Agriculture, Forestry and Fisheries
2024, Vol. 13, No. 2, pp. 31-45
https://doi.org/10.11648/j.aff.20241302.13

Research Article

A Review on the Impact of Soil Acidification on Plant Nutrient Availability, Crop Productivity, and Management Options in the Ethiopian Highlands

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Abstract

Soil acidity is a type of soil deterioration that has a negative impact on Ethiopia's overall and Western Oromia's specific sustainable agricultural production. Currently, soil acidity in highland portions of Western Oromia, including Gimbi, Nedjo, and surrounding areas, is a major problem that can impede agricultural productivity. Reviewing the mechanisms of soil acidification, which can affect soil nutrient availability and agricultural production, as well as management choices, were done in this context for this review topic. The main causes of acid soils are leaching of exchangeable basic cations and topsoil erosion caused by high temperatures and heavy rains, which promote the loss of organic matter the most. In most of Ethiopia's highland regions, the removal of agricultural waste and ongoing use of inorganic fertilizers that produce acidity are major factors in the development of soil acidity. Al and Mn toxicity are caused by acid soil, which also reduces nutrient availability. Furthermore, agricultural yield decreases due to acidity in the soil. The management options for acid soils include crop types resistant to Al toxicity, liming, and the use of organic materials as integrated forms of soil fertility control. Therefore, lime and organic fertilizers should be employed as crucial agricultural techniques for small-holder farmers in acidic soil locations in order to decrease the effects of soil acidity.

Keywords

Soil Acidity, Liming, Nutrient Availability

1. Introduction

Soil acidity is one of the primary soil degradation processes that impacts 50% of the world's potentially arable soils and approximately 30% of the world's total land area [1]. Soil acidity affects large parts of Ethiopia's highlands, which are spread throughout almost all of the country's regional states. According to Karltun [2], highly acid soils (pH 4.1–5.5) account for around 28.1% of Ethiopia's soils, and about 43% of the country's arable area is impacted by soil acidity. Because of the potential for Al, Fe, Zn, and Mn toxicities as well as Ca, Mg, P, and molybdenum (Mo) deficits, very acidic soils are often unsuitable for cultivation [3, 4]. Since acidic cations like aluminum, manganese, iron, and hydrogen activity are hazardous to plants, acid soils are phytotoxic because they deprive plants of vital minerals including calcium, magnesium, molybdenum, and phosphorus. This indicates that the majority of acidic soils have

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Received: 29 January 2024; **Accepted:** 29 February 2024; **Published:** 2 April 2024

subpar physical and chemical characteristics, which may make nutrients less available. As per Osundwa [5, 6], it restricts the accessibility of vital nutrients for plants, including P, Mo, Ca, Mg, and K. It results in a drop in soil pH, which can eventually lower crop productivity by lowering cation exchange capacity, losing soil fertility, and so on. This demonstrates the extent to which agricultural productivity is being jeopardized by soil acidity, hence decreasing food security, especially in the highlands of Ethiopia where soil acidification processes are more likely to occur [7]. According to Tessema [8] and Melese and Yli-Halla [9], reduced yields, poor crop growth, poor nodulation of legumes, stunted root growth, the persistence of acid-tolerant weeds, increased incidence of diseases, and abnormal leaf colors are some of the major symptoms that indicate a problem with soil acidity (pH below 5).

Elevated rainfall that washes organic matter and basic cations away through soil erosion and leaching, overgrazing, and complete removal of crop residues from crop fields are the main causes of the aggravated soil acidity in Ethiopia's highlands [10, 11]. The replacement of basic elements retained by soil colloids by acidic cations cause's soils to become acidic. These elements include calcium, magnesium, sodium, and potassium. Bases can be eliminated by artificial methods like heavy fertilizer application including ammonium and unceasing cropping without the use of organic inputs, or by natural processes like leaching brought on by rainfall. While urea and diammonium phosphate have been used repeatedly over many years as an element that promotes soil acidity, Ethiopian soils have received minimal amounts of inorganic fertilizers applied [12, 13]. This would suggest that one of the main obstacles to obtaining sustainable production and ensuring food security is soil acidity and the resulting limited nutrient availability. The essential component continuing to raise and maintain agricultural yields is the health and fertility of the soil, which is necessary to meet the growing demand for food and raw resources. In order to enhance agricultural output, this calls for appropriate use of understanding of soil acidity and its amelioration procedures. To achieve sustainable levels of agricultural output, it is therefore essential to research appropriate management strategies. To solve these problems in the nation's highlands, a number of strategic programs for managing soil acid have been developed. Numerous investigations have been conducted about soil management, which affects agricultural yield and the physiochemical characteristics of the soil in different ways. Therefore, this seminar's goal was to examine the mechanisms of soil acidity that affect nutrient availability and agricultural output, as well as management strategies for reducing it in the highlands of Ethiopia.

2. Methodology of Review

This seminar aimed to contribute to current theories and literature on soil acidity through extensive literature searches and secondary sources such as books, scholarly journal articles, magazine articles, newspaper articles, and technical reports. A review question was created to guide the discussion and maintain focus on the issue. Important notes were gathered logically and based on outlines. The seminar paper also benefited from the advisor's advice on science. The information on the impact of soil acidity on crop productivity and nutrient availability, along with management alternatives, is discussed in Chapter 3.

3. Discussion and Literature Review

3.1. The Nature of Soil Acidification

Soil acidity is linked to the exchangeable forms of aluminum and hydrogen. The idea was developed in relation to the behavior of aqueous solutions, which are defined as acidic when large amounts of hydrogen ions (H^+) are produced, more than hydroxyl ions, and interact with clay particles to release aluminum, which then produces more H^+ ions. The clay minerals easily adsorb aluminum and hydrogen, which allows Ca^{2+}, Mg^{2+}, and a K^+ ion to be leached from the soil by percolating water and causes shortages in those ions [14]. Because of losses from leaching and crop removal of such basic elements as calcium, magnesium, and potassium, most soils in wet places are acidic or "sour," whereas soils in arid or desert regions are often alkaline. [15].

