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RESEARCH PAPER

Exchangeable Acidity Management with Integrated Amendments to Enhance Potato (*Solanum tuberosum*) Productivity and Nutrient Use Efficiency in Acidic Soils

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ABSTRACT

Potato cultivation is severely hampered by acidic soils, particularly in the Kenyan highlands, where crop growth, yield, and nutrient availability are all impacted. With an emphasis on combining organic and inorganic amendments, this paper looks at how soil additions might improve potato yield and reduce soil acidity. Anthropogenic and natural factors are the main determinants of soil acidity, which is common in the highlands of Kenya. The pH of soil has significantly decreased as a result of the acidic parent material, which is derived from volcanic rocks, as well as human-induced behaviors like constant cultivation and an over-reliance on inorganic fertilizers. The presence of hazardous acidic cations (H^+ and Al^{3+}) causes exchangeable acidity, which hinders potato root growth and nutrient uptake and lowers crop output. Although a number of amendments, including mineral fertilizers, lime, and organic manure, have demonstrated promise in reducing soil acidity and enhancing soil fertility, little is known about how these amendments work together to affect exchangeable acidity and how that affects potato production. Given that soil acidity changes at different depths and influences nutrient availability, root penetration, and water infiltration, this review emphasizes the need for a greater understanding of soil profile characteristics. Although they provide temporary advantages, traditional supplements like lime efficiently neutralize the pH of soil. Compost, biochar, and farmyard manure are examples of organic amendments that enhance soil structure, water retention, and nutrient cycling, all of which promote long-term soil health. Potato yield has been demonstrated to rise when organic and inorganic additions work in concert to promote soil fertility and nutrient uptake. More focused treatments, including deep liming and subsurface amelioration, can be guided by accurate profiling, improving crop yields and nutrient usage efficiency (NUE). Furthermore, sustainable additives like biochar are becoming more well-known due to their capacity to raise soil pH and sequester carbon. These strategies have potential, but there are still issues with high amendment costs, restricted access to soil testing, and a lack of farmer understanding. In order to support the adoption of sustainable soil management practices for increased potato productivity in acidic soils, this review emphasizes the need for more research into integrated amendment strategies, the creation of affordable and environmentally friendly amendments, and better extension services. Notwithstanding the difficulties, maintaining soil acidity in potato farming appears to have a bright future thanks to the combination of organic and inorganic amendments, improvements in precision agriculture, and simulation models. The purpose of this review is to fill in the information gap about how these changes can boost potato yield and manage exchangeable acidity, which would ultimately increase regional food security.

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HIGHLIGHTS

- Acidic soils significantly hinder potato productivity due to low pH and exchangeable acidity, affecting nutrient uptake and root growth.
- The integration of organic and inorganic amendments can effectively reduce soil acidity and improve nutrient availability, leading to enhanced potato yield and nutrient use efficiency (NUE).
- Future trends in soil management, including precision agriculture, eco-friendly amendments like biochar, and the adoption of simulation models, offer promising solutions for sustainable and efficient management of acidic soils in potato farming.

Keywords: Nutrient use efficiency, root growth, pH, acidic soils, soil fertility, crop growth

Potato (*Solanum tuberosum* L.) is the most dominant food crop after rice, wheat, and maize; potatoes rank the fourth most–consumed food crop worldwide (Haile *et al*. 2023; Shao *et al*. 2023). Over the past several decades, potato production has increased dramatically on a global scale. Today, more than 160 nations produce around 370 million tons of potatoes yearly (FAOSTAT, 2024; Mwakidoshi *et al*. 2023). Potatoes ideally are productive in cool climates with particular ecological features that immediately impact their productivity (Onditi *et al*. 2019). Potatoes thrive well in areas that are between 1,500 and 3,000 meters above sea level and have temperatures between 10 and 25°C, as high temperatures impede tuber development (Haverkort, 2018; Shadrack *et al*. 2019). To ensure potatoes' optimal growth, they need between 850 and 1,200 mm of rainfall per growing season, which is sufficient for optimal growth (Ireri *et al*. 2020; Onditi *et al*. 2019). The recommended pH range for potato growth is between 5.0 to 6.5 since too much acidity in the soil might limit the availability of nutrients, which can impede growth and lower yields (FAO, 2019; Mugo *et al*. 2021; Midya *et al*. 2021; Sairam *et al*. 2023). In addition to being high in starch and other carbohydrates, potato tubers also have dietary fiber, vitamin B6, and other important vitamins (Brown, 2018). Due to the shallow root structure, the crop is extremely dependent on the quality of the soil and the availability of water, essential nutrients (NPK) for plant development, tuber formation, and yield. It is imperative to control these nutrients (Gitari *et al*. 2018). During the vegetative and reproductive growth periods, potatoes are susceptible to environmental stressors such as severe temperatures and waterlogging, which can result in lower yields (Shadrack *et al*. 2019; Maitra *et al*. 2025; Kumar *et al*. 2021; Hossain *et al*. 2022).

Potatoes are essential in both national and international economic and nutritional situations. The crop is a mainstay of global food security plans due to its versatility, high production potential, and nutritional value. Potatoes are broadly grown from the tropical highlands of Africa, Asia, and Latin America to the temperate areas of Europe and North America (KALRO, 2016). The biggest producers of the crop include Germany, Poland, and the Netherlands in Europe, where it was first produced. Nonetheless, Asia currently produces about half of the world's potatoes, with China and India leading the way (KALRO, 2016; FAOSTAT, 2024; CIP, 2019). The crop is a useful tool in the fight against hunger and malnutrition because of its comparatively short growth cycle and high production per unit area (Bambara and Ndakideminekesa, 2010). Furthermore, potatoes are high in minerals, vitamins (particularly C), and carbohydrates, which help to satisfy global nutritional demands and provide a balanced diet (Nekesa *et al*. 2011).

The crop's adaptability to climate change further emphasizes its importance on a worldwide scale, as a sustainable crop from the perspective of climate-smart agriculture, since it emits fewer greenhouse gases than other main crops (Bambara and Ndakidemi, 2010; Maitra *et al*. 2022; Mukesh *et al*. 2024; Santosh *et al*. 2024; Sairam *et al*. 2025). According to studies, growing potatoes reduces emissions of CO_2 and N_2O (nitrous oxide) in comparison to other crops like sweet corn, moreover cereals, which help to slow down global warming (Bambara and Ndakidemi, 2010; Nekesa *et al*. 2011).

Notably in Kenyan highlands, potatoes rank second in importance among basic foods, behind maize. Particularly for smallholder farmers, the crop is essential for employment, revenue generation, and food security (Gitari *et al*. 2019; Haile *et al*. 2023). Because of the crop's quick growth cycle, farmers may harvest numerous times a year, which increases their income stream and lessens their exposure to weather and market shocks (GoK, 2012; KMT, 2019). Additionally, Kenya's potato value chain supports several auxiliary sectors, such as seed cultivation, processing, and marketing, which increases its economic viability.

It is impossible to overestimate the importance of potatoes in local diets; for many Kenyan homes, they provide a vital source of energy and vitamins that support national nutrition and food security (GoK, 2012; KMT, 2019; FAOSTAT, 2024). In Kenya, potatoes are an essential food and a major source of revenue, particularly in the highland zones where they are an essential crop. The crop's potential to address local and global food security issues must be maximized via ongoing study and investment in sustainable potato growing techniques. With an anticipated yearly yield of 2 million tons, valued at nearly KES 50 billion (almost USD 460 million), the crop is also very important to the nation's economy (KMT, 2021). In addition, potatoes develop quickly, typically in approximately three to four months, which enables several harvests yearly and makes them a desirable crop for small–scale growers.

