoxic levels of Al, resulting in increased yield. The main processes responsible for these benefits are assumed to be the development of organo-Al complexes that make Al less poisonous or direct neutralization of Al from the rise in pH generated by organic materials. Organic materials such as agricultural residues, manures, compost, and biochar can be used as lime alternatives [6].

Crop yields in tropical locations often diminish with time, due in part to a decrease in exchangeable base levels caused by acidity of the top layers of the soil. The treatment of acid soils via integrated soil fertility and plant nutrition management improves not only crop yields but also soil chemical characteristics. Organic residues applied on a regular basis can result in a long-term increase in SOM and nutritional content. According to many research, Al complexation by freshly generated organic matter tends to diminish the quantities of exchangeable and soluble Al. Phosphorous is released as organic wastes degrade and can be adsorbed to oxide surfaces. This can lower the degree of adsorption of later additional phosphorous, improving Phosphorous availability. These processes have the practical implication that organic wastes can be employed as a strategic tool to minimize the rates of lime and fertilizer Phosphorous required for optimum crop development on acidic, P-fixing soils. Chala et al. [21] discovered that applying 50% FYM + 50% NP, 50% CC + 50% NP, and 50% VC + 50% NP to acid soil in Ethiopia's central highlands enhanced teff production by 93.1, 100.9, and 151%, respectively, when compared to the control (Table 11). The same rates resulted in increases in soil pH, TN, P, and OC. Generally, the aforementioned results indicate that integrated use of nutrient sources have significant improvement in the overall condition of the soil as well as crop productivity if best alternative option is adopted in the area.

Table 9. *Effects of combine organic and inorganic fertilizers on selected chemical properties of acidic soil.*

Treatment	Rate	pH	Ex. Ac	Ex. Al	CEC	P	PAcs	PAl
			cmolc kg^{-1}			mg kg^{-1}		%
Control	0	4.89	2.22	1.28	25.7	5.7	8.6	5.0
Lime (tons $CaCO_3$ ha^{-1})	3.5	5.15	0.85	0.13	25.8	5.8	3.3	0.5
	7.0	5.43	0.35	0.09	26.1	6.3	1.3	0.3
	9.2	5.63	0.23	0.07	26.4	6.5	0.91	0.3
	11.2	6.03	0.14	0.07	26.4	6.8	0.5	0.3
Wood ash (tons $CaCO_3$ ha^{-1})	3.5	5.16	0.78	0.12	25.9	9.0	3.0	0.5
	7.0	5.42	0.35	0.10	26.1	9.4	1.3	0.4
	9.2	5.66	0.19	0.08	26.2	9.8	0.7	0.3
	11.2	5.93	0.16	0.06	26.3	10.2	0.6	0.2
Manure P (kg ha^{-1})	32.5	4.97	1.90	0.90	26.0	7.1	7.3	3.5
	65.0	4.98	1.74	0.72	26.2	7.8	6.6	2.7
	130.0	5.03	1.32	0.45	26.1	9.9	5.1	1.7
Mineral P (kg ha^{-1})	32.5	4.88	2.22	1.27	25.9	7.0	8.6	4.9
	65.0	4.90	2.17	1.28	26.2	8.0	8.3	4.9
	130.0	4.96	2.13	1.25	26.6	10.7	8.0	4.7
Mineral P (kg ha^{-1}) plus lime (7 tons $CaCO_3$ ha^{-1})	32.5	5.58	0.27	0.09	25.8	7.1	1.0	0.3
	65.0	5.67	0.23	0.08	25.7	8.1	0.9	0.3
	130.0	5.61	0.22	0.09	25.8	10.2	0.9	0.3
Manure P (kg ha^{-1}) plus lime (7 tons $CaCO_3$ ha^{-1})	32.5	5.57	0.31	0.09	26.4	7.0	1.2	0.3
	65.0	5.64	0.20	0.10	26.7	7.6	0.8	0.4
	130.0	5.71	0.12	0.09	26.5	8.9	0.5	0.3
Mineral P (kg ha^{-1}) plus wood ash (7 tons $CaCO_3$ ha^{-1})	32.5	5.53	0.31	0.08	25.9	10.6	1.2	0.3
	65.0	5.56	0.24	0.09	25.9	11.6	0.9	0.3
	130.0	5.52	0.22	0.08	26.0	14.0	0.8	0.3
Manure P (kg ha^{-1}) plus wood ash (7 tons $CaCO_3$ ha^{-1})	32.5	5.62	0.32	0.07	25.7	10.3	1.2	0.3
	65.0	5.64	0.20	0.09	25.8	11.4	0.9	0.3
	130.0	5.62	0.15	0.07	26.4	13.4	0.6	0.3

Source: [39].

