Journal homepage
www.ajas.uoanbar.edu.iq
Anbar Journal of Agricultural Sciences
(University of Anbar – College of Agriculture)

IMPROVING THE CHEMICAL PROPERTIES OF ACIDIC SOIL WITH AFFORDABLE LIME APPLICATION FOR INCREASING POTATO GROWTH AND YIELDS IN SEDIE DISTRICT, NORTHWESTERN ETHIOPIA

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Article info

Received: 2024-09-26
Accepted: 2024-11-10
Published: 2024-12-31

DOI-Crossref:
10.32649/ajas.2024.151978.1333

Cite as:
Yenesew, S. A. (2024). Improving the chemical properties of acidic soil with affordable lime application for increasing potato growth and yields in sedie district, northwestern Ethiopia. Anbar Journal of Agricultural Sciences, 22(2): 1457-1476.

Abstract

Soil acidity remains a critical issue in Ethiopia, particularly in the highland regions, where over 43% of arable lands has low pH levels. Enhancing the chemical properties of the soil and subsequent potato growth and yield through affordable lime application is a critical area of agricultural research in the country. This study examined the effects of various lime application methods in enhancing the chemical properties of acidic soils on the growth, yields, and economic returns of potato cultivation. Each experimental plot had gross and net sizes of 2.1 m × 4.5 m (9.45 m^2) and 1.5 m × 3 m (4.5 m^2), respectively. The buffer method application involved a range of 2.5 t ha^{-1} to 10 t ha^{-1}, while the exchangeable acidity method was from 0.84 t ha^{-1} to 3.36 t ha^{-1}. The experiment layout included lime treatments of full broadcast, fractional, and drill-applied methods, evaluated against a control. Results showed that lime application significantly ($P \leq 0.01$) enhanced soil chemical properties, achieving a pH of 6.26, exchangeable acidity 0.32 $Cmol_{(+)}$ kg^{-1}, exchangeable aluminum 0.00 $Cmol_{(+)}$ kg^{-1}, cation exchange capacity 29.43 $Cmol_{(+)}$ kg^{-1}, available phosphorus of 13.32 mg kg^{-1}, and organic carbon of 2.06%. Additionally, potato productivity reached 26.21 t ha^{-1} for total yield with the full buffer method

(FBM). In particular, 0.25 EAM demonstrated a superior marginal rate of return (MRR) of 829%, indicating an optimal balance between yield gains and economic feasibility. These findings reveal that partial lime applications offer an affordable alternative for smallholder farmers.

Keywords: Affordable, Fractional, Buffer method, Drilling, Potato, Sedie district, Soil acidity.

تحسين الخصائص الكيميائية للتربة الحمضية بتطبيق الجير بتكلفة ميسورة لزيادة نمو وإنتاجية البطاطس في منطقة سيدي، شمال غرب إثيوبيا

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الخلاصة

تبقى حموضة التربة المشكلة الاهم في إثيوبيا، خصوصا في المناطق المرتفعة، حيث أن أكثر من 43% من الأراضي الصالحة للزراعة لها مستويات منخفضة من الرقم الهيدروجيني. إن تعزيز الخصائص الكيميائية للتربة ونمو البطاطس وإنتاجيتها بواسطة مادة الجير بأسعار معقولة هو مجال بالغ الأهمية للبحث الزراعي. فحصت هذه الدراسة آثار طرق تطبيق الجير المختلفة في تعزيز الخصائص الكيميائية للتربة الحمضية على نمو وانتاج البطاطس والعائدات الاقتصادية. كان لكل وحدة تجريبية مساحة إجمالية وصافية تبلغ 2.1 م × 4.5 م (9.45 م^2) و1.5 م × 3 م (4.5 م^2). تشمل تطبيق طريقة العازل (buffer) نطاقًا يتراوح بين 2.5 طن هكتار$^{-1}$ إلى 10 أطنان هكتار$^{-1}$، بينما كانت طريقة الحموضة القابلة للتبادل من 0.84 طن هكتار$^{-1}$ إلى 3.36 طن هكتار$^{-1}$. وقد تضمن مخطط التجربة معالجات الجير بأساليب النشر الكامل والجزئي والاضافة بالحفر، والتي تم تقييمها مقابل وحدة تجريبية للمقارنة(control). وأظهرت النتائج أن تطبيق الجير عزز بشكل كبير (P ≤ 0.01) خصائص التربة الكيميائية، حيث حقق درجة حموضة 6.26، وحموضة متبادلة 0.32 سي مول (+) كجم$^{-1}$، وألمنيوم متبادل 0.00 سي مول (+) كجم$^{-1}$، وسعة تبادل الكاتيون 29.43 سي مول (+) كجم$^{-1}$، والفوسفور الجاهز 13.32 مجم كجم$^{-1}$، والكربون العضوي 2.06٪. بالإضافة إلى ذلك، وصلت إنتاجية البطاطس إلى 26.21 طن هكتار$^{-1}$ للغلة الكلية مع طريقة العزل الكامل .(FBM) وعلى وجه الخصوص، أظهرت طريقة 0.25 EAM معدل عائد متفوق (MRR) بنسبة 829٪، مما يشير إلى توازن مثالي بين

مكاسب الغلة والجدوى الاقتصادية. وتكشف هذه النتائج أن تطبيقات الجير الجزئية تقدم بديلاً ميسور التكلفة لمزارعي الحيازات الصغيرة.