Global food production has significant challenges due to soil acidity, which is defined as pH levels less than 5.5 [16]. Because critical minerals like calcium, magnesium, molybdenum, and phosphorus are unavailable in acidic soils, and because aluminum, manganese, and hydrogen activity are hazardous, acidic soils are phytotoxic [17]. One specific management issue is aluminum toxicity, which mostly happens when the pH of the water is lower than 5.0. According to Deressa [18], intensive farming and ongoing use of acid-forming inorganic fertilizers are to blame for the rising trend of soil acidity and exchangeable Al^{3+} in arable and abandoned areas.

3.2. Extent and Distribution of Acid Soils in Ethiopia

In the western region of Ethiopia, one of the main obstacles to maintaining agricultural productivity and output is soil acidity, which poses a major risk to crop yield. According to Tegbaru [19], strong soil acidity affects 43% of agricultural land and 28% of the country overall, mostly in the highlands of Oromiya, Amhara, and the Southern Nation Nationalities and Peoples area. Both the most fertile and most acidic regions of Ethiopia are found in the southwest of the nation. Gimbi, Nedjo, Hosanna, Sodo, Chencha, Hagere-Mariam, Endibir, and the Awi Zone of the Amara regional state are among the regions that are known to be negatively impacted by soil acidity [20]. Elias [21] further proposed that the main source of fertility problems and barriers in Ethiopia's north-central and south-western highlands is acidic soil response, which causes the soils to become more depleted and infertile due to poor management.

It is becoming more widespread and intense in Ethiopia, where it can range from mildly acidic to drastically reducing crop yield [22]. Deressa [18] reported that soils from several districts in the West Wollega, East Wollega, and West Showa zones had pH values that were outside of the typical range needed for agricultural cultivation. A small number of the soils are moderately to slightly acidic, while the majority are extremely highly acidic [18]. The availability of vital nutrients is severely impacted by such a low pH. Aluminum's toxicity to plants has a significant impact on nutrient and water absorption, as well as root and shoots development.

The state of the acidity of the Nitisols found in western and central Ethiopia was assessed in 2006 using an inventory. The findings showed that all samples were acidic, but to varying degrees depending on the region [17]. Over 80% of landmasses that originated from nitisols are thought to be acidic in nature, partially due to the leaching of basic cations. Nitisols are the principal soil groups dominated by acidity [23]. Elisa [21] has observed that eighty percent of the Nitisols and Luvisol subgroup soils found in Ethiopia's north-central and south-western highlands have a pH of 4.5–5.5, making them extremely strong to severely acidic. Acidic parent material, which is found in heavy rainfall locations linked to nitisols and cambisols, is often the source of acrisol. Moderate to steep slopes are home to these soil types.

3.3. Main Causes of Soil Acidity

Acidic soil is created by a complicated series of events known as soil acidification. It can be interpreted, in the widest sense, as the culmination of both man-made and natural processes that reduce the pH of soil solutions [24]. The problem is made worse by anthropogenic causes such as monocropping, improper land use systems, nutrient mining, and insufficient nutrient supplies [20].

3.3.1. Rainfall and Leaching

The primary factor for basic cations to be leached out over an extended length of time is heavy rainfall. As a result, the hazardous and insoluble Al and Fe compounds may remain in the soil, worsening its acidity [25]. Because of the acidic nature of these compounds, soil solutions containing their oxides and hydroxides react with water to release hydrogen (H^+) ions, which turns the soil acidic. Furthermore, the basic cations of the colloidal complex are replaced when the soluble bases are lost by the (H^+) ions of carbonic acid and other acids that have evolved in the soil. The soil eventually loses its exchangeable bases due to continuous leaching, which causes it to become de-saturated and more acidic. Because it speeds up the leaching of bases, rainfall is most effective at turning soils acidic when it percolates through the soil profile [26].

Soil acidification caused by agriculture is primarily caused by the leaching of nitrogen in the nitrate form. When organic matter or ammonium forms of nitrogen break down in the soil, nitrate nitrogen is created. The process by which fertilizer and organic materials are converted chemically into nitrate nitrogen makes the soil somewhat more acidic. Plants absorb nitrate nitrogen and, to a lesser extent, convert it to nitrogen gas, which neutralizes the acidity [27]. Plants also discharge an alkaline material during this process.

3.3.2. Parent Material

Soil acidity and alkalinity are determined by the sorts of rocks that are used to produce land. Stones such as granite and rhyolite are classified as acid rocks because they have higher concentrations of quartz or silica relative to other basic minerals or elements. Because worn granite is more acidic than shale or limestone, the soils formed from it are probably more acidic [28]. The majority of acidic soils, however, are the consequence of crop base removal and leaching losses. According to Abbaslou [29], the origin and makeup of the parent materials affect the intrinsic fertility of Ethiopian soils that were created under a variety of climates and parent materials.

3.3.3. Application of Ammonium Fertilizers

Acidity of the soil ultimately rises with continuous use of inorganic fertilizer without soil testing and amendments. Acidification can occur as a result of applying N fertilizers in the form of ammonia [30]. Although acidity results from the use of ammonium fertilizers, crop N removal is similar to fertilizer N. Fertilizers based on urea ($CO(NH_2)_2$), ammonia (NH_4), and proteins (amino acids) in organic fertilizers can all include hydrogen. Acidity in soil is produced when such sources of N fertilizers are converted into nitrate (NO_3), which releases hydrogen ions (H^+). According to Guo [31], N fertilizer actually makes soil more acidic by raising crop yields, which in turn increases the quantity of basic elements harvested by crop harvest without being incorporated.

Urea, the most extensively used fertilizer in Ethiopia [32], can raise soil acidity by enhancing the release of H^+ [33]. Long-term use of this fertilizer to arable fields may also promote the development of eutrophication in freshwater resources [34]. Acid soils may require more fertilizer to achieve desired crop output due to lower nitrogen usage efficiency [35, 36].