Soil acidity is prevalent in the Kenyan highlands, which can be traced to both natural and anthropogenic factors (Mugo *et al*. 2021; Esilaba *et al*. 2023). The parent material from which soils are formed comes from acidic volcanic rocks (andesites, basalts, and rhyolites), which naturally give acidic soils. These soils are usually low in base cations (Ca^{2+}, Mg^{2+}, K^{+}), which help in buffering soil pH (Fageria and Baligar, 2008). Human factors such as continuous cultivation with over-reliance on inorganic fertilizers also contribute to a decline in soil pH. This prolonged decline results in the presence of acidic cations (H^{+}, AL^{3+} and Fe^{+}) on the soil exchange sites, a characteristic of exchangeable acidity (Mokwunye and Bationo, 2011).

Exchangeable acidity is typified by the presence of acidic cations (H^{+} and Al^{3+}) on the soil's exchange sites and is harmful since it is directly associated with the presence of harmful aluminum ions, which can significantly hinder potato root growth and intake of nutrients. There are limited studies that have focused explicitly on how various soil amendments affect exchangeable acidity and, in turn, potato production, particularly in Kenya highlands, despite the well-established detrimental impacts of exchangeable acidity on crop productivity. The usage of lime, organic manure, and mineral fertilizers is an example of inorganic and organic soil additions that have been demonstrated to minimize soil pH and increase nutrient availability. However, the combined impacts of these amendments on exchangeable acidity and their consequent consequences on potato production and nutrient utilization efficiency have not been well investigated. This information gap is crucial because efficient exchangeable acidity control has the potential to boost nutrient usage efficiency, support effective utilization of nutrients in the area, and significantly increase potato productivity.

Understanding the constraints and possibilities of soils for crop production depends heavily on the in-depth investigation of soil layers and morphological traits (Nungula *et al*. 2024). When it comes to acidic soils, profiling can be used to find hidden problems that surface soil tests might miss, like subsurface acidity, poor structure, or nutrient imbalances. The depth at which soil acidity varies can have an impact on root penetration, water infiltration, and nutrient availability. Researchers can target management treatments, such as subsoil amelioration or deep liming, by pinpointing the precise layers in the soil profile where acidity is most problematic. This is made possible by a detailed understanding of the soil profile. Better land management methods and increased crop yields are a result of this (Meriño-Gergichevich *et al*. 2010).

Understanding the profile enables one to better target the application of lime, organic matter, and fertilizers to particular soil types, resulting in a more effective use of inputs. Various soil types react differently to additions (Gitari *et al*. 2018). Comprehensive profiling sheds light on long-term concerns such as nutrient depletion, inadequate drainage, or compacted layers that worsen acidity issues in the context of Kenya's highland acidic soils. Understanding the hydrological characteristics of the soil is another benefit of profiling, which is important for managing water resources and addressing climate-related issues.

Furthermore, it is critical to comprehend how these soil amendments affect exchangeable acidity in particular throughout the short and long term. Through the determination of several soil amendments on potato growth, yield, and NUE in acidic soils, this study seeks to close the knowledge gap and offer a viable solution for raising the productivity of farming and food security in the area (Fig. 1).

ACIDIC SOILS AND THEIR IMPACT ON POTATO FARMING

When the soil pH is < 7, it is referred to as acidity, and it can have a major impact on crop productivity (Gitari *et al*. 2018). Some variables, including both human activity and natural processes, cause the acidity of the soil (Taye, 2008; Parecido *et al*. 2021). The natural source of soil acidity is from the cations leached from the soil, such as calcium, magnesium, and potassium. High rainfall areas speed up this leaching because water seeps through the soil, removing these bases and leaving behind aluminum (Al^{3+}) and hydrogen (H^+) ions that are acidic (Havlin *et al*. 2005; Taye, 2008; Gitari *et al*. 2018).

The weathering of acidic parent materials is another natural source of acidity in soil. Naturally low in basic cations and rich in acidic components, soils formed from granite, shale, or sandstone are generally more acidic (Sumner and Noble, 2003). Furthermore, the breakdown of organic matter results in weak organic acid production, which over time contributes to soil acidity (Havlin *et al*. 2005).

Acidification of soil has also been a result of human activity, especially agricultural operations such as overuse of fertilizers containing ammonium, among them urea and ammonium sulfate, which can cause hydrogen ions to build up in the soil (Havlin *et al*. 2005; Pankova *et al*. 2009; Preshow, 2014). Following the application of these fertilizers, soil bacteria convert the ammonium ($NH_3^{4^+}$) to nitrate ($NO_3^{3^-}$) in a process known as nitrification, producing hydrogen ions as a byproduct (Fageria and Baligar, 2008). Additionally, by diminishing the soil's base cation stores, continual cropping without appropriate soil management techniques might worsen soil acidity.