كلمات مفتاحية: ميسور التكلفة، جزئي، طريقة المخزن المؤقت، الحفر، البطاطس، منطقة سيديي، حموضة التربة.

Introduction

Soil acidity is a critical factor influencing agricultural productivity and the health of ecosystems worldwide (60). It affects approximately 50% of the world's arable land, posing significant challenges to crop yields and soil fertility (59). In Ethiopia, the issue is particularly severe due to the country's diverse agro-ecological zones and heavy reliance on traditional farming practices, with soil acidity affecting over 43% of the arable land and significantly impairing agricultural productivity (35). This widespread problem limits crop growth and development, serving as a major constraint in achieving optimal agricultural productivity (43).

Potato production holds great agricultural importance worldwide (7). With an annual area coverage of roughly 19 million hectares, global potato yields reach around 370 million metric tons, emphasizing its role as a staple food and a critical component of food security (22). In Africa, potatoes cover about 1.76 million hectares, yielding 26.53 million tons at an average productivity of 15.04 tons per hectare (18 and 29). Potato cultivation in Ethiopia covered 85,988 hectares in 2020/21, producing 1.14 million tons and an average yield of 13.28 tons per hectare, placing Ethiopia 11th in Africa and contributing 0.25% to global potato production (4). Potatoes are crucial to food security in Ethiopia due to their high yield, nutritional value, short growth period, and adaptability.

Despite its widespread cultivation, potato production worldwide is significantly constrained by soil acidity. In Ethiopia, the issue is especially pronounced in the highlands of Amhara and Oromia, where ongoing cultivation and high rainfall accelerate soil degradation (41). Soil pH levels below 5.5 cause aluminum toxicity and phosphorus deficiency, reducing potato yields (42). Potatoes thrive best in soils with a pH range of 5.0 to 6.5, and acidic soils disrupt this balance leading to nutrient deficiencies, aluminum and manganese toxicity, and reduced microbial activity (44). Acidic soils reduce the availability of essential nutrients like phosphorus, calcium, and magnesium, which are critical for potato growth (32). Aluminum and manganese toxicity under acidic conditions inhibits root development and nutrient uptake, while soil acidity suppresses beneficial microorganisms involved in nitrogen fixation and organic matter decomposition, further limiting nutrient availability (27). The high presence of aluminum (Al^{3+}), manganese (Mn^{2+}), and hydrogen (H^{+}) ions in Ethiopian soils is largely attributed to acidic parent materials, high rainfall, and ongoing soil weathering processes (53). Intense rainfall in the Ethiopian highlands leaches away basic cations, leaving behind H^{+}, Al^{3+}, and Mn^{2+}, which accumulate in soils with poor drainage (40). Continuous weathering further releases these ions, raising acidity levels, while some agricultural practices, such as ammonium fertilizer use, exacerbate the problem (3).

Additionally, Ethiopian soils exhibit a diverse range of buffering capacities influenced by variations in soil mineralogy, organic matter content, and management practices across different agro ecological zones (21). Land use and soil management practices further influence soil-buffering capacity. Intensive farming, particularly with high fertilizer use and limited organic residue retention, has led to gradual soil acidification and a reduction in CEC, especially in highly weathered soils (58).

Lime application practices significantly raise the soil pH, temporarily increasing buffering capacity while neutralizing acidity in soils with low pH and high exchangeable acidity (24). Therefore, this study focused on improving soil chemical properties and the growth and yield of potatoes in acidic soils through affordable lime applications, particularly in the Sedie District of the East Gojjam Administrative Zone in North West Ethiopia. Specifically, the study aimed to: 1- enhance soil chemical properties with affordable lime applications, 2- evaluate the effect of different lime application rates on potato growth and yield, and 3- determine the optimal lime rate feasible for small-scale farmers for reducing soil acidity with minimal expenditure.

Materials and Methods

Study Area: The study was conducted in Sedie district located within the East Gojjam Administrative Zone of the Amhara National Regional State, Ethiopia. Geographically, the district lies between latitudes 10° 52' to 11° 3' N and longitudes 36° 38' to 37° 8' E. It is situated approximately 137 and 370 kilometers south of Bahir Dar, and northwest of Addis Ababa, respectively. The altitude of the district ranges from 1889 to 4082 meters above sea level (Fig 1).