Diammonium phosphate (DAP) is a popular fertilizer in the region that provides P, a limited nutrient [32, 37]. Crops typically absorb only 15-20% of sprayed P [37]. Furthermore, phosphorus is strongly immobilized in acidic soils and less accessible to plants, meaning that a larger amount of P-containing fertilizer may be necessary to provide the plant with optimal nutrients. The remaining majority can be stored in the soil, where it is less likely to seep into other ecosystems such as fresh water [38]. The destiny of this long-term accumulation of P is undetermined, however it is likely that it will be reused around 46 times [37], this may not hold true for all soil types [39]. To correct this condition; reducing soil acidity should be the first focus when suggesting optimal fertilizer usage.

In agricultural systems, nitrogen can be fixed from the atmosphere by legumes, degraded from soil organic matter (dead plant and animal remnants) by soil organisms, or given to various forms of fertilizers. Different nitrogen fertilizers break down in the soil in somewhat different ways, contributing varying quantities of hydrogen ions (acid). Fertilizer nitrogen that enters and exits the system in the same form, such as potassium nitrate, does not contribute to soil acidification. Ammonium-based fertilizers are substantial contributors to soil acidity, which is exacerbated by leaching. The end consequence is a net increase in hydrogen ions. If plant roots absorb a negatively charged nitrate ion, they emit a negatively charged hydroxide ion to maintain electrical equilibrium. The hydroxide ion reacts with a hydrogen ion in the soil to generate water (the hydrogen ion no longer contributes to soil acidity). If the plant absorbed potassium nitrate, there would be a liming effect since the fertilizer did not give hydrogen ions to the soil. If this nitrate ion leached, there would be no liming action and no soil acidification as shown in Figure 1.

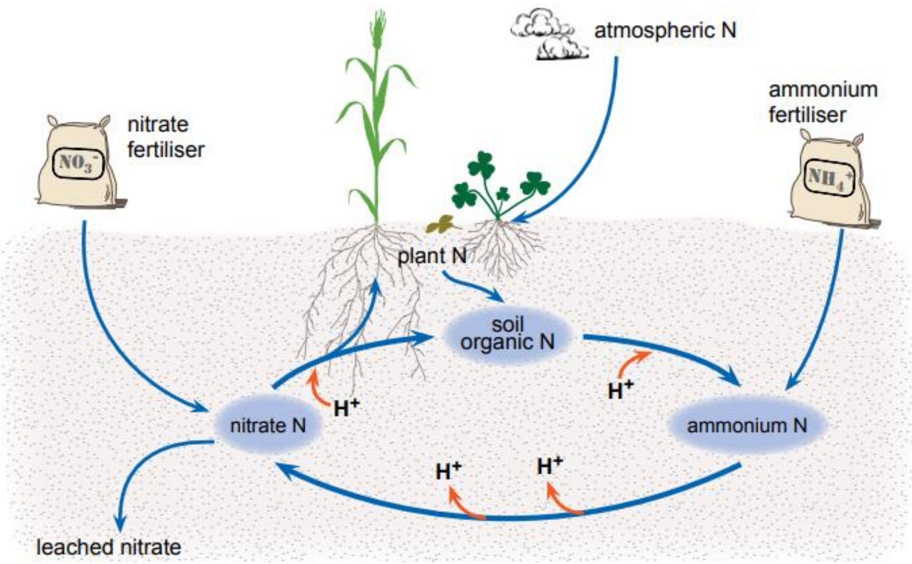


***Figure 1.** The main pathways showing the involvement of nitrogen (N) fertilizers in soil acidification.*

3.3.4. Decomposition of Organic Matter

According to Sosena and Sheleme [40], humus materials are the end product of the microbial breakdown of organic matter in soils. They are composed of several functional groups, such as carboxylic (-COOH), phenolic (-OH), and others, which have the ability to attract and dissociate hydrogen ions. Although H^+ ions are produced during the breakdown of organic matter and are the cause of acidity, the short-term effects of this process on soil acidity are negligible [10].

Carbonic acid is created when water in the soil combines with carbon dioxide (CO_2), which is released during the decomposition of organic waste. When CO_2 in the atmosphere combines with precipitation to naturally create acid rain, the resulting acid is the same. While organic matter decomposes, it also produces a number of weak organic acids. Analogously to precipitation, decomposing organic matter typically makes up very little of the contribution to acid soil formation, and the impacts of years' worth of accumulation would be the only ones that could ever be evaluated in a field [41].

3.3.5. Removal of Mineral Elements Through the Harvest of High-Yielding Crops

The loss of elements from soils due to high-yield crop harvesting, especially in soils with a limited reservoir of bases, is what causes soil acidity. Soil disturbance caused by mechanical work upsets the balance and increases the acidity of the soils when crops are put on it. Brady and Weil [24] explain that this is the result of base cations being removed with crops and the simultaneous increase in leaching brought on by soil disturbance and activities. Harvesting high-yielding crops is the main factor contributing to the increasing acidity of the soil. Throughout their growth, crops absorb essential minerals such as calcium, magnesium, and potassium to satisfy their nutritional demands.

As crop yields increase, more of these lime-like fertilizers are being withdrawn from the field. The development of soil acidity is influenced by the absorption of lime-like components by harvested crops, which serve as cations for nutrition [42].

Diressie [43] claims that some fundamental materials necessary to balance the acidity produced by other processes are lost during the disposal of agricultural remnants and/or the harvesting of these crops from the field. As a result, the acidity of the soil eventually rises. Greater removal of essential material will follow from increasing agricultural production.