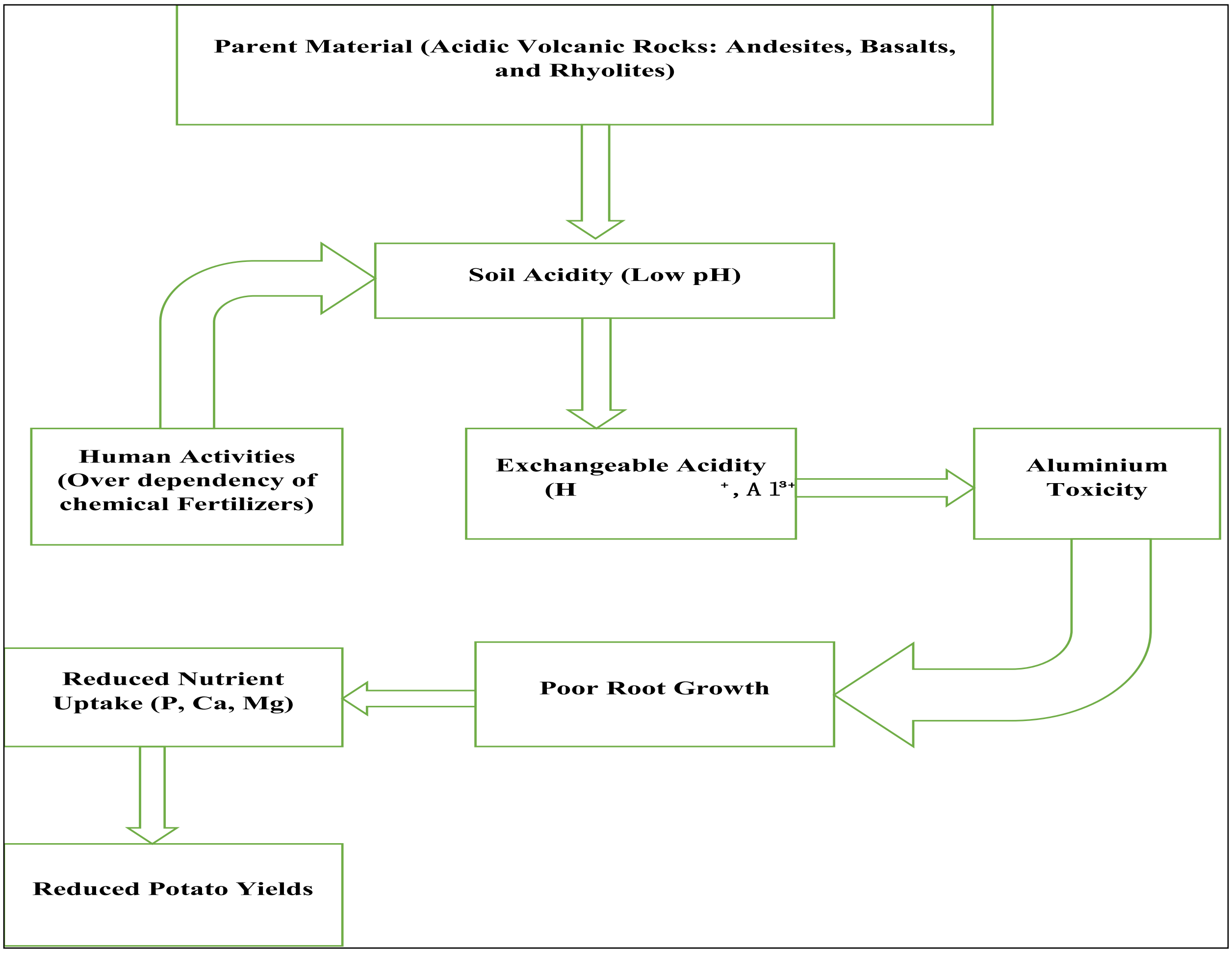

Fig. 1: Exchangeable acidity formation process

Acidification of soil is further facilitated by acid rain, which is produced when industrial sulfur and nitrogen oxides are released into the atmosphere. These oxides are transformed into nitric and sulfuric acids when they are precipitation–deposited into the soil's surface, further depressing the pH of the soil (Sanchez, 1977; Sanchez, 2019).

The acidity–causing hydrogen ions are produced when organic matter decomposes. Soil water and carbon dioxide (CO_2) from decomposing organic matter combine to form a weak carbonic acid. It is also produced in the event of atmospheric rain, spontaneously combines with $CO_{2,}$ and in the breakdown process of organic compounds. Similar to rainfall, the contribution of decomposing OM to soil acidity is often extremely minor, and in a field, the impacts of several years' worth of accumulation would be the only ones that could ever be quantified (Pankova *et al*. 2009; Preshow, 2014).

Soil acidity classes

Soil acidity is determined using the pH scale, which is a good indicator of active acidity. A mix of soil and water determines the quantity of hydrogen ions in the ground, which is referred to as active acidity. According to Yirga *et al*. (2019b), the pH of the soil is a broad identifier for free lime (calcium carbonate), the availability of nutrients, and the overabundance of specific ions like sodium, hydrogen, aluminum, and manganese.

Active acidity: It is the concentration of H^+ ions in the soil solution, and it is assessed in terms of soil pH. This happens because of the soil solution's H^+ ion concentration, which is caused by hydrolytically acid salts, water-soluble organic acids, and carbonic acid ($H_2CO_3^-$) (Getaneh and Kidanemariam, 2016). The pH value of a water suspension or soil extract can be measured to ascertain it. It has an immediate impact on how plants and soil microbes grow (Muindi *et al*. 2016; Getaneh and Kidanemariam, 2016).

Exchange acidity: There exists an equilibrium for the absorbed H^+ and Al^{3+} ions on soil colloids. The adsorbed and soil solution ions (active and exchange acidity) strike a balance (Pankova *et al*. 2009), allowing for a quick transition between a single form and another. In a basic salt solution like KCl, it is the acidity brought on by hydrogen and aluminum, which are readily exchangeable (Goulding, 2016; Yirga *et al*. 2019b).

Reserve acidity: The engrossment of hydrogen ions bound to clay with OM is evaluated as buffer pH in a buffer solution where the adsorbed H^+ and Al^{3+} ions flow into the soil solution (Getaneh and Kidanemariam, 2016; Pankova *et al*. 2009). The soil absorbs the majority of the H^+ available in acidic soil, a process known as reserve acidity (Thomas, 1996; Taye, 2008). There exists a correlation between the reserve and the acidity of the active. However, there are fluctuations in the way the soils interact. It was governed by the kind and quantity of clay in the soil as well as by the amount of organic matter and free lime. The soil's buffer potential, or its capacity to withstand pH changes as the amount of clay and organic matter in the soil rises, is known as the reserve–to–active acidity ratio (Sumner and Yamada, 2002; Havlin *et al*. 2005). As a result, the reserve acidity, or buffer capacity, of a sandy soil is substantially lower than that of a silt loam, or soil with a higher clay content. The pH buffer is determined to find the quantity of lime required to neutralize a significant portion of the reserve acidity when the pH of the soil is 6.3 or below (Goulding, 2016).

Effects of soil acidity on crop productivity

Crop production is significantly impacted by soil acidity, especially in terms of accessibility to nutrients and aluminum toxicity. Important minerals, including phosphorus, calcium, magnesium, and molybdenum, are less accessible to plants in acidic soils because they are either incorporated into soil fragments or changed into forms that are difficult for crops to utilize (Esilaba *et al*. 2023). For example, in acidic soils, phosphorus, which is essential for plant root growth and energy transmission, is frequently deposited in insoluble forms, rendering it unavailable to plants (Sumner and Yamada, 2002).

A major issue related to acidity in the soil is aluminum poisoning. Aluminum ions (Al are poisonous to plants, which become soluble under acidic circumstances (usually below pH 5.5). Stunted root systems that restrict the intake of water and nutrients might result from these ions interfering with the division and elongation of root cells. Because of this, crops cultivated on acidic soils frequently show poor development, lower yields, and a greater vulnerability to nutrient deficits and drought (Delhaize and Ryan, 1995).

For crops that are sensitive to acidity, including maize, beans, and potatoes, the effect of soil acidity on plant productivity is very severe. For best growth, these crops need a pH close to neutral, and they are extremely vulnerable to aluminum's harmful effects and nutrient imbalances in acidic soils (Fageria and Baligar, 2008). Consequently, around the world, particularly in tropical and subtropical climates where acidic soils are common, soil acidity poses a significant barrier to agricultural output (Maitra *et al*. 2020).

Traditional and modern methods for managing acidic soils

To preserve soil fertility and guarantee sustained crop production, managing soil acidity is essential. Lime (calcium carbonate) has long been used in traditional soil acidity management techniques as a way to neutralize soil acidity. According to Rengel (2003), lime raises the pH of soil by interacting with H^+ ions in the soil to produce carbon dioxide and water. The purity of the lime, the size of the particles, and the application rate all affect how effective the lime is (Soratto *et al*. 2021). In very acidic soils, especially in areas with considerable rainfall, regular liming is required to combat continuing acidification processes (Sumner and Yamada, 2002).

Compost and manure are examples of organic materials that may be used to control soil acidity in addition to lime (Rahimi *et al*. 2023). According to Haynes and Naidu (1998) and Mugo *et al*. (2021), OM strengthens the soil's structure, promotes microbial activity, and expands the soil's potential to function as a buffer against the negative impacts of acidity. Additionally, using organic amendments might lessen the need for acidifying synthetic fertilizers by offering a slow release of nutrients (Bolan *et al*. 2003; Havlin *et al*. 2005).