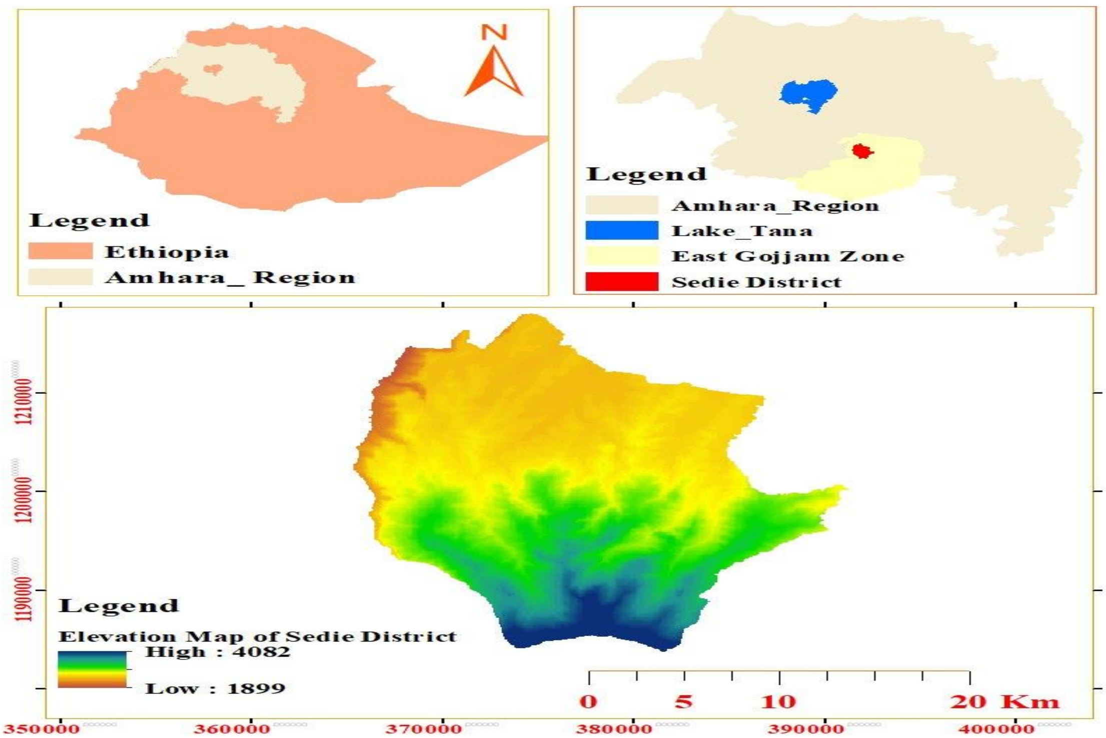

Figure 1: Location Map of Sedie District, East Gojjam Zone, Amhara Region, Ethiopia.

Soil Sampling: Soil sampling procedures were conducted in two critical stages: before liming and after liming (harvesting of the potato crop). These stages were chosen to evaluate the soil's response to liming and its influence on the potato crop. Pre-liming soil sampling was conducted in a systematic manner to ensure uniformity and representativeness. Composite soil samples were collected in a crosswise pattern across the experimental field to capture soil variability. Samples were taken from the surface layer, between a depth of 0 to 20 cm, which is the active root zone for many crops and crucial for assessing nutrient availability and soil condition. To ensure sample size consistency, each sub-sample (n = 10) was extracted using a vertical auger, a tool designed to penetrate the soil to a precise depth and retrieve a uniform core of soil.

This method was repeated at ten different points across the field, following a crosswise pattern. These sub-samples were then combined to form a single composite sample representing the average condition of the soil prior to liming. Once collected, the sub-samples were carefully handled to prevent contamination. Each sample was labeled both inside and outside the plastic bags to avoid any mix-up during transport or storage. Labels included detailed information such as plot number, date, and specific treatment. From the composite sample, 1 kg of soil was carefully separated and packed for transportation to the laboratory for detailed analysis. This sample was then subjected to a series of tests to determine baseline soil properties.

Post-liming soil sampling was carried out after the potato crop was harvested, ensuring that the effect of the liming treatment on soil properties could be accurately assessed. Soil samples were collected from each individual plot within the replications (n = 28), immediately following harvest to capture any changes in soil characteristics resulting from the liming treatment and the crop's growth cycle. In this phase, similar sampling techniques were applied. The same depth of 0 to 20 cm was maintained, and the vertical auger was again used to ensure consistency in sample volumes. These post-harvest samples were also carefully labeled and transported to the laboratory for comparative analysis against the pre-liming samples. This allowed for a detailed evaluation of the impact of liming on soil chemical properties over the course of the potato crop's growth period.

Soil Sample Preparation: The dried soil samples were first finely ground using a pestle and mortar to ensure the soil particles were broken down to a consistent size, promoting uniformity in subsequent analyses. Following this, the ground samples were passed through a 2-mm sieve, ensuring that only fine particles remained. This sieving step was essential for eliminating larger debris and ensuring a homogeneous sample suitable for testing various soil parameters. To obtain an accurate estimation of total nitrogen (TN), an additional step was performed where the samples were further refined by passing them through a 0.5 mm sieve. This finer sieve was used specifically for nitrogen testing to ensure precise measurements, as finer particles provide more reliable results.

Soil Analysis Procedures: Soil texture was analyzed using the Bouyoucos Hydrometer method, which determines the proportions of sand, silt, and clay by dispersing soil particles in water and measuring their settling rates with a hydrometer (13). Soil bulk density was determined using the core sampler method, where a known volume of soil is extracted, oven-dried at 105°C for 24 hours, and weighed. Bulk density is calculated as the dry soil mass divided by the soil volume (9). The soil pH was measured using a 1:2.5 soil-to-liquid ratio. This involved mixing a predetermined amount of soil with distilled water and thoroughly stirring the mixture. The pH was measured using a pH meter, providing essential information about the soil's acidity or alkalinity.