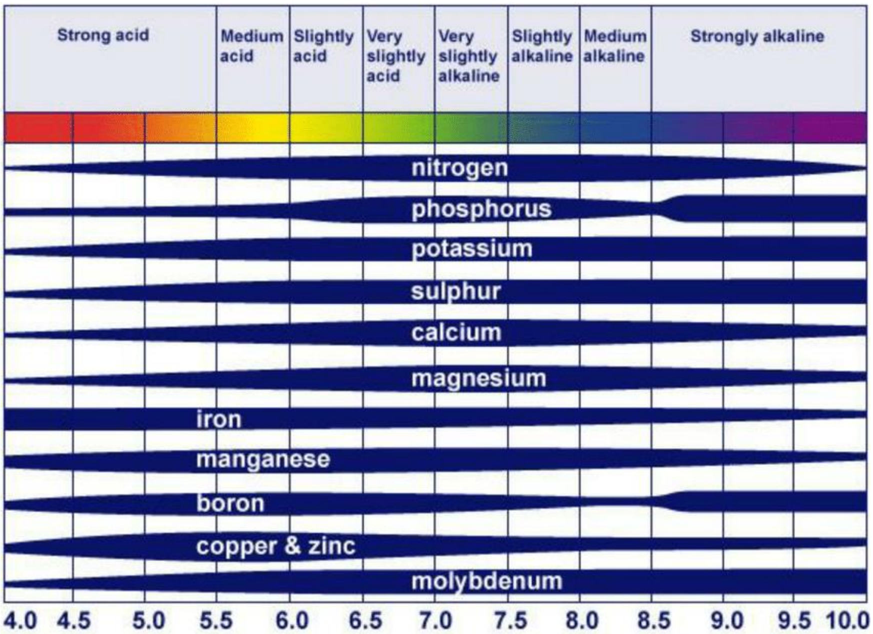
3.4. Effect of Soil Acidification on Plant Nutrient Availability

For plants, the availability and solubility of vital nutrients are greatly influenced by the pH of the soil. It is easy to make phosphate ($PO4^{-3}$) unavailable to plant roots in soils with pH values below 5.5 since it is the most immobile of the key plant nutrients. According to Marschner [44], crop yields in these kinds of soils are so frequently rather low. It may be possible to prevent toxicity and shortages in iron and magnesium if the soil reaction is maintained between pH values of 5.5 to 7, which seem to promote the simplest availability of plant nutrients. Increased acidity of the soil causes an excess of soluble nutrients and a shortage of readily available calcium, phosphorus, and magnesium. According to Tadele [44], there is an imbalance between the quantity of accessible Ca, P, and Mo and the amount of soluble Al, Mn, and other metallic ions caused by elevated soil acidity. Not only does acidic soil hinder the movement of soil organisms that plants need for optimal health, but it also makes important minerals like $PO4^{-3}$, K^{2+}, Ca^{2+}, and Mg^{2+} less accessible. The main cause of the detrimental effects of acidity on plant growth and productivity, according to Guo [31], is phosphorus deficiency. This is caused by iron, manganese, and aluminum toxicity, conversion to insoluble Al and/or Fe compounds, and adsorption of P into colloidal fractions.

P fertilizer input may cause Al and Fe phosphates to precipitate at extremely low soil pH values (≤4.5–5.0). P concentrations in soil solutions are, however, mostly controlled by particular adsorption processes in many cases. It is thought that soils with pH values between 6.0 to 7.0 which are the range that popular field crops like, will have the optimum nutrient availability and crop yields [44].

There is a strong correlation between the function of pH and the availability of macro- and micronutrients, which are critical plant nutrients. The macronutrients that are more easily accessible in a pH range of 6.5-8 include nitrogen (N), calcium (Ca), potassium (K), magnesium (Mg), sulfur (S), and with phosphorus being the exception. However, the micronutrients are accessible at a pH of 5-7, which is somewhat acidic. These are the ideal ranges where plants may access nutrients in suitable amounts. Outside of these pH levels, availability becomes less uncommon. Cations are firmly bound to the soil and are not easily exchangeable when the pH rises and approaches 8. As a result, in alkaline circumstances, the availability of micronutrients decreases with the exception of molybdenum.

Furthermore, at lower pH values, the nutritional elements Fe, Cu, Mn, Zn, and Ni are more easily accessible due to their tight binding at alkaline pH levels. In acidic soils, this can cause toxic symptoms in plants. The pH of the soil affects the nutrients that are available to plants (Figure 2). The main plant nutrients nitrogen, phosphorus, potassium, sulfur, calcium, manganese, and the trace element molybdenum are less readily available and may not be present in adequate amounts in acidic soils. Acidic soils have higher concentrations of iron, manganese, copper, zinc, and aluminum.



Source: [46].

Figure 2. *Nutrient availability based on soil pH.*

There is a substantial variation in soil pH, total nitrogen, and accessible phosphorous among the five sample locations before and after liming, as indicated in (Tables 2 and 3), according to study on the impact of soil acidity on plant nutrient availability conducted by Dinkecha [47]. In contrast, there is no discernible variation in soil organic matter at ($P < 0.05$). Prior to liming, the soil pH of the Gefersa Minjaro, Gutu, and Gudu sample sites differs significantly from those of the Minjaro and Kore sample sites at ($P < 0.05$). All other sample sites show no significant differences in pH. Between the GM, Gutu, and Kore sample sites as well as between the Minjaro and Gudu sample sites, there was no discernible variation in exchangeable acidity. Available phosphorus concentration differs significantly between the Kore sample site and the other sample sites, however there is no discernible variation between the GM, Gudu, and Minjaro sample sites. Still, there were a lot of parallels between the GM and Gutu sites (Table 1).

Table 1. *Before liming, several acidic soil characteristics were compared across various sample sites.*

Sample site	pH (H_2O)	pH (KCl)	EA (Cmol/Kg)	EA (Cmol/Kg)	LR (g/Kg)	%OC	%TN	AP (ppm)
Minjaro	4.67^{ab}	3.83	3.820^{a}	2.17^{a}	2.317^{d}	1.227^{a}	0.227^{ab}	12.97^{ab}
GM	4.69^{a}	3.87	3.377^{c}	1.98^{ab}	2.350^{d}	1.233^{a}	0.203^{b}	15.31^{a}
Gutu	4.38^{b}	3.53	3.513^{b}	1.81^{ab}	2.733^{b}	1.247^{a}	0.230^{ab}	13.017^{ab}
Kore	4.25^{c}	3.46^{b}	3.443^{bc}	1.94^{a}	2.900^{a}	1.257^{a}	0.220^{ab}	10.527^{b}
Gudu	4.37^{b}	3.56^{b}	3.697^{ab}	2.12^{a}	2.517^{c}	1.227^{a}	0.233^{a}	13.963^{a}
Mean	4.51	3.68	3.6	2.0	2.58	1.22	0.21	13.15
CV	2.43	2.17	12.49	9.36	1.98	9.64	6.40	10.28
LSD<0.05	0.188	0.139	0.167	0.235	0.096	Ns	0.027	0.340

Source: [47]

Acid soils are ideal for disrupting the movement of soil organisms that plants require for health, as well as the growth and production of crops, because they lead to nutritional disorders, deficiencies or unavailability of essential plant nutrients like calcium, magnesium, molybdenum, and phosphorus, and the toxicity of aluminum, manganese, and hydrogen ions in the soil [49-51]. Thus, this study may demonstrate the impact of acidic soil on plant nutrition availability.