Using crop types that can withstand acidity and the use of integrated soil fertility management (ISFM) techniques are some contemporary methods for controlling soil acidity. In acid–prone areas, agricultural production has been successfully increased by breeding and variety selection for crops that can flourish in acidic soils. For instance, in nations like Brazil, where soil acidity poses a serious agricultural problem, acid-tolerant cultivars of maize, rice, and wheat have been created and extensively embraced (von Uexküll and Mutert, 1995; Rengel, 2003; Esilaba *et al*. 2023).

ISFM technologies blend in with inorganic and organic inputs, which are being pushed more and more as a sustainable way to control soil acidity. To gradually increase soil health and production, these methods include crop rotation, cover crops, and the prudent use of fertilizers, lime, and organic matter (Vanlauwe *et al*. 2010; Maitra *et al*. 2024, 2026). ISFM procedures provide a comprehensive approach to the problems related to soil acidity in agriculture by addressing both the physical and chemical components of soil fertility.

Conclusively, the complicated problem of soil acidity has significant effects on agricultural yield and soil health. Creating efficient management plans requires an understanding of the elements that affect soil acidity, including how it affects nutrient availability and aluminum toxicity. The use of crop types resistant to acidity and ISFM technologies, in addition to more conventional techniques like liming, offers useful instruments for the reduction of the negative impact of acidity in the soil and guaranteeing sustainable agricultural output.

EXCHANGEABLE ACIDITY IN SOILS

The term "exchangeable acidity" describes the acidic cations in the soil solution that may be exchanged with other cations, mainly Al^{3+} and H^+. As the pH drops, these ions are discharged into the ground, raising the soil pH. Excessive exchangeable acidity is bad for plant growth, especially for crops that are sensitive to low pH, like potatoes. Because it can prevent roots from elongating and decrease the absorption of vital minerals like phosphorus (P), calcium (Ca), and magnesium (Mg), the presence of $Al\cdot^{+}$ in the soil solution is particularly detrimental (Sumner and Noble, 2003; Mbakaya, 2015).

Exchangeable acidity represents the acid cations maintained on soil colloids and active acidity, and the concentration of H^+ ions in the soil solution (measured as pH), which make up the two primary components of soil acidity (Getaneh and Kidanemariam, 2016). It is important because it shows how acidic the soil can get over time, especially when affected by acid rain, the leaching of basic cations like calcium and magnesium, and the continuous use of fertilizers containing ammonium (Rengel, 2011).

Mitigation of exchangeable acidity through soil amendments

Liming: A popular technique for lowering exchangeable acidity in soils is liming. The acidity of the soil is neutralized by lime ($CaCO_3$ or $MgCO_3$), which raises pH and precipitates Al^{3+} as insoluble aluminum hydroxide (Al $(OH)_3$) (Mutonyi *et al.* 2014). This procedure raises the availability of vital nutrients while simultaneously lessening Al's harmful effects. By lowering exchangeable acidity, lime has been shown in several studies to be beneficial in raising potato yields in acidic soils (Nuwamanya 1984; Kamprath, 1984; Bolan *et al.* 2003).

Organic amendments: Organic additions, for example, compost, charcoal, and farmyard manure (FYM), reduce exchangeable acidity. These substances are part of the OM in the soil, which can combine with Al^{3+} to lessen its availability in the soil solution. Additionally, organic additions increase soil microbial activity, which can help improve nutrient availability and aid in Al^{3+} detoxification. Studies have indicated that the utilization of lime in conjunction with organic amendments can be very successful in lowering exchangeable acidity and raising potato yield (Hue, 1992; Kumar *et al.* 2013).

Integrated Nutrient Management (INM): Using combined amendments in INM techniques is becoming more widely acknowledged as an efficient way to control exchangeable acidity in potato production. Improved soil structure and nutrient supply balance (INM) can reduce the detrimental impacts of exchangeable acidity and increase nutrient usage efficiency (NUE). For example, it has been discovered that adding lime to NPK fertilizers greatly increases potato yields by minimizing exchangeable acidity and maximizing nutrient availability (Islam *et al.* 2013).

Summarily, in acidic soils, exchangeable acidity has a major role in determining potato productivity. Lime is a necessary component for all amendments used to improve soil health and lessen the negative effects of exchangeable acidity (Palai *et al.* 2024). These amendments increase nutrient availability, boost root growth, and eventually result in greater potato yields by lowering the concentrations of Al^{3+} and H^+ ions in the soil. In areas with acidic soils, continued study into the optimization of soil amendment techniques will be essential for sustainable potato production.

Relationship between exchangeable acidity and nutrient availability

Exchangeable acidity poses a challenge to nutrient availability for plants, which influences crop yield and soil fertility. For example, high exchangeable aluminum concentrations are harmful to plant development. According to Tang *et al.* (2003), aluminum may solubilize in acidic environments and then combine with phosphorus to form insoluble complexes, which reduces the amount of this crucial nutrient that is available to plants. Furthermore, aluminum poisoning can hinder root development, which restricts the plant's capacity to utilize nutrients and water, resulting in stunted growth and lower yields (Kochian *et al.* 2004). Soil fertility is also affected by hydrogen ions (H^+), which, in high quantities, cause base cations to be displaced from soil colloids, leading to crop nutrition shortages. This displacement leads to the soil's continued acidification in addition to lowering the soil's cation exchange capacity (CEC) (Fageria and Baligar, 2008).

Exchangeable acidity and nutrient availability have a complicated connection that is impacted by several variables, including soil texture, OMC, and the existence of carbonates or other buffering agents. For instance, in sandy soils, variations in exchangeable acidity can cause abrupt pH changes and nutrient availability due to the absence of buffering capacity. On the other hand, because of their greater CEC and organic matter content, clay-rich soils could be more resilient to variations in acidity (Brady and Weil, 2008).

Long–term effects of amendments on exchangeable acidity in soils

Assuring sustainable crop output and preserving soil fertility need long–term exchangeable acidity control. Applying lime (calcium carbonate) is one of the best ways to lessen exchangeable acidity because it precipitates aluminum as a less hazardous hydroxide and neutralizes soil acidity by interacting with H⁺ ions to create carbon dioxide and water (Haynes, 1982). Frequent liming improves nutrient availability and soil fertility by lowering exchangeable aluminum and raising soil pH (Fageria *et al*. 2007).

Compost, manure, and biochar are examples of organic amendments that are important in controlling exchangeable acidity (Shao *et al*. 2024; Alkharabsheh *et al*. 2023). By complexing with aluminum and other acid cations, these amendments increase soil organic matter, which can buffer pH fluctuations by lowering their availability in the soil solution (Hue, 1992). Additionally, as organic matter breaks down, organic acids are released, which can chelate aluminum and lessen its harmful effects (Abreu *et al*. 2003; Chepkorir *et al*. 2024). Exchangeable acidity can gradually decrease as a result of the ongoing addition of organic amendments, which can also improve soil structure, boost microbial activity, and raise the soil's overall buffering capacity (Agegnehu *et al*. 2016).

Gypsum, or calcium sulfate, is another organic amendment that has been demonstrated to be useful in reducing exchangeable acidity in addition to lime, especially in subsurface layers where lime is less efficient. In acidic soils, gypsum enhances root development by supplying a calcium source that replaces aluminum at exchange sites, lowering its toxicity (Sumner, 1993).