Additionally, a buffer pH assessment was conducted. For this, 20 ml of Shoemaker, McLean, and Pratt (SMP) buffer solution was added to the soil-water mixture, allowing for a more in-depth understanding of the soil's buffering capacity. Exchangeable acidity was quantified using McLean's method (39). In this procedure, the soil was saturated with potassium chloride (KCl) to displace exchangeable hydrogen ions. The solution was then titrated with sodium hydroxide (NaOH), allowing the exchangeable acidity to be precisely measured. The estimation of exchangeable aluminum followed Thomas's method (54) where 10 ml of 1M sodium fluoride (NaF) solution was added to the soil. This process helped to complex the aluminum ions, which were then titrated with 0.1M hydrochloric acid (HCl) until the pink color disappeared, indicating the endpoint.

The cation exchange capacity (CEC), a crucial indicator of soil fertility, was measured following Chapman's method (15). The soil was first saturated with 1N ammonium acetate (NH_4OAc), which replaced other cations on the soil's exchange sites with ammonium ions. The displaced cations were then extracted using 1N sodium acetate (NaOAc), and the CEC calculated based on the ammonium ions exchanged. The available phosphorus was determined using the Olsen method (45) involving the extraction of phosphorus from the soil using a sodium bicarbonate ($NaHCO_3$) solution. The phosphorus content in the extract was then measured using a colorimetric analysis, which determines phosphorus concentration based on the intensity of the color produced in the solution.

The organic carbon content of the soil was analyzed using (57) method. This involved oxidation of organic matter in the soil using potassium dichromate ($K_2Cr_2O_7$) in the presence of sulfuric acid (H_2SO_4). The resulting reaction indicated the amount of organic carbon, which was then measured through titration. Total nitrogen content was determined using the Kjeldahl method (26), which involves digestion of the soil's organic matter with sulfuric acid (H_2SO_4) to convert nitrogen into ammonium sulfate. The ammonia (NH_3) released during the process was distilled and then quantified, providing an accurate measure of the total nitrogen in the soil.

Experimental Set up and Treatments: On-farm field experiments were conducted to evaluate the effects of different lime application methods and rates on soil properties and potato crop performance for the 2023 irrigation season using a randomized complete block design (RCBD) with four replications. Each experimental plot had a gross size of 2.1 m x 4.5 m (9.45 m^2) and a net of 1.5 m x 3 m (4.5 m^2). Row spacing was maintained at 0.75 m, while individual potato plants were placed at intervals of 0.3 m. A 1-meter spacing was maintained between both blocks and individual plots to reduce potential edge effects and ensure consistent environmental conditions across treatments.

Two methods of lime amount determination were followed. The buffer method relied on SMP soil-buffer pH values calibrated by (51) to achieve a targeted soil pH of 6.5, starting from an initial pH of 5.7. Conversely, the lime requirement based on exchangeable acidity was contingent upon specific factors including soil mass per 15 cm hectare-furrow-slice, soil bulk density (BD = 1.4 Mg m^{-3}), and concentrations of exchangeable Al^{3+} and H^{+} ions at the site. It was presumed that the neutralization of one mole of exchangeable acidity required an equivalent mole of $CaCO_3$ (30).

$$LR, CaCO_3\ (kg/ha) = \frac{EA * 0.15\, m * 10^4\ m^2 * B.D. * 1000}{2000} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

Equation 1

The determined amounts of lime were applied through broadcast and drilling applications. The former included treatments with a full dose of the buffer method (10 t ha^{-1}), half of the buffer method (5 t ha^{-1}), and a full dose of the exchangeable acidity method (3.36 t ha^{-1}). For drilling along the row, the treatments consisted of half of the exchangeable acidity method (1.68 t ha^{-1}) and quarter doses of both the buffer (2.5 t ha^{-1}) and the exchangeable acidity (0.84 t ha^{-1}) methods. The amounts of lime applied in each plot are as shown in Table 1.

Table 1: Lime amount treatment and application methods.

No	Treatment	Description	Lime t ha^{-1}	Lime kg $plot^{-1}$	Application method
1	T1	Control	----	----	----
2	T2	Full buffer method (FBM)	10	9.45	Broadcast
3	T3	Half buffer method (1/2 BM)	5	4.73	Broadcast
4	T4	Full exchangeable acidity (FEAM)	3.36	3.18	Broadcast
5	T5	One fourth buffer method (1/4 BM)	2.5	2.36	Drilling
6	T6	Half exchangeable acidity (1/2 EAM)	1.68	1.59	Drilling
7	T7	One-fourth exchangeable acidity (1/4 EAM)	0.84	0.79	Drilling

Cultural techniques: Four rounds of ploughing were involved to ensure that the soil was well prepared in the best possible condition for successful cultivation. Finely powdered lime, with precise particle sizes of 0.045 mm, was integrated into the soil to a depth matching the furrow slices. This thorough incorporation aimed to enhance reactivity and ensure complete interaction with the soil prior to planting, across six distinct treatment regimes.

Growth and potato yield data collection: The following yield and yield components of potato were collected.

1. Days to 50% emergence: number of days from sowing to emergence of 50% of the plants in each plot.
2. Days to 50% flowering: number of days for 50% of the plants in a plot to reach flowering stage.
3. Plant height (cm): measured from the base (soil surface) to the apex (highest point) of the plant. This was determined by measuring the height of 5 randomly selected plants within the central three rows of each plot at the flowering stage.