The five sample locations' soil pH, total nitrogen, and accessible phosphorus after liming varied significantly, according to the results of the ANOVA test by Dinkecha [47] in (Table 2). While the pH of the Monjaro, GM, and Gutu sample sites does not differ significantly from each other, the pH content of the Kore and Gudu sample sites does differ significantly, while the GM and Gudu sample sites do differ significantly from each other. There is a noticeable variation in the exchangeable acidity concentration across all sample locations. The OC content of the GM and Gudu sample sites does not significantly differ from that of the Gutu and Kore sample sites; however the OC content of the Minjaro sample site differs significantly from that of the other sample sites. The available phosphorus concentration varies significantly across all study locations according to the study (Table 2).

Table 2. *Comparison of several acidic soil characteristics following liming at various sample locations.*

Sample site	pH (H_2O)	pH (KCl)	EA (Cmol/Kg)	EA (Cmol/Kg)	%OC	%TN	AP (ppm)
Minjaro	6.81^{b}	6.17^{b}	0.25^{d}	0d	1.14^{c}	0.24^{a}	20.66^{d}
GM	6.97^{a}	6.29^{ab}	0.84^{b}	0.14^{b}	1.24^{ab}	0.17^{a}	23.39^{c}
Gutu	7.11^{a}	6.31^{a}	0.69^{c}	0.083^{c}	1.26^{a}	0.18^{a}	26.08^{b}
Kore	7.04	6.23^{ab}	0.77^{bc}	0.16^{b}	1.26^{a}	0.23^{a}	27.06^{ab}
Gudu	6.91^{ab}	6.19^{a}	1.10^{a}	0.23^{a}	1.21^{b}	0.24^{a}	28.09^{a}

Sample site	pH (H_2O)	pH (KCl)	EA (Cmol/Kg)	EA (Cmol/Kg)	%OC	%TN	AP (ppm)
Mean	6.98	6.23	0.78	0.122	1.23	0.22	24.98
CV	0.44	0.39	1.72	2.17	0.86	24.49	2.66
LSD<0.05	0.097	0.074	0.037	0.279	0.029	Ns	1.872

Source: [47]

As demonstrated in Tables 1 and 2, this study indicates that the lime effect caused exchangeable acidity and exchangeable Al to decrease from (3.6 to 0.78) and (2.0 to 0.122 Cmol/kg); in contrast, pH (H_2O), OC, TN, and AP increased from 4.51 to 6.98, 1.22 to 1.23%, 0.21 to 0.22%, and 13.15 to 24.98 ppm, respectively. In line with Birhanu Agumas's [48] study, the study found that lime was impacted by acidic soil and nutrient availability.

Likewise, five soil samples compared in micronutrients and exchangeable cations across various sample locations prior to liming, and they differ significantly in terms of their Ca, CEC, Cu, Fe, and Zn contents, according to an ANOVA test by Dinkecha [47]. (2019) (Table 3). Manganese, potassium, and sodium, on the other hand, do not exhibit appreciable variations. In each of the five sample sites, the patterns for calcium and CEC are comparable. The Ca and CEC concentrations of sample sites Gudu and Minjaro do not differ significantly from one another; however there are considerable variances between the other sample sites and between Gudu and Minjaro. Fe contents at sample sites GM, Gutu, Minjaro, and Gudu do not differ significantly from one another; nevertheless, there is a considerable difference between sample sites Kore and the remaining sample sites. While sample sites Minjaro, Kore, GM, and Gutu do not exhibit a significant variation in Cu concentration, sample site Gudu does exhibit a significant difference in Cu content from the other sample sites. There are notable variations in the Zn concentration across all sample locations. While sample sites Kore exhibit variances in their metal contents, GM and Gutu, Minjaro, and Gudu exhibit commonalities in the majority of their metal contents according to the study by Dinkecha [47]. (Table 3).

Table 3. *Comparison of the metal components in the five distinct locations prior to liming.*

Sample sites	Exchangeable Cation (ppm)					Micronutrient (ppm)			
	Na	K	Ca	Mg	CEC	Cu	Fe	Mn	Zn
Minjaro	1.47^{a}	5.6^{a}	24.77^{c}	13.91^{a}	107.6^{cd}	6.37^{a}	208.46^{a}	108.5^{a}	2.61^{b}
GM	1.10^{a}	6.0^{a}	21.27^{d}	11.49^{b}	97.93^{d}	4.69^{bc}	192.61^{c}	117.3^{a}	2.37^{c}
Gutu	1.17^{a}	5.6^{a}	27.5^{b}	13.74^{a}	127.9^{b}	4.57^{c}	192.93^{c}	109.8^{a}	1.98^{e}
Kore	1.23^{a}	5.4^{a}	3.63^{a}	12.86^{ab}	142.2^{a}	6.057^{a}	202.34^{b}	101.7^{a}	2.70^{a}
Gudu	1.20^{a}	5.6^{a}	25.13^{c}	14.03^{a}	115.6^{c}	4.947b	206.26^{a}	106.1^{a}	2.23^{d}
Mean	1.234	5.44	25.86	13.21	118.246	5.24	204.52	108.68	2.38
CV	15.98	7.25	2.40	2.13	5.40	3.47	2.70	21.73	1.26
LSD<0.05	Ns	Ns	0.1168	0.127	1.2022	0.3476	2.624	Ns	0.07

Source: [47]