INTEGRATED APPROACHES: COMBINING ORGANIC AND INORGANIC AMENDMENTS

Organic amendments

Compost, animal dung, plant leftovers, and other organic waste products are examples of natural sources from which organic amendments are made. As these components break down over time, nutrients are released into the soil, enhancing its structure, ability to store water, and microbial activity (Marschner, 2012). Compost, manure, green manure (cover crops), and biochar are examples of common organic additions (Rahimi *et al*. 2023; Mwadalu *et al*. 2022). Every kind of organic amendment has distinct qualities and nutrient contents that might affect how successful it is in various soil types and climates (Bünemann *et al*. 2018; Chepkorir *et al*. 2024).

Inorganic amendments

Conversely, inorganic amendments are made of artificial or extracted minerals, including gypsum, lime, fertilizers, and other soil conditioners. According to Havlin *et al*. (2014) and Parecido *et al*. (2021), to correct certain nutrient deficits or to change their pH, structure, or salinity, the addition of these amendments is fundamental. The main source of vital nutrients for plant development, such as potassium, phosphorus, and nitrogen (NPK), is inorganic fertilizers. While gypsum is administered to enhance soil structure and reduce salinity, lime is frequently used to elevate the soil pH (Sumner and Miller, 1996).

Role of amendments in improving soil health and crop productivity

A key determinant of agricultural production is soil health, and soil supplements are essential for preserving and improving soil health. By strengthening soil structure, retaining more water, and boosting microbial diversity and activity, organic additions improve soil health (Lehmann and Kleber, 2015). Organic matter breaks down gradually to release nutrients, giving plants a consistent supply of nutrients they need to grow. Furthermore, adding organic materials to the soil raises its cation exchange capacity (CEC), improving its capability to hold onto and provide nourishment to plants (Brady and Weil, 2016; Chepkorir *et al*. 2024).

Additionally, solid soil aggregates that increase root penetration, lessen erosion, and improve soil aeration are formed by the addition of organic materials. These advantages are especially significant in deteriorated or compacted soils, where organic additions can assist in reestablishing soil fertility and promoting sustainable agricultural production (Lal, 2015). Furthermore, organic fertilizers help mitigate the negative consequences of climate change through carbon storage in the soil and reducing greenhouse gas emissions (Paustian *et al*. 2016).

Fertilizers in particular, which are inorganic amendments, are vital in providing certain nutrients required for crop development. High crop yields and the maintenance of global food security have been made possible by the use of chemical fertilizers (Tilman *et al*. 2002). To improve access to nutrients and lessen aluminum toxicity, which can be detrimental to plant roots, in acidic soils, inorganic amendments like lime are used (Fageria and Baligar, 2008; Cheptoek *et al*. 2021). Another common inorganic supplement used to enhance soil structure and relieve salinity and compaction–related issues is gypsum (Shainberg *et al*. 1989).

Comparative effectiveness of organic and inorganic amendments in acidic soils

The particular context and soil management objectives determine how beneficial organic and inorganic additions are in acidic soils. Organic additions may improve soil structure, increase organic matter content (OMC), and encourage helpful microbial activity. They are typically more successful at promoting long–term soil fertility (Bünemann *et al*. 2018). Organic additions can lower the mobility of hazardous metals like aluminum, increase access to nutrients, and assist in buffering the pH of acidic soils (Hue, 2001). The slow–release quality of nutrients from organic amendments enhances crop nutrient usage efficiency and helps stop nutrient leaching.

Nevertheless, compared to inorganic supplements like lime, the impact of organic amendments on soil pH is often gradual and less noticeable. Lime is an essential tool for controlling acidic soils in areas where immediate pH correction is required to avoid agricultural production losses because of its great efficacy in quickly elevating soil pH and neutralizing acidity (Sumner and Yamada, 2002). While instant nutrient availability is offered by inorganic fertilizers, they do not increase soil structure or organic matter content over the long term and, if improperly managed, might eventually cause soil acidification (Guo *et al*. 2010).

To properly manage acidic soils, a mix of inorganic and organic amendments is frequently advised. Utilizing the advantages of both kinds of amendments, ISFM improves soil fertility, boosts nutrient use efficiency, and maintains crop yield (Vanlauwe *et al*. 2010). Farmers may boost crop yields, soil fertility, and sustainable development by utilizing organic amendments to promote soil health and using lime to neutralize acidity (Cheptoek *et al*. 2021; Krishna *et al*. 2024).

In conclusion, soil health and acidity management are two important agricultural uses for both organic and inorganic supplements. Inorganic supplements give quick nutrient availability and fast pH correction in acidic soils, whereas organic amendments improve soil structure and fertility over the long term. A balanced and long-lasting solution to the problems associated with soil management in agriculture may be achieved by utilizing an integrated strategy that incorporates the use of both kinds of amendments.

Effects of soil amendments on soil properties, soil pH, Organic Matter Content (OMC), and Nutrient Availability

Organic or inorganic soil amendments are essential for boosting soil health because they increase microbial activity, fertility, and soil structure. However, depending on how long they are used, these modifications may have quite different effects. Soil additives frequently have immediate impacts on the pH, microbial activity, and availability of nutrients in the soil. For example, applying lime (calcium carbonate) can raise soil pH fast, which can help with crop development by lowering soil acidity and relieving aluminum toxicity (Fageria and Baligar, 2008). Similar to this, applying inorganic fertilizers can immediately enhance the availability of vital elements (NPK), which can temporarily increase crop productivity (Marschner, 2012).

Continuous amendment treatments, however, have more complicated long–term consequences that include slow alterations to the characteristics of the soil. Lehmann *et al*. (2011) have demonstrated that the prolonged application of organic amendments such as compost, manure, and biochar may lead to a notable increase in the amount of organic matter in the soil, as well as improvements in soil structure, water retention, and microbial diversity and activity. These alterations strengthen the soil system's overall resilience and increase its capacity to maintain high production levels over time.

Conversely, in sandy soils with little buffering capacity, prolonged use of inorganic fertilizers without OM addition can result in a decrease in soil organic carbon, a decrease in microbial diversity, and soil acidity (Bünemann *et al.* 2018). The significance of integrated soil fertility management techniques that incorporate both organic and inorganic amendments is highlighted by the possibility of reduced soil fertility and a higher dependence on outside inputs to sustain crop yields (Vanlauwe *et al.* 2010).

Important markers of soil health include pH, OMC, and nutrient availability, all of which are impacted by the kind and frequency of soil amendments used. Nutrient availability, microbial activity, and general soil fertility are all influenced by the pH of the soil. One of the best strategies to increase soil pH and prevent soil acidification is to apply lime over an extended period (Psiwa *et al.* 2022). This is especially crucial in acidic soils since low pH can cause manganese and aluminum toxicity, which can stunt plant root development and decrease nutrient absorption (Sumner and Miller, 1996). However, with time, especially in heavy rainfall locations where base cation leaching occurs, the benefits of lime on soil pH might wane, requiring periodic applications to maintain appropriate pH values (Fageria *et al.* 2007).

Organic amendments application has an impact on soil organic matter (SOM), which is another essential aspect of soil health. Compost, manure, or crop leftovers are long–term organic matter additions that can greatly raise SOM levels. This can then improve soil structure, boost water–holding capacity, and offer a slow–release source of nutrients (Lal, 2004; Nyawade *et al.* 2021). A diversified and active soil microbial population is supported by higher SOM content and is important for nutrient cycling and the prevention of illness (Six *et al.* 2002).