4. Number of main stems per hill: counted based on the stems originating from the tuber in 5 randomly selected hills per plot. The average number of stems was calculated and used as a parameter to determine the plant's branching pattern and its potential impact on tuber yield.
5. Marketable tuber yield (t ha^{-1}): total weight of tubers that were free of diseases, insect pests, and other defects, as well as those weighing 25 g or more. Only tubers meeting these criteria were considered marketable. The total weight of marketable tubers was recorded for each plot and expressed in tons per hectare (t ha^{-1}). This yield was crucial in evaluating the economic value of the crop.
6. Total tuber yield (t ha^{-1}): provides an overall assessment of the crop's productivity under the different lime application treatments and recorded in tons per hectare.

Statistical and Economic Analysis: Following collection, the data underwent rigorous statistical scrutiny using analysis of variance (ANOVA) conducted with SAS version 9.3 software. Mean comparisons among treatments were performed using the least significance difference (LSD) test at both 1% and 5% significance levels. Further differentiation of treatment outcomes was accomplished through mean separation using the Duncan multiple range test (DMRT).

Economic Analysis: A partial budget analysis was conducted following the (16) methodology to evaluate the costs and benefits of the treatments. Market prices were determined from actual field rates received by local farmers near the experimental site in Sedie. Inputs such as $CaCO_3$, urea, and NPS served as sources of lime, nitrogen, and phosphorus fertilizers, respectively, with their costs calculated in Birr per kilogram. Gross benefits were computed by multiplying the marketable tuber yield (kilograms per hectare) by the prevailing field price of potatoes. Total variable costs (TVC) were derived from expenses specific to each treatment relative to the control. Net income (NI) was subsequently determined by deducting total variable costs from gross benefits. The marginal rate of return (MRR) was computed as below:

$$MRR = \frac{\text{Mariginal increase in gross marign}}{\text{Mariginal increase in variable cost}} * 100$$

Results and Discussion

Pre-Liming Soil Properties of the Study Area: These indicate the need for soil management interventions in the study area (Table 2). Textures comprising 22% sand, 31% silt, and 47% clay classified the soil as clayey, and known for their high water-holding capacity but also susceptibility to compaction and poor aeration (14). The bulk density of 1.4 Mg m^{-3} falls within the optimal range for clay soils, indicating moderate compaction, which could benefit from further improvement through liming and organic matter addition (23). The strongly acidic pH of 5.2 suggests significant limitations for plant nutrient availability, with potential aluminum toxicity due to solubilization of aluminum and other metals (12). The buffer pH of 5.7 indicates some resistance to drastic pH changes, providing valuable insights for determining lime requirements.

A 3.2 cmol $_{(+)}$ kg^{-1} exchangeable acidity and very high exchangeable aluminum (2.1 cmol $_{(+)}$ kg^{-1}) (31) point to substantial soil acidity challenges, where aluminum toxicity is likely to hinder root development and nutrient uptake (49). The medium cation exchange capacity (CEC) of 20.6 cmol $_{(+)}$ kg^{-1} reflects moderate soil ability to retain and supply nutrients, which could be enhanced through liming and organic matter inputs to improve soil fertility (25). Very low available phosphorus levels (7.4 mg kg^{-1}) (31) show the need for liming to increase phosphorus availability, as it is likely bound to aluminum and iron oxides in such acidic conditions (52). Additionally, low total nitrogen (0.1%) and organic carbon (1.8%) (34) suggest limited organic matter and nitrogen availability, which are critical for plant growth and overall soil health (56).

Table 2: Pre-liming soil measurements in the study area.

No	Soil Properties	Results	Ratings	References
1	Texture (%)			
	Sand	22		
	Silt	31	Clay	(14)
	Clay	47		
2	Bulk density (Mg m^{-3})	1.4	Optimum	(23)
3	pH	5.2	Strongly acidic	(34)
	Buffer pH	5.7		
4	Exchangeable Acidity (Cmol $_{(+)}$ kg^{-1})	3.2		
5	Exchangeable Aluminum Cmol $_{(+)}$ kg^{-1})	2.1	Very high	(31)
6	CEC (Cmol $_{(+)}$ kg^{-1})	20.6	Medium	(34)
7	Available Phosphorus (mg kg^{-1})	7.4	Very low	(31)
8	Total Nitrogen (%)	0.1	Low	(31)
9	Organic Carbon (%)	1.8	Low	(34)

Impact of Lime Application on Soil Chemical Properties: Lime application significantly ($P \leq 0.01$) raised soil pH, with the full buffer method (FBM) treatment achieving the highest pH at 6.26 compared to 5.17 for the control (Table 3). This increase aligns with the method described by (14), where lime adds basic cations that neutralize acidic hydrogen ions, creating a more suitable pH for nutrient uptake. Similar studies, like that of (17), confirm that broadcast lime effectively enhances soil pH over fractional applications by covering the entire soil surface and providing more consistent lime contact. Conversely, fractional applications such as 1/2 BM and 1/4 BM reached pH values of 6.22 and 5.86, respectively, while drill-applied methods like FEAM had a lower increase at 5.74 (Table 3). This discrepancy is in line with studies indicating that spot or row applications of lime may limit pH adjustment to localized zones, reducing overall effectiveness (55).