After liming, the research demonstrates once more how exchangeable cations and micronutrients vary. There is a significant change in the Ca, CEC, Cu, Fe, and Zn contents across the five soil sample locations following liming, according to Dinkecha [47] ANOVA test. Still, Table 4 shows that there were no statistically significant variations in sodium and potassium among the five sample locations. No discernible variation in the Ca concentrations is seen between sample sites Minjaro and GM, or between Gutu and Gudu; nevertheless, there is a significantly difference between sample site Kore and the remaining sample sites. Minjaro, Gutu, and Gudu are sample sites where there is no substantial variation in Ca concentration; however, GM and Kore exhibit a considerable difference. Gudu, Kore, and Gudu are the sample locations; there is no discernible variation in the amount of Cu present. The Fe concentration of sample sites Gudu, GM, and Minjaro does not differ significantly from that of the other sample sites; nevertheless, there is a significantly difference between Gutu and Kore and the remaining sites. The Minjaro, GM, Gutu, and Gudu sample sites do not significantly differ from one another, while the Kore sample sites significantly differ from the other sample sites. The Zn concentration of sample sites GM and Kore does not significantly differ from each other, however the Zn content of the remaining sample sites does significantly differ (Table 4).

This study illustrates the impacts of lime on soil mineral content availability and soil acidity on plant nutrition availability. The availability of micronutrients Cu (5.24 to 2.91), Fe (204.52 to 30.83), Mn (108.68 to 23.74), and Zn (2.38 to 1.84ppm) is decreased when soil acidity is reduced (Tables 3 and 4). Exchangeable cations Ca (25.86 to 140.9), Mg (13.20 to 36.41), and CEC (118.24 to 218.84) are increased. The results of the same soil pH obtained by Birhanu Agumas [48] and Achalu Chimdi [52] supported the effects of lime on acidic soil. The primary source of the negative effects of soil acidity on plant development and output is phosphorus shortage, which is brought on by P adhering to colloidal fractions, converting to insoluble Al and/or Fe compounds, and being poisonous to iron, manganese, and aluminum [31].

Table 4. *Comparison of the metal elements in ppm following liming at each of the five sites.*

Sample sites	Exchangeable Cation (ppm)					Micronutrient (ppm)			
	Na	K	Ca	Mg	CEC	Cu	Fe	Mn	Zn
Minjaro	10.7^{b}	15.6^{a}	153.4^{ab}	38.41^{a}	216.4^{ab}	2.94^{a}	21.07^{d}	26.1^{ab}	1.25^{d}
GM	11.0^{a}	14.2^{a}	165.9^{a}	38.93^{a}	207.0^{b}	2.52^{a}	25.03^{c}	23.40^{b}	1.52^{c}
Gutu	10.01^{a}	14.6^{a}	143.0^{bc}	35.78^{b}	208.0^{ab}	2.95^{a}	47.14^{a}	24.02^{b}	1.64^{b}
Kore	10.2^{a}	14.9^{a}	98.8^{c}	33.97^{bc}	235.1^{a}	3.14^{a}	36.29^{b}	17.15^{c}	1.52^{c}
Gudu	12.0^{a}	15.4^{a}	143.4^{bc}	34.94^{b}	227.0^{ab}	3.01^{a}	24.63^{cd}	28.06^{a}	2.27^{a}
Mean	10.98	14.94	140.9	36.41	218.84	2.91	30.83	23.74	1.84
CV	10.68	8.86	3.97	7.19	4.12	2.58	4.59	5.55	2.37
LSD<0.05	Ns	Ns	2.31	3.48	0.082	Ns	3.5	1.86	0.099

Source: [47]

The pH of the soil has a direct bearing on the availability and solubility of critical nutrients for plants [53]. Since phosphate is the most immobile of the key plant nutrients, it can easily be rendered inaccessible to plant roots in soils with pH values below 5.5 [54]. As a result, crop yields in these types of soils are often quite poor. P fixation is low while plant availability is higher in soil pH ranges of 5.5 to 7. If the soil response is kept within the pH range of 5.5 to 7, which appears to encourage the quickest availability of plant nutrients, toxicity and deficiencies of Fe and Mn may be prevented. Since developing crops absorb around 0.44 kilogram P ha^{-1} per day, the amount of P in the soil solution required for optimal crop growth is between 0.13 and 1.31 kg P ha^{-1} [14].

3.5. Effect of Soil Acidity on Crop Productivity

Because different crops are more or less sensitive to acidic soil, the ideal pH depends on the type of crop being grown. According to Duncan [55], the pH range that popular field crops enjoy is between 6.0 and 7.0, which is also thought to provide the highest nutrient availability and crop yields. Table 1 provides an overview of the crop-to-soil response. It is thought that neutral soils with a pH range of 7-8 are ideal for growing cotton, alfalfa, oats, and cabbage since they cannot survive in acidic soils. Soils with a pH of 6-7 are ideal for the growth of wheat, barley, corn, clover, and beans. Since grasses can withstand acidic soils more than legumes can, bringing the pH down to 5.5 could regulate acidity without affecting yield. Conversely, legumes thrive in pH ranges between 6.5 and 7.5 and require more calcium. Millet, sorghum, sweet potatoes, potatoes, tomatoes, flax, tea, rye, carrots, and lupine are among the crops that can withstand acidic soils [56]. The main signs of elevated soil acidity, which can result in lower yields, include poor plant vigor, uneven crop development, poor legume nodulation, stunted root growth, persistence of acid-tolerant weeds, increased disease incidence, and aberrant leaf colors [56, 57] (Table 5).

Because of nutritional imbalances and inadequacies, as well as induced toxicity from aluminum and magnesium, increased acidity is likely to result in poor plant growth and water usage efficiency. Excessive levels of aluminum also have an impact on plant respiration, cell division, glucose phosphorylation, nitrogen mobilization, and the uptake and translocation of nutrients, particularly the immobilization of P in the roots [58-61] (Baquy et al., 2017; Fageria and Baligar, 2008; Fox, 1979; Haynes and Mokolobate, 2001).