Soil pH and OM levels in the soil correspond directly to the nutrients available. Inorganic fertilizers can offer an instant supply of nutrients that are easily absorbed by plants in the near term. However, if these fertilizers are not used in combination with organic amendments, they may cause nutritional imbalances and the depletion of specific micronutrients over time (Jamal *et al.* 2022; Bünemann *et al.* 2018). Conversely, organic amendments release nutrients more gradually throughout their decomposition, offering a longer–lasting nutrient supply that can eventually improve soil health and crop production (Drinkwater *et al.* 1998).

Influence of different soil amendments on potato growth and yield.

Soil fertility, which is frequently increased by the use of both organic and inorganic soil amendments, has a major impact on potato productivity. Organic additions such as compost, manure, and green manures are well recognized for their ability to fortify soil structure, stimulate microbial activity, and increase the soil's nutrient–storing capacity (Barker and Bryson, 2007). These advantages are especially crucial for crops like potatoes, which need a well–structured soil that retains water and allows for enough aeration to develop tubers to their full potential (Jatav *et al.* 2020).

Conversely, inorganic amendments, mostly synthetic fertilizers, offer a quicker source of minerals, including potassium, phosphorus, and nitrogen (NPK), all of which are critical for the growth of potatoes (Cameron *et al.* 2007; Shadrack *et al.* 2020). Particularly in soils that are initially nutrient–deficient, the rapid release of nutrients from inorganic fertilizers can cause a rapid response in plant growth and output. However, over-dependence on inorganic fertilizers may result in microbial diversity loss, soil acidification, and other long–term soil health problems (Guo *et al.* 2010).

According to studies, using both organic and inorganic amendments together can have synergistic effects that increase potato yields when compared to using only one kind of amendment alone (Pandey *et al.* 2013; Mwakidoshi *et al.* 2023; Shao *et al.* 2023; Ray *et al.* 2025). While inorganic fertilizers meet the developing crop's immediate nutritional demands, organic additions gradually enhance the physical characteristics of the soil and increase its nutrient availability. Better crop growth is supported by this integrated strategy, which also helps to maintain soil fertility over time (Vanlauwe *et al.* 2015).

Studies on potato productivity under various amendment practices

Several research works have examined the effects of various methods of soil amendment on the yield of potatoes. Studies carried out in Pakistan by Ahmad *et al.* (2017) showed that the use of chemical fertilizers in conjunction with farmyard waste greatly enhanced potato productivity and tuber quality. The study found that the soil's organic matter content rose when organic matter was added. Consequently, this enhanced the soil's capacity to hold onto water and supply nutrients, encouraging more robust plant growth.

Similarly, Vos and MacKerron's (2000) study conducted in the Netherlands investigated the impact of various nitrogen sources on potato output. The study discovered that the maximum yields were obtained when organic manures and inorganic nitrogen fertilizers were combined, indicating that optimizing potato output requires a balanced nutrient supply. While the inorganic nitrogen met the crop's immediate nutritional demands, the organic manure helped to improve the soil's health over the long run.

Jatav *et al*. (2020) researched the effects of using organic amendments, including vermicompost and biofertilizers, in conjunction with lower dosages of inorganic fertilizers on potato output in India. The outcome showed that this integrated strategy boosted the potato's nutritional content, making it more nutritious, in addition to increasing tuber output. Significant improvements in soil health measures, such as elevated soil enzyme activity and increased microbial biomass, both of which are essential for nutrient cycling, were observed.

Case studies from regions with similar soil conditions

Acidic soils are a problem for potato growing because of nutrient shortages and possible aluminum toxicity. Potatoes are a staple crop in areas like Ethiopia's highlands, where similar soil conditions exist. It has been demonstrated in these areas that adding lime as an inorganic supplement together with organic materials like manure or compost raises soil pH, increases nutrient availability, and increases potato yields (Taye *et al*. 2013).

Research in Kenya's highlands has demonstrated that using fertilizers rich in phosphorus and lime may greatly increase crop and soil productivity. The combination of lime and triple superphosphate (TSP) increased maize yields significantly, as shown by Kisinyo *et al*. (2014). This finding emphasizes the need to address both soil pH and nutrient availability. Corroboratively, Opala *et al*. (2018) observed that combining organic and inorganic amendments improved maize productivity in acidic soils in Western Kenya. This suggests that a balanced approach may be required for crop performance and long–term soil health.

For instance, Wondimu and Tekalign's (2011) study in the Ethiopian highlands showed that adding lime to acidic soils combined with organic fertilizers greatly raised their pH, lowering aluminum toxicity and boosting the availability of vital nutrients like phosphorus. As a result, tuber quality improved, and potato yield increased significantly. Because organic additions improve SOM and enhance soil structure, the study also stressed the need to apply them to preserve long–term soil fertility.

Researchers like Bizimana *et al*. (2012) observed that utilizing both organic and inorganic fertilizers together improved potato yields in Rwanda when compared to using only one kind of amendment. This research focused on the application of ISFM technologies in potato cultivation. According to the study, the region's acidic soils reacted well to lime treatment, which enhanced crop production and nutrient usage efficiency when coupled with organic inputs.

These case studies imply that the combined use of these amendments can be a successful tactic for overcoming the difficulties presented by acidic soils and obtaining high potato yields in areas with the same soil characteristics. The potato industry in Kenya's highlands, where soil acidity is a significant productivity barrier, can benefit from the knowledge gained from these investigations.

It is commonly known that both organic and inorganic amendments affect potato productivity and that an integrated strategy produces the greatest results. Organic additions improve the soil's long–term health and fertility while artificial fertilizers supply the necessary minerals for crop development right away. Case studies from areas where the soil is acidic, like Molo's, show that a combination of these amendments may efficiently reduce acidity in the soil, increase nutrient availability, and increase yields of potatoes. The significance of using sustainable and well–balanced soil management techniques in potato cultivation is highlighted by these results.

Sustainability of amendment practices in potato farming

The long–term viability of soil amendment techniques in potato farming relies on striking a balance between high crop yield and soil health maintenance. For maximum development and productivity, potatoes are a nutrient–demanding crop that needs sufficient amounts of phosphorus, potassium, and nitrogen. Consequently, to provide the crop with the nutrients it requires while preserving soil fertility over time, it is frequently required to apply both inorganic and organic amendments. Compost and manure are two examples of organic amendments that are very helpful in potato farming because they improve soil structure, retain more water, and increase nutrient availability—all of which are essential for the growth of tubers (Larkin *et al*. 2010; Nyawade *et al*. 2021). Furthermore, organic amendments aid in the accumulation of SOM, which improves the soil's capacity to absorb nutrients and buffer pH variations, thereby lowering the frequency of lime or inorganic fertilizer treatments.

In potato growing, inorganic supplements like lime and synthetic fertilizers are also crucial, especially in soils with high acidity or poor fertility. However, it is crucial to apply these techniques sparingly and in conjunction with organic amendments to guarantee the sustainability of these methods (Otieno *et al*. 2022; Ranjan *et al*. 2025; Sumit *et al*. 2025). Long–term soil health maintenance, environmental impact reduction, and high levels of potato production may all be achieved using INM techniques that incorporate the benefits of both organic and inorganic amendments (Vanlauwe *et al*. 2010).