Table 3: Effect of lime application methods on chemical properties of the soil.

Treatments	pH	Ex. Ac ($Cmol_{(+)}kg^{-1}$)	Ex. Al ($Cmol_{(+)} kg^{-1}$)	CEC ($Cmol_{(+)} kg^{-1}$)	AvP ($mg\ kg^{-1}$)	OC %	TN %
Control	5.17^{e}	3.24^{a}	2.04^{a}	19.89^{d}	7.43^{e}	1.66^{d}	0.10^{bc}
FBM	6.26^{a}	0.32^{d}	0.00^{d}	29.43^{a}	13.32^{a}	2.63^{a}	0.13^{a}
1/2 BM	6.22^{a}	0.48^{d}	0.00^{d}	27.03^{b}	12.68^{b}	2.41^{ab}	0.12^{ab}
FEAM	5.74^{b}	0.49^{d}	0.08^{d}	26.34^{bc}	11.56^{bc}	2.48^{ab}	0.12^{ab}
1/4 BM	5.86^{b}	0.67^{cd}	0.11^{d}	24.94^{bc}	10.84^{c}	2.36^{ab}	0.11^{b}
1/2 EAM	5.47^{c}	1.03^{c}	0.68^{c}	23.72^{c}	11.06^{bc}	2.28^{b}	0.11^{b}
1/4 EAM	5.35^{d}	1.42^{b}	0.92^{b}	24.06^{b}	10.45^{d}	2.09^{c}	0.10^{bc}
CV	0.68	10.96	12.76	3.14	1.81	4.62	5.82
SE ±	0.11	0.24	0.21	1.09	0.23	0.05	0.00
LSD (0.01)	0.08	0.38	0.23	1.49	0.42	0.26	0.01
P	**	**	**	**	**	**	**

Means followed by the same letters in a column are not significantly different at $p<0.01$.

Exchangeable Acidity (Ex. Ac): Exchangeable acidity was significantly ($P \leq 0.01$) reduced by lime, with FBM lowering it to 0.32 cmol $_{(+)}$ kg^{-1} compared to 3.24 cmol $_{(+)}$ kg^{-1} for the control plot (Table 3). This highlights lime's capacity to neutralize acidic ions in the soil, fostering a less toxic environment for roots as high acidity can stunt root growth and limit nutrient uptake (3). FEAM also reduced Ex. Ac to 0.49 $cmol_{(+)}$ kg^{-1}, though it was less than FBM. According to (46) surface broadcast methods create a broader reduction in exchangeable acidity than banded applications, as broadcast lime better infiltrates the soil profile. This decline is attributed to the concomitant elevation in soil pH following lime application (19).

Exchangeable Aluminum (Ex. Al): Exchangeable aluminum was significantly ($P \leq 0.01$) reduced with lime application, with the untreated control at 2.04 cmol $_{(+)}$ kg^{-1} and FBM reducing it to near-zero levels (0.00 cmol $_{(+)}$ kg^{-1}) (Table 3). This outcome is essential, as high aluminum, concentrations can damage root structures and inhibit nutrient absorption (48). Moreover, similar reductions were seen in other Ex. Al in studies, where full-rate lime application was shown to neutralize aluminum toxicity by increasing soil pH and precipitating aluminum as inert hydroxide compounds (33). Fractional applications were beneficial but had a smaller impact as some crops might tolerate moderate aluminum levels with fractional lime doses (1 and 47). This variability points to the importance of selecting lime rates based on specific crop tolerance and soil acidity levels (11).

Cation Exchange Capacity (CEC): The soil's CEC, which reflects its ability to retain and supply essential nutrients, was significantly ($P \leq 0.01$) enhanced by lime application. In particular, FBM achieved a notably high CEC of 29.43 cmol(+) kg^{-1}, a marked improvement compared to the control's 19.89 cmol(+) kg^{-1} (Table 3). This increase in CEC with lime application indicates an improvement in soil fertility, as the soil becomes more capable of holding critical nutrients, including calcium and magnesium, which are vital for plant health and productivity (8). The higher CEC in soils treated with broadcast lime, as compared to fractional or drill-applied lime, suggests that evenly spreading lime across the soil surface optimizes cation retention capacity (19).

Available Phosphorus (AvP): Lime application enhanced available phosphorus (AvP), with the FBM treatment resulting in an AvP of 13.32 mg kg^{-1}, compared to 7.43 mg kg^{-1} for the control (Table 3). The improvement is consistent with the findings of (61), who noted that lime raises soil pH, thereby reducing phosphorus binding with aluminum and iron in acidic soils, making it more accessible to plants. According to (19) broadcast lime consistently increases phosphorus availability more than row or drill applications, which are often restricted to localized phosphorus release. Fractional applications, though effective, provided lower AvP levels compared to FBM, indicating that broad coverage is crucial in phosphorus-limited soils, particularly in high-phosphorus-demanding crops like potatoes (28).