***Table 5**. Relationship between crop and pH of the soil.*

Crop	Optimum pH for best growth	Crop	Optimum pH for best growth
Alfalfa	7.0-8.0	Sugar beet	5.8-7.0
Cotton	7.0-8.0	Millets	5.5-7.5
Oats	7.0-8.0	Sorghum	5.5-7.5
Cabbage	6.0-6.5	Sweet potato	4.5-6.5
Wheat	6.0-7.0	Potato	4.5-6.5
Barley	6.0-7.0	Tomato	5.5-7.5
Maize	6.0-7.2	Deciduous fruits	6.5-7.5
Clover	6.0-7.0	Mango	5.0-6.0
Faba bean	6.0-8.0	Papaya	6.0-6.5
Field pea	6.0-7.0	Avocado	5.0-8.8
Chick pea	7.0-8.0	Pineapple	4.5-6.5
Lentil	6.5-8.0	Flax	5.0-7.0
Soybean	6.2-7.0	Tea	4.0-6.0
Beans	5.5-8.0	Carrot	5.5-7.0
Onion	5.8-6.5	Rye	5.0-7.5
Sugarcane	5.0-8.5	Lupin	4.5-6.0

Source: [56]

Even at pH lower than 4, insensitive plant species are not greatly affected by soil acidity, whereas sensitive plant species might be inhibited in their growth at pH 5.5 or below. Al and Mn toxicity as well as Ca and Mo shortage exacerbate and frequently outweigh this pH impact [56, 58, 60]. Due to acid toxicity, roots frequently experience damage first, becoming stunted and stubbly. Acid soils can contain low levels of immobile nutrients, which stunted roots find difficult to get. There is a significant reduction in the plant's capacity to absorb water and nutrients, especially those that are stationary like P [60].

Plants are therefore very vulnerable to drought and nutritional shortages. The red discolorations generally associated with P shortage are widespread; micronutrient deficiency symptoms are regularly noted; and, due to the direct antagonistic impact of Al on Mg absorption, Mg deficiency symptoms give a useful signal of acidity concerns [44]. Exchangeable Al is the primary cation linked with soil acidity. When the concentration of aluminium in the soil solution surpasses 1 mg kg^{-1}, sensitive crop species' root development suffers. Al typically occupies 60% or more of the soil's exchangeable capacity. Mn, which becomes highly soluble at pH levels below 5.5, can also cause damage [56].

3.6. Soil Acidity Management Alternatives

3.6.1. The Use of Agricultural Lime

When the pH of a certain soil is too low for plants to thrive, an alkaline material must be added to increase the pH. One of the main methods for repairing acidic soils is liming, which raises the pH of the soil and boosts plant nutrient availability. Applying lime or gypsum can increase the amount of nutrients available to plants and bring the pH of the soil closer to neutral [62, 63]. Additionally, liming could mitigate the impacts of Al toxicity, which would otherwise have a detrimental impact on crop yield [21].

According to Abate [64] and Paradelo [65], liming has advantages beyond lowering soil acidity, lowering Al toxicity, and preserving macronutrient availability. Liming can also help with soil organic carbon sequestration. Over time, it could also provide some financial benefits. Due to the fact that treated soils require less fertilizer than untreated soils, farmers can profit from decreased costs associated with purchasing inorganic fertilizers. That is to say, farmers could have to apply more fertilizer, which might raise costs, if soil acidity is not reduced by using lime or other additions [35].

A number of experiments found that applying lime significantly increased the pH and phosphorus availability of the soil while decreasing exchangeable acidity [52]. Increased pH and decreased soil exchangeable acidity are associated with the presence of basic cations (Ca^{2+} and Mg^{2+}) and anions (CO_3^{2-}) in lime that may exchange H+ from exchange sites to produce H_2O and CO_2. The pH rises when cations take up the space that H^+ leaves behind during the exchange. Other researchers noticed that Ca^{2+} ions moved H^+ and Al^{3+} ions out of the soil adsorption sites, causing the pH of the soil to rise following lime treatment [66].

When acidic soils are limed, the pH of the soil is raised, releasing phosphate ions that precipitate with Al and Fe ions and facilitating plant uptake of P [73, 26, 67]. Agegnehu [68] reported that the growth of faba beans under limed and unlimed circumstances on acidic soils in Welmera, Woreda, Ethiopia, illustrates the considerable influence of lime on crops (figures 3 and 4, respectively).

Figure 3. *Faba bean development on acidic soils in limed circumstance source: [66].*

Source: [66]

Figure 4. *Faba bean growing on acidic soils under unlimed circumstances.*

The application of lime to acidic soil with the innate characteristic of high P fixation was significantly reduced, according to studies conducted by Ayalew [69] and Desalegn [26]. The concentration of Al in the soil solution is also decreased by raising the pH of the soil because it precipitates exchangeable and soluble Al as insoluble Al hydroxides. Further evidence that the exchangeable acidity was altered by the administration of lime and P fertilizer was provided by Melese and Yli-Halla [9].

3.6.2. Supplementing Acidic Soils with Organic Fertilizers

In place of lime, organic fertilizers like vermicompost, manure, and biochar can be used. These fertilizers are crucial for changing the chemical properties of acidic soil because they reduce the amounts of Al that are phytotoxic, which increases crop production. It is thought that the primary mechanisms causing these advantages are either the direct neutralization of Al from the pH increase caused by organic materials or the formation of organo-Al complexes that render Al less toxic [70]. In the acidic soils of the Ethiopian highlands, numerous studies have documented the advantageous effects of the aforementioned fertilizers. They have also unequivocally demonstrated that growing teff, maize, barley, wheat, and several kinds of legumes in an equitable manner is possible when an integrated nutrient application technique is employed, as opposed to obtaining nutrition from a single source.

Teff, for instance, responded significantly to integrated soil fertility management treatments containing both organic and inorganic forms under farmers' field conditions, according to studies by Ayalew [69] and Teshome [71]. This suggests that they could be taken into consideration as alternate options for sustainable soil and crop productivity in Ethiopia's degraded highlands. Additionally, it was found by Chala [72], Mellese and Yli-Halla [9], and Bekele [73] that the productivity of chickpeas, barley, and maize was positively impacted by mixed organic and inorganic fertilizers. Variations in soil types have led to differing crop responses to N and P treatments. In Ethiopia's central highlands, the use of biochar also improves pH, accessible phosphorus, CEC, and reduces exchangeable acidity [74]. In central Ethiopia, the author also noted that biochar had a good effect on soil pH, CEC, and Av. P, leading to an increase in teff grain and biomass output (Table 6).