The combined use of lime and organic amendments has been demonstrated to be very beneficial in lowering soil pH, promoting nutrient availability, and raising potato yields in areas like Molo, where soil acidity is a key barrier to potato cultivation (Mugwe *et al*. 2009). Rotational cropping and cover cropping techniques are used to preserve soil fertility and lower the risk of soil degradation, as well as routine monitoring of soil pH, SOM levels, and nutrient status is necessary for the sustained viability of these activities (Onyuka *et al*. 2025; Nungula *et al*. 2023; Nasar *et al*. 2025).

NUTRIENT USE EFFICIENCY (NUE) IN ACIDIC SOILS

Concepts and metrics of NUE in crop production

NUE describes a plant's capacity to take in and use nutrients from the soil for its productivity (Nduwimana *et al*. 2020). The ratio of crop yield to the quantity of fertilizer applied or accessible in the soil is typically used to quantify it. Physiological Efficiency (PE), which measures the increase in biomass per unit of nutrient uptake, Apparent Recovery Efficiency (ARE), which indicates the percentage of applied nutrients that are absorbed by the crop, and Agronomic Efficiency (AE), which measures the increase in crop yield per unit of nutrient applied, are important metrics used to quantify NUE (Ladha *et al*. 2005; Dobermann, 2007; Raza *et al*. 2025).

Challenges brought on by low pH levels make the idea of NUE especially crucial in acidic soils. Acidic soils frequently increase the solubility of harmful elements like aluminum (Al) and manganese (Mn) while decreasing nutrient availability, especially important macronutrients like phosphorus (P) and potassium (K) (Fageria and Baligar, 2008). These elements have the potential to greatly diminish NUE, which would result in decreased crop output and a need for farmers to use more fertilizer—a practice that is unsustainable from an economic and environmental standpoint.

Factors influencing NUE in acidic soils

NUE is a complicated and changeable measure that depends on soil conditions, crop types, and management approaches. Several factors impact NUE in acidic soils, and pH is one of the main variables. Sims and Pierzynski (2005) found that low pH values, usually less than 5.5, increase the solubility of aluminum and iron, which can combine with phosphorus to create insoluble compounds and reduce the amount of phosphorus available to plants. One significant barrier to NUE in acidic soils is the decrease in phosphorus that is readily accessible.

OM available in the soil is another important component. By strengthening soil structure, raising cation exchange capacity, and offering a slow–release source of nutrients, organic matter can increase NUE (Chivenge *et al*. 2011). However, because there is less microbial activity in acidic soils, organic waste might decompose more slowly, which can worsen problems with nutrient availability.

NUE is also significantly influenced by the type of crop and its genetic ability to withstand low pH and nutrient-poor environments. Reduced growth and productivity can result from some crops, such as potatoes, being more susceptible to nutrient imbalances and acidic soil (Marschner, 2012). NUE can also be impacted by crop management techniques, such as when and how fertilizer is applied. By coordinating nutrient availability with crop demand, slow-release formulations or split applications of nitrogen fertilizers, for instance, might enhance NUE (Fageria, 2009; Shadrack *et al.* 2020).

Role of amendments in enhancing NUE for potatoes

For crops that require a lot of nutrients, like potatoes, improving NUE in acidic soils requires both organic and inorganic soil additions. One of the most popular inorganic additions for increasing soil pH and lowering aluminum toxicity is lime. Lime may dramatically increase phosphorus and other vital nutrient availability by counteracting soil acidity, which raises NUE (Haynes, 1982). According to studies, liming acidic soils can significantly increase potato yields because they reduce aluminum toxicity and enhance the soil's general nutritional balance (Fageria and Nascente, 2014).

In acidic soils, organic amendments like compost, manure, and charcoal are also essential for increasing NUE. By adding organic matter to the soil, these amendments improve nutrient cycling, microbial activity, and the soil's physical characteristics (Agegnehu *et al.* 2016; Sagar *et al.* 2024). To support potato growth throughout the growing season, compost, for instance, can improve the soil's ability to hold onto nutrients, lower leaching losses, and offer a slow–release supply of nutrients (Wolfe *et al.* 2003).

Demonstrably, enhancing NUE in acidic soils is especially possible with the application of ISFM techniques, which incorporate both organic and inorganic inputs. Farmers may establish a more sustainable and balanced nutrient supply that satisfies potato demands while also enhancing soil health by combining lime, OM, and inorganic fertilizers (Nasar *et al.* 2022; Saeid *et al.* 2023; Mishra *et al.* 2026; Vanlauwe *et al.* 2015). This integrated method improves agricultural systems' long–term sustainability on acidic soils while simultaneously increasing crop yield.

FUTURE TRENDS IN ACIDIC SOIL MANAGEMENT

In the future, there are several interesting trends and avenues for study in acidic soil management, especially as it relates to potato production. The application of precision agricultural technology is one growing field of interest (Sagar *et al.* 2023; Bhat *et al.* 2025). The application of soil amendments will now be done more precisely and site–specifically, thanks to technology like GPS–guided application devices and soil sensors. Because of this accuracy, soil management techniques are more affordable, environmentally friendly, and accessible to smallholder farmers (Ngugi *et al.* 2022). Waste is also reduced, and expenses are minimized (Mulla, 2013).

The creation of more affordable and environmentally friendly soil supplements is a significant area of ongoing study. For example, biochar, a type of charcoal made from organic waste, has demonstrated the ability to improve soil structure and water retention in addition to neutralizing soil acidity (Sahoo *et al.* 2024). The creation and use of biochar for use in a variety of soil types, including those prevalent in potato–growing regions, is still being researched (Lehmann and Joseph, 2015).

Another strategy for managing soil holistically that is gaining traction is the combination of organic and inorganic amendments (Jamal *et al.* 2022). By combining these amendments, one may benefit from both the long–term benefits of organic matter for soil health and the quick pH adjustment that lime offers. Particularly in places with limited resources, this integrated strategy may offer a better long–term solution for controlling acidic soils in potato cultivation (Sistani *et al.* 2004).

In summary, while controlling acidic soils for potato farming comes with many obstacles, there are also many chances for creativity and advancement. Eliminating these obstacles and improving potato yield in acidic soils will need ongoing research and development in soil amendment technologies in conjunction with efficient extension services.

Simulation models for predicting amendment effects

In agricultural research, simulation models are now essential tools, especially for anticipating how soil amendments would affect crop production and soil attributes. Using these models, researchers can mimic the intricate relationships that exist between crop growth, soil, water, and nutrients in a variety of environmental settings and management scenarios. To comprehend and forecast the behavior of agricultural systems, simulation models are computational illustrations of real-world processes. Models like CERES (Crop Environment Resource Synthesis), APSIM (Agricultural Production Systems Simulator), and DSSAT (Decision Support System for Agro–Technology Transfer) are frequently used in soil research. These models mimic how different elements, such as soil amendments, affect crop performance and soil characteristics. They can evaluate the long–term effects of various management techniques, including lime addition, on soil health.

Applications of models in predicting amendment effects on soil properties

It has proven successful in forecasting how soil additions, such as lime and organic matter, would affect the attributes of the soil and crop yields using models like APSIM and DSSAT. To produce precise forecasts, these models take into account a variety of factors, including crop type, weather patterns, and soil type. For example, models can replicate the effects of lime treatment on soil pH in acidic soils and how this alteration affects potato yield and nutrient availability across many growing seasons. These kinds of simulations are helpful in fine-tuning amendment tactics so that crops get the nutrients they need without degrading the soil over time (Zhang *et al*. 2021; Nungula *et al*. 2023).