Organic Carbon (OC %): Lime application improved organic carbon content, with FBM reaching 2.63% compared to 1.66% in the control (Table 3). Lime supports organic matter breakdown and microbial activity, which increases organic carbon levels, enhancing soil structure and nutrient cycling (14). Drill-applied and fractional lime treatments also improved organic carbon, though less than full broadcast (61). By creating a neutral pH environment, broadcast lime encourages microbial communities that help in organic matter decomposition, while fractional applications result in slower and less uniform improvements (19). Thus, the findings underscore the role of lime not only in nutrient supply but also in soil organic matter dynamics.

Total Nitrogen (TN %): Total nitrogen increased with lime application, from 0.10% in the control to 0.13% with FBM (Table 3). Enhanced microbial nitrogen cycling in limed soils leads to increased nitrogen mineralization, making nitrogen more available for plant uptake (EthioSIS, 2016). Although the TN percentage increase was modest, it highlights lime's positive effect on nitrogen availability, especially through full broadcast applications that provide uniform soil pH adjustments. Fractional and drill-applied lime treatments also raised TN but were less than FBM, supporting findings by (38) that lime's influence on soil nitrogen is maximized with uniform, high-rate applications.

Effect of lime application on potato growth and yields:

Germination Rate (50%): The study found no significant effect of lime application on germination rates (Table 4). Lime primarily affects later growth stages rather than germination (2). The lack of impact on germination aligns with the theory that lime's benefits, such as acidity reduction and nutrient availability, accumulate gradually over time (6). Furthermore, early-stage germination relies more on seed nutrient reserves than on external soil conditions, including pH and nutrients affected by lime application (5). This study suggests that potatoes are less responsive to lime during germination, possibly due to their relatively high reliance on seed reserves during early growth.

Table 4: Effect of lime application on growth and yield of potatoes.

Treatments	50% Germination	50% Flowering	Plant Height (cm)	No of Main Stems	Marketable Yield (t ha^{-1})	Total yield (t ha^{-1})
Control	18.23	46.32^{c}	38.26^{c}	2.36^{d}	17.68^{c}	19.32^{c}
FBM	18.16	61.64^{a}	49.02^{a}	4.22^{a}	24.32^{a}	26.21^{a}
1/2 BM	18.02	58.68^{b}	48.13^{a}	3.64^{b}	22.46^{ab}	24.09^{ab}
FEAM	17.98	57.47^{bc}	48.01^{a}	3.03^{c}	21.08^{b}	22.44^{ab}
1/4 BM	17.42	55.84^{bc}	44.67^{ab}	2.86^{c}	20.09^{bc}	21.47^{ab}
1/2 EAM	17.01	51.35^{bc}	43.25^{ab}	2.92^{c}	19.68^{bc}	20.92^{b}
1/4 EAM	17.13	50.92^{bc}	42.89^{b}	2.69^{c}	19.87^{bc}	20.98^{b}
CV	5.67	6.89	7.23	8.26	5.74	5.62
SE ±	0.16	0.73	0.81	0.12	0.26	0.31
LSD (0.01)	1.21	4.84	5.26	0.45	1.37	1.64
P	ns	**	**	**	**	**

Means followed by the same letters in a column are not significantly different at $p<0.01$.

Time to 50% flowering: The time to reach 50% flowering was significantly affected by lime treatment ($P \leq 0.01$). The FBM treatment had the earliest flowering at 61.64 days, while the no-lime control extended the period to 46.32 days (Table 4). Lime improves phosphorus availability due to pH adjustment, which is essential for early flowering (2). The current findings further align with (37), who emphasized that pH stabilization enhances calcium and phosphorus accessibility, both of which are vital for accelerating flowering. However, the effect of lime on flowering may be crop-specific, depending on nutrient demands and pH sensitivity (50). For potatoes, lime-enhanced phosphorus availability appears critical for reproductive timing, emphasizing that crops with higher phosphorus sensitivity, like potatoes, may exhibit more pronounced responses to lime than cereals (10).

Plant Height: Plant height increased significantly with lime application ($P \leq 0.01$), with the tallest plants in the FBM treatment at 49.02 cm and the shortest in the no-lime control 38.26 cm (Table 4). This supports findings by (14), who identified improved root development in limed soils as a key factor in promoting greater nutrient absorption and vegetative growth. This study's results align with this understanding, as the FBM method uniformly distributes lime, thereby enhancing soil conditions for root expansion and nutrient uptake across the plot.

Number of Main Stems: The number of main stems was significantly affected by lime treatment ($P \leq 0.01$), with the FBM having the highest number at 4.22 stems per plant and the no-lime control the lowest at 2.36 stems (Table 4). The positive response to lime application agrees with (62), who reported that lime enhances calcium and magnesium availability, which are crucial for cellular development and branching. According to (20) improved soil structure and fertility due to liming encourages increased vegetative growth and stem formation in crops like potatoes. These findings emphasize the importance of soil pH in influencing the number of main stems and other structural growth factors.

Marketable Yield: Marketable yield showed a significant response to lime application ($P \leq 0.01$), with the FBM treatment producing the highest at 24.32 t ha^{-1} and the lowest in the no-lime treatment 17.68 t ha^{-1} (Table 4). This aligns with (2), which stressed the role of phosphorus more available in limed soils in tuber development. Similarly observed that lime application enhances nutrient availability and soil structure, contributing to improved yield in tuberous crops (20). In this study, the pronounced improvement in marketable yield under acidic soil conditions highlights the need for lime in such environments.