Table 10. *The effect of integrated application of FMY and inorganic fertilizers on tuber yield of potato at chencha.*

Treatments	Mean yield (q/ha)	
	2007	2008
$N_0P_0K_0$ + 0 Lime	79.6_h	40.6_f
$N_{110}P_{40}K_0$ + 0 lime	117.7_{efg}	40.2_f
$N_{110}P_0K_{100}$ + 0 lime	108.2_{fgh}	42.1_f
$N_0P_{40}K_{100}$ + 0 lime	227.2_c	161_c
$N_{110}P_{40}K_{100}$ + 0 lime	349.3_b	268.8_b
N_0PK_0 + 1.75t/ha	91.2_{gh}	38_f
$N_{110}P_{40}$ + 1.75	142.5_{def}	63.8_{ef}
$N_{110}P_0K_{100}$ + 1.75	144.3_{de}	125.8_{cd}
$N_0P_{40}K_{100}$ + 1.75	288.5_c	158_c
$N_{110}P_{40}K_{100}$ + 1.75	372.1_b	280.2_b
$N_0P_0K_0$ + 3.5t/ha	102.5_{gh}	52.0_f
$N_{110}P_{40}$ + 3.5t/ha	148.1_{de}	$74.0d_{ef}$
N110P0K100 + 3.5t/ha	159.5_d	117.8_{cde}
$N_0P_{40}K_{100}$ + 3.5t/ha	277.2_c	247.2_b
$N_{110}P_{40}K_{100}$ + 3.5t/ha	410.0_a	346.2_a
LSD(0.05)	8.6	6.4
CV (%)	10.5	24

Source: [33].

Table 11. *Mean GY of maize in kg/ha as influenced by application of lime-NPK in acidic soil.*

No.	Treatment	1st year (2007)	2nd year (2008)	3rd year (2009)
1	Control (without fertilizer and lime)	2847.2	3015.5	2661
2	No fertilizer and 900 kg lime/ha	2708.3	2851.1	2662
3	No fertilizer and 1800 kg lime/ha	2968.8	3094.8	2324
4	69 kg N + 20 kg P + 0 lime/ha	3802.1	4722.0	4015
5	69 kg N + 20 kg P + 900 kg lime/ha	4513.9	4715.8	5562
6	69 kg N + 20 kg P + 1800 kg lime/ha	5034.7	5160.0	7033
7	69 kg N + 75 kg K + 0 lime/ha	2517.4	2815.5	2995
8	69 kg N + 75 kg K + and 900 kg lime/ha	2152.8	2421.5	4639
9	69 kg N + 75kg K + 1800 kg lime/ha	3437.5	4041.4	3725
10	20 kg P + 75 kg K+ 0 lime/ha	3576.4	3679.5	3333
11	20 kg P + 75 kg K+ and 900 kg lime/ha	3784.7	3935.5	5297
12	20 kg P + 75 kg K+ 1800 kg lime/ha	4097.2	4133.4	3541
13	69 kg N + 20 kg P + 75 kg K + 0 lime/ha	3750.	3862.9	3625
14	69 kg N + 20 kg P +75 kg K + and 900 kg lime/ha	3750.0	3810.2	3225
15	69 kg N + 20 kg P + 75 kg K 1800 kg lime/ha	4340.3	4445.3	4473

5.3. Management of Acid Soils Using Acid Tolerant Crop Varieties

Several researchers across the globe have concentrated their efforts over the last decade on discovering and defining the mechanisms utilized by agricultural plants to endure Al hazardous levels in acid soils. There are two types of Al tolerance mechanisms: those that prevent Al from entering the root apex and those that allow the plant to tolerate Al buildup in the root and shoot system. Although there has been much conjecture regarding a variety of Al tolerance mechanisms, the majority of experimental data has focused on root Al exclusion based on Al-activated organic acid exudation from the root apex. Evidence for a second tolerance mechanism based on internal detoxification of symplastic Al via complexation with organic ligands, especially OAs, is also growing [36, 42].