Case studies of simulation models in acidic soils

In acidic soils, case studies utilizing computer models have demonstrated how additions may dramatically change the characteristics of the soil and increase crop productivity. Studies that used the CERES model, for instance, showed how adding lime to acidic soils increased nutrient absorption and decreased soil acidity, which in turn promoted maize root development. Similar to this, APSIM has been used to model how different organic and inorganic additions affect the carbon content of soil and the cycling of nutrients, providing information about how sustainable these techniques are over the long run (CERES, 1993; Lizaso and Ritchie, 1997).

Summarily, researchers may optimize amendment techniques for improved soil health and crop production by using simulation models, which are useful tools for forecasting the impacts of soil amendments. These models offer a scientific foundation for agricultural decision–making, where soil acidity is the main obstacle to potato production.

CHALLENGES AND OPPORTUNITIES IN MANAGING ACIDIC SOILS FOR POTATO FARMING

Major challenges in adopting amendment practices

Specifically in potato growing, managing acidic soils poses several technical and socioeconomic difficulties. The high expense of lime and other additions needed to neutralize soil acidity is the major obstacle. Parts of Kenya and many other poor nations sometimes lack the financial means for farmers to buy these amendments in large enough amounts. Due to this financial barrier, soil correction techniques are not widely adopted, which keeps potato production conditions below ideal levels (Kisinyo *et al*. 2014).

One major obstacle is the variation in soil properties among small–scale farms; soil acidity can differ significantly even among farms, which makes it challenging for farmers to apply amendments consistently and efficiently. This problem is exacerbated by the restricted availability of soil testing services, which are crucial for identifying the precise requirements for lime and other amendments. In the absence of accurate soil pH information, farmers cannot apply the right number of amendments, which can result in either over– or under–application, both possibly having detrimental effects on soil health and crop productivity (Bolan *et al*. 2013).

Furthermore, farmers are not well–informed about the advantages of using soil amendments. Many farmers are reluctant to engage in these methods because they are unaware of the long–term benefits of utilizing lime and other organic and inorganic amendments. Inadequate extension services that do not give farmers the required information and training frequently make this knowledge gap worse (Vanlauwe *et al*. 2010).

Comparison of methodologies, findings, and implications for potato farming

A popular methodology used in this research to compare approaches is the application of randomized complete block designs (RCBD) to evaluate the effect of various amendments on crop yields and soil attributes. This strategy yields more dependable findings and permits controlling variability within the experimental location. The target crops and the local soil conditions, however, have a significant effect on the particular types of amendments and the rates at which they should be applied. For instance, Haile *et al*. (2023) included organic additions such as farmyard manure, which has implications for sustainability and long–term soil health, whereas Kisinyo *et al*. (2014) concentrated on the usage of lime and phosphorus fertilizers. The particular requirements of the crops under study have an impact on the variations in amendment selection. When growing potatoes, the consequences of soil acidity in potato farming are obvious: the most effective way to control soil acidity and increase potato productivity may be to combine organic and inorganic amendments. Reduced tuber quality and production might result from acidic soil (Kisinyo *et al*. 2014).

According to the results of these investigations, lime can immediately neutralize soil acidity, but its benefits cannot last long and may need to be applied again. On the other hand, organic additions such as farmyard manure not only aid in adjusting pH levels over time but also enhance soil organic matter and nutrient availability. This suggests that an approach for potato cultivation that combines long–term soil health management with an immediate pH adjustment may be more successful.

Economic and environmental considerations in soil management

For farmers, the cost-benefit ratio of applying soil amendments is a crucial factor when making financial decisions. Although using lime and other amendments might greatly boost potato yields, there is a chance that the upfront expenses will exceed the long–term gains. Due to the volatile potato market, smallholder farmers face unclear returns on their investments, making it a hazardous financial move (Chivenge *et al*. 2011). The necessity for periodic lime treatments adds to this uncertainty because the benefits of lime are not long-lasting and tend to wear off over time.

Acidic soil management also heavily relies on environmental considerations. Overuse of inorganic fertilizers, especially those containing nitrogen, can make soil acidity issues worse (Shadrack *et al*. 2020). This is because soil pH is lowered and hydrogen ions are produced during the nitrification process. Furthermore, fertilizer runoff poses a serious environmental risk by contributing to the eutrophication of neighboring water bodies (Guo *et al*. 2010; Nyawade *et al*. 2021). However, even though they are usually better for the environment, organic supplements cannot always offer the quick pH adjustment that is required for the best possible potato yield. Thus, successful soil management requires a balanced strategy that takes into account both environmental sustainability and economic feasibility.

Future Research

There are still a lot of unanswered questions regarding soil amendments in acidic soils despite the abundance of studies in this area. Research on the long–term impacts of integrated organic and inorganic amendments in potato growing and exchangeable acidity is severely lacking, especially in areas with unique agro-ecological circumstances. Long–term trials are required to evaluate the sustainability and financial feasibility of these techniques, as most studies have concentrated on short–term results.

Inadequate studies on the application of substitute amendments in acidic soils, such as biochar, are another gap. Although biochar has demonstrated potential for enhancing soil characteristics, its use in acidic potato growing has not been thoroughly investigated. Future studies should examine biochar's potential as a sustainable supplement that improves soil water retention, carbon sequestration, and pH neutralization.

Furthermore, further site-specific research is required, taking into account the distinct soil and climate of various potato–growing locations. Research of this kind might aid in the creation of customized amendment strategies that optimize potato yields while preserving soil health. Future study in the field of contemporary technology integration into amendment methods, such as precision agriculture and remote sensing, seems promising since they might lead to more effective and focused soil management techniques.

CONCLUSION AND RECOMMENDATION

In conclusion, a comprehensive strategy incorporating both organic and inorganic amendments is needed to manage acidic soils for increased potato productivity. Although its advantages are frequently fleeting, the reviewed literature highlights the value of lime as a conventional supplement for balancing soil acidity and enhancing nutrient availability. However, in addition to raising soil pH over time, organic amendments like compost, biochar, and farmyard manure also help to improve soil structure, nutrient cycling, and water retention. The combination of inorganic and organic amendments has proven to be especially successful since it increases soil fertility, improves nutrient uptake, and increases potato yields. However, a number of factors, including soil characteristics, climate, and application rates, affect how successful these supplements are, so careful thought and accuracy are required. The application of amendments could be optimized with the integration of precision agriculture technologies, such as soil sensors and GPS-guided application devices, making it more economical and ecologically friendly. Furthermore, the creation of more environmentally friendly and sustainable additions, like biochar, presents encouraging ways to boost carbon sequestration, improve soil health, and slow down environmental deterioration. Notwithstanding these developments, obstacles still exist that prevent the broad use of these techniques, such as the high price of amendments, a lack of farmer awareness, and restricted access to soil testing services.

Future studies should therefore concentrate on removing these obstacles, investigating the long-term effects of integrated amendment strategies on soil productivity and health, and assessing the viability of sustainable soil management techniques from an economic standpoint. Enhancing extension services, providing farmers with greater access to resources and training, and encouraging the creation of reasonably priced, eco-friendly amendments should also be top priorities for policymakers in order to facilitate the widespread adoption of soil management techniques and guarantee long-term increases in potato sustainability and productivity.

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