Total Yield: Total yield was also significantly affected ($P < 0.01$), with the highest recorded in the FBM treatment 26.21 t ha^{-1} and the lowest in the no-lime control 19.32 t ha^{-1} (Table 4). This is consistent with (36), who found that lime applications in acidic soils reduced soil toxicity, thereby optimizing growth and increasing total yield. This study reinforces that the FBM method, which ensures a more even distribution of lime, leads to a more consistent improvement in yield, as opposed to other application methods.

Economic Analysis: The economic analysis of lime rate application methods on potato yield revealed the cost-effectiveness and profitability of various treatments (Table 5). By establishing a baseline through the control no-lime treatment, the study allowed for a comparative evaluation of the economic benefits of lime application. The control treatment achieved a marketable yield (MYT) of 17.68 t ha^{-1}, with a total variable cost (TVC) of 21,645 Birr ha^{-1}. This resulted in a gross benefit (GB) of 247,520 Birr ha^{-1} and a net benefit (NB) of 225,875 Birr ha^{-1}. This baseline illustrates that even without lime application, there is a profitable return; however, it highlights the potential for enhanced yields and returns through the application of lime.

Among the lime treatments, the 1/4 EAM stood as particularly efficient and profitable with the highest marginal rate of return (MRR) of 829% (Table 5) indicating its strong return on investment where a modest increase in costs can yield significant returns. This finding aligns with (61), which emphasized that lower lime application rates can maximize profitability in crop production systems by minimizing input costs while still enhancing yields. In comparison, the FBM treatment demonstrated notable advantages, achieving the highest MYT of 24.32 t ha^{-1}. However, it incurred a higher TVC of 53,445 Birr ha^{-1}. Despite the higher costs, the MRR of 192% indicates solid economic returns, albeit less favorable than the more efficient 1/4 EAM treatment. This suggests that while FBM can significantly enhance yields, the return on investment is not as strong as that observed with lower-rate applications. While full broadcast applications improved yields, they often resulted in diminishing returns on investment due to the high associated costs (1). This economic analysis indicates that lime application, particularly at partial rates like 1/4 EAM, enhances potato yield economically by raising soil pH and increasing nutrient availability while controlling input costs.

The results suggest that while both FBM and 1/2 FBM treatments yield considerable economic benefits, methods that utilize lower lime rates, such as 1/4 and 1/2 EAM, may optimize economic gains relative to investment. This shows the potential for lime rate application in improving not only agricultural productivity but also farmer profitability, which is essential for sustainable agricultural practices. The contrast in MRR values across treatments highlights the importance of evaluating both economic and agronomic factors when determining the most effective lime application rate.

Table 5: Economic analysis of lime rate application methods on potato yield.

Treatments	MYT (t ha^{-1})	TVC (Birr ha^{-1})	GB (Birr ha^{-1})	NB (Birr ha^{-1})	MRR (%)
Control	17.68	21645	247520	225875	
FBM	24.32	53445	340480	287035	192
1/2 BM	22.46	37945	314440	276495	311
FEAM	21.08	32445	295120	262675	341
1/4 BM	20.09	29695	281260	251565	319
1/2 EAM	19.68	27445	275520	248075	383
1/4 EAM	19.87	24945	278180	253235	**829**

Conclusions

Lime application significantly enhances soil chemical properties, achieving a pH of 6.26, exchangeable acidity of 0.32 Cmol(+) kg^{-1}, exchangeable aluminum of 0.00 Cmol(+) kg^{-1}, cation exchange capacity of 29.43 Cmol(+) kg^{-1}, available phosphorus of 13.32 mg kg^{-1}, and organic carbon of 2.06%. Additionally, potato productivity reached 24.32 t ha^{-1} for marketable yield and 26.21 t ha^{-1} for total yield in acidic soils, particularly with the full buffer method broadcasting application, producing substantial gains in pH, nutrient retention, and reduced soil acidity. While FBM produced the highest yield and most favorable soil conditions, fractional applications especially the 1/4 EAM treatment proved highly efficient in terms of economic returns, offering a balance between input costs and yield improvements.

The economic analysis revealed that although FBM increased yield, the marginal rate of return (MRR) for the 1/4 EAM treatment was more advantageous (829%). This emphasizes that lower-rate applications can yield substantial profitability while improving soil health. These results suggest that lime application is an effective agronomic practice for increasing potato yield and economic sustainability on acidic soils, with partial applications providing smallholder farmers with a viable strategy for managing soil acidity.

Supplementary Materials:

No Supplementary Materials.

Author Contributions:

Selomon Afework: Conceptualization, data collection, data analysis, data interpretation, draft writing and critical revisions.

Funding:

This work was not supported through any funding.

Institutional Review Board Statement:

The study was conducted following the protocol authorized by the Head of the Ethics Committee, University of Bahir Dar, Ethiopia Republic.

Informed Consent Statement:

No Informed Consent Statement.

Data Availability Statement:

The study was based on primary data collected from a random sample of eggplant farmers in Anbar Governorate.

Conflicts of Interest:

The authors declare no conflict of interest.

Acknowledgments:

None.

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