Among the techniques for enhancing and controlling soil fertility and health is ISFM. Soils may be made better both physically and chemically by using organic plant nutrition sources like farmyard manure (FYM) and crop leftovers. According to Agegnehu and Amede [76], FYM treatment produces a range of organic acids that can bind to Al and Fe to form stable complexes that block retention sites and increase P availability and utilization efficiency in acidic soils where P fixation is a problem.

Based on the findings of other researchers, acidic soil benefits from the use of both organic and inorganic fertilizers (Table 7). Furthermore, in Chencha, southern Ethiopia, the application of FYM and NP fertilizer together considerably enhanced the production of potato tubers on acid soil, according to Haile and Boke [77]. According to Chala [72], as compared to the control, chickpea output was increased when integrated treatments of organic and inorganic soil amendments were applied to acid soil in Ethiopia's highlands (Table 7). Overall, the results above showed that, provided the optimum choice is chosen for the region, integrated usage of nutrient sources significantly improves both crop yield and the general state of the soil.

Table 6*. Impact of organic amendments on biomass and grain yields.*

Treatments	Rate	GY (t h^{-1})	BY (t h^{-1})	Crop	Reference
	0	2.18	16.1		
Vermi-Compost (VC)	2.5	3.03	17	Maize	[73]
	5	4.03	18.7		
	0	1.437	1.55		
	4	1.724	13.15		
Biochar	8	1.98	13.67	Teff	[74]
12	2.668	17.77	12	2.668	17.77
0	1.343	2.873	0	1.343	2.873
Manure (t/ha)	2.5	1.528	3.243	Faba-Bean	[75]
	5	1.759	3.7		

Table 7*. Impacts of both organic and inorganic fertilizers on the development 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

Sources: [72]

3.6.3. Tolerant Crop Varieties

Over the past ten years, a number of researchers worldwide have focused their attention on identifying and characterizing the mechanisms that agricultural plants employ to withstand Al dangerous levels in acid soils [1, 78]. Al tolerance mechanisms are in two varieties: those that enable the plant to withstand Al buildup in the root and shoot systems and those that keep Al from getting to the root apex. While significant speculation has been made about various mechanisms of Al tolerance, most experimental evidence has concentrated on Al exclusion from the root based on Al-activated organic acid exudation from the root apex. There is mounting evidence also in favor of a second tolerance mechanism that involves complexation with organic ligands, particularly OAs, to facilitate internal detoxification of symplastic Al [79, 80].

In Ethiopia's highlands, barley is mostly grown on Nitisol soils, which have low pH levels. This implies that barley has already adjusted to soil that is acidic. Using this data, five released barley cultivars were evaluated in both limed and unlimed circumstances on acidic soils at Endibir. With yield improvements of 366 and 327 percent, respectively, above the equivalent yields of the same barley types under unlimed settings, barley cultivars HB-42 and Dimtu performed well under limed conditions. Barley varieties HB-1307 and Ardu, on the other hand, performed better in unlimed settings; their yields were, respectively, 48 and 49 percent lower than those of the same barley types under limed conditions (Table 8).

Table 8. 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

Sources: [66]

4. Conclusions

Soil acidity, a natural process influenced by factors like climate, topography, vegetation, and rainfall, is a significant issue in Ethiopia, particularly in highland regions. This acidity hinders agricultural productivity by reducing nutrient availability. Soil response, expressed in pH, indicates soil's neutral, acidic, or alkaline state. Soil features like nutrient availability, biological activity, and physical state are significantly impacted by soil acidity. Soil acidity typically has negative impacts when the pH drops below 4.5.

This study emphasized the issues with soil acidity related to plant nutrient availability and the beneficial effects of lime and organic fertilizers on smallholder farmers' sustainable crop yield. Soil acidity impacts crop yield and nutrient availability, and its mitigation mechanisms are influenced by natural processes like terrain, vegetation, parent material, rainfall, and climate. It is a major cause of production limitations in sustainable agriculture in many regions, including Ethiopia, with issues becoming more prevalent in Ethiopia's highlands. Natural processes such as terrain, vegetation, parent material, rainfall, and climate contribute to the creation of soil acidity.

A key component of agricultural sustainability is the preservation of soil quality and the use of sustainable soil management techniques. Lime is a sustainable choice for managing sour soils, as it improves soil health, fertility, and nutrient concentration for leguminous plants and microbes. It raises soil pH and precipitates exchangeable aluminum, making it a popular method for increasing crop yields in acidic soils. Liming the soil reduces soil acidity and lowers phytotoxic levels of Mn and Al, resulting in better crop performance. Nevertheless, applying lime is not a means to an end in and of itself to attain potential production; rather, it should be viewed as a strategy for raising soil pH to maximize nutrient availability for ideal plant development and output.

Furthermore, in order to increase soil pH to a level that is ideal for optimum nutrient availability, plant development, and crop production, liming should be taken into consideration as a soil supplement. Generally speaking, it is very important from a practical standpoint to utilize all of the resources that are available, including crop species and acid-tolerant varieties, in order to maintain and enhance soil and agricultural output. The best way to address Ethiopia's current soil nutrient issues, such as soil acidity and infertility, is through integrated soil fertility management. Thus, liming, the use of organic fertilizers and crop types resistant to Al toxicity are some of the key strategies to ameliorate acid soils in farmers' fields for sustainable agricultural output among Ethiopia's small-scale farmers. Future studies should be conducted as long-term field experiments to assess the advantages of agricultural lime and organic fertilizers as pertinent processes of lowering soil acidity in order to draw a more certain conclusion.

Abbreviations

AP: Available Phosphorus
BY: Biomass Yield
CEC: Cation Exchange Capacity
EA: Exchangeable Acidity
GY: Grain Yield
LR: Lime requirement
OC: Organic Carbon
pH: Power of Hydrogen
TN: Total Nitrogen

Conflicts of Interest

The authors declare no conflicts of interest.

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