A large number of economically important plant species are typically thought to be acid soil resistant. Many of them have their origins in acidic soil locations, suggesting that adaptation to soil restrictions is part of the evolutionary process. Although the species as a whole does not survive acid soil, some variants of particular species do. Tolerance to high amounts of Al or Mn, as well as shortages in Ca, Mg, P, and other nutrients, is quantified in plant tolerance to acid soil stressors. It has been shown that tolerance to Al and Mn varies greatly between species and genotypes within a species. It is critical to pick varieties or species that function well at high Al saturation levels and hence require only a fraction of the regular lime requirement [36, 46].

Barley is mostly cultivated on Nitisols in Ethiopia's highlands, where soil pH is low. This suggests that barley has already adapted to acidic soil. With this information, five released barley varieties were assessed on acidic soils at Endibir under limed and unlimed conditions. Under limed conditions, barley cultivars (HB-42 and Dimtu) fared well, with yield increments of 366 and 327 percent, respectively, over the comparable yields of the same barley types under unlimed conditions. In contrast, barley varieties (HB-1307 and Ardu) fared better in unlimed conditions, with yields of 48 and 49 percent lower than the comparable yields of the same barley types under limed conditions (Table 12).

Table 12. *Effects of organic and inorganic amendments on the growth of chickpea in acidic soil.*

No.	Treatments	GY (kgh^{-1})
1	control	1253
2	Conventional Compost (CC)	1941
3	Farmyard manure (FYM)	1920
4	Vermi-Compost (VC)	1904.7
5	50% VC + 50% CC	2027.3
6	50% VC + 50% FYM	1933.5
7	33% VC + 33% CC + 33% FYM	2293
8	50% VC + 50% NP	3144.8
9	50% CC + 50% NP	2516.7
10	50% FYM + 50% NP	2420
11	Recommended NP	2846

Source: [21].

Table 13. *Performance of five released barley varieties and one local check under limed and un-limed conditions.*

Variety	Grain yield (kg ha^{-1})		Yield increment (%)
	Limed	unlimed	
HB-42	1752	376	366
Shegie	1690	982	72
local	1933	1189	63
HB-1307	2162	1459	48
Ardu	2020	1355	49
Dimitu	1818	426	327

Source: [5].

6. Conclusion

Soil acidity is a natural process that is influenced by factors such as climate, terrain, vegetation, parent material, and excessive rainfall. It is one of the primary problems limiting and preventing lucrative and long-term agricultural output in many regions of the world, including Ethiopia. The goal of this study is to analyze the soil acidity issue to crop production in Ethiopia's highlands, as well as strategic management options for minimizing soil acidity and increasing crop yield. Soil acidity is currently predicted to harm around 40.9 percent of Ethiopia's total arable land, which covers 95 percent of cultivated area and nearly 85 percent of the Ethiopian population. Around

27.7 percent of these are moderate to weak acids with pH 5.8-6.7 and 13.2 percent are strong to moderate acidic soils with pH less than 5.5.

Crop production can be reduced by acidic soil. According to the Ethiopia soil information system, soil acidity affects around 43 percent of Ethiopian arable land, with highly acid soils accounting for approximately 28.1 percent of Ethiopian soils (pH 4.1-5.5). Soil acidity has a negative impact when the pH of the soil goes below 4.5. The two main reasons limiting acid soil fertility are P, Ca, and Mg deficiency and Al phytotoxicity. Liming, the use of organic materials as integrated soil fertility management, and the adoption of crop types resistant to Al toxicity are some of the management alternatives for acid soils. Liming has the capacity to lessen toxicity effects by lowering their concentrations while boosting the availability of plant nutrients such as P, Ca, Mg, and K in the soil and decreasing heavy metal solubility and leaching. Because of its high concentration of alkaline cations such as Ca, Mg, and K, which were freed from OM during mineralization, OM treatment has a liming effect.

Soil organic matter raises soil pH and helps with soil acidity amendments. Soil acidity issues can also be solved by cultivating genotypes that are suited to acid soil conditions in situations when other soil amendment procedures are impractical. Liming, the use of integrated soil fertility management, and crop cultivars resistant to Al toxicity are the methods utilized for acid soil management in Ethiopian small-scale farming and should be shown and marketed on farmers' fields.

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