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Effects of Integrated Soil Acidity Reclamation Measures on Soil Properties and Barley (*Hurdium vulgarae*) yield in the Central Highlands of Ethiopia

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Abstract

Soil acidity is a major constraint in the Ethiopian highlands, affecting about 43% of the farmlands is severely limiting barley yields. The study assessed the effects of agricultural lime, compost, and chemical fertilizers on soil properties and barley yield in Jeldu district. Six soil reclamation treatments, combining lime, compost, and chemical fertilizers were tested along with no-input and conventional practice controls. The experiment was laid out in randomized complete block design with three replicates. Results demonstrated that combining lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}), as well as the integration of lime with mineral fertilizers, boosted barley grain and biomass yields by three to four times higher compared to conventional mineral fertilizers alone. These improvements were linked to enhanced soil properties, including increased soil porosity, available water content, pH, available phosphorus, organic carbon, total nitrogen, cation exchange capacity, and exchangeable calcium and magnesium. The treatments improved soil properties by up to 202%, while reducing bulk density and exchangeable acidity by up to 70% and 97%, respectively. The benefits of these integrated practices were several times greater compared to the control treatment with no inputs. In conclusion, these findings highlight that combining lime along with compost and chemical fertilizers is the most effective strategy for reclaiming acid soils and improving barley production. By addressing the pressing issue of soil acidity through sustainable practices, this study underscores the importance of integrated nutrient management for achieving long-term agricultural resilience and food security in the Ethiopian highlands.

Keywords: agricultural lime, barley yield, compost, nutrient availability, soil acidity, soil properties.

Introduction

Soil acidity is a significant agronomic challenge that severely limits crop yields in the Ethiopian highlands, affecting approximately 43% of country’s agricultural land (Elias, 2017; Agegnehu *et al*., 2021). This condition is one of the primary forms of soil degradation in these areas, with estimates indicating that 28% of soils are moderately acidic (pH 4.5 - 5.5) and 13% are strongly acidic (pH < 4.5) (EthioSIS, 2015). Strongly acidified soils are predominantly situated in Ethiopia's northwestern, southwestern, and central highlands, regions that receive high precipitation (1800 – 2000 mm per annum), leading to the leaching of essential basic cations from the exchange sites (Abebe, 2007).

The causes of soil acidity are multifaceted. Acidic parent materials rich in aluminum ions contribute to this problem (Agegnehu *et al.*, 2019). High rainfall facilitates the leaching of basic cations from the soil (Tadesse and Bekele, 2001), while decomposing organic materials release hydrogen ions (H^+), further acidifying the soil in the root zone. Additionally, continuous application of ammonia-based fertilizers such as DAP ($(NH_4)_2HPO_4$) and urea ($CO\ (NH_2)_2$) can exacerbate soil acidity through hydrolysis and ammonification processes (Elias, 2002). Specifically, ammonium-based fertilizers generate two H^+ ions for each ammonium molecule converted to nitrate (NO_3) during nitrification (Jamil *et al.*, 2022; Powlson and Dawson, 2022). The hydrolysis of ammonium polyphosphate also contributes to soil acidification (Elias, 2017). In acid soils, phosphate reacts with aluminum and iron oxides to form highly insoluble compounds, a phenomenon known as phosphate fixation, which is a serious limitation for crop yields in the Ethiopian highlands (Elias, 2017; Elias and Agegnehu, 2020).

To combat soil acidity, the Ethiopian extension system promotes the application of agricultural lime as an effective reclamation strategy (Bekele *et al.*, 2022). When lime dissolves in the soil solution, calcium ions replaces H^+ and Al^+ ions on soil colloids, thereby reducing acidity (Noori *et al.*, 2021). Calcium carbonate ($CaCO_3$) is the most extensively used type in Ethiopian agriculture. The recommended application rate depends on soil pH, and exchangeable acidity levels; for instance, the Ministry of Agriculture suggests applying 6 t ha^{-1} for soils with a pH of 4.5, and 4.5 t ha^{-1} for soils with a pH of 4.5 - 5.5 (Tilahun *et al.*, 2019).

Despite government initiatives to expand lime production and distribution among smallholder farmers, adoption rate remain very low (Gurmessa, 2021). So far, only about 5,100 ha out of 3.5 million ha of acid-affected agricultural land have been treated with lime. Bulk transportation challenges from lime production sites to application areas have been identified as a key barrier to wider adoption. Furthermore, despite blanket applications of nitrogen and phosphorus fertilizers at 100 kg DAP and 100 kg urea ha^{-1}, phosphate deficiency is widespread in the Ethiopian highland soils due to their strongly acidic nature and high levels of exchangeable acidity coupled with high phosphorus-sorption capacities (Alemu *et al.*, 2022).

The Jeldu district in the west Shewa zone of Oromia Region is among the central highland areas where soil acidity poses serious threat to agricultural production. The German Technical Cooperation (GIZ) Ethiopia program has initiated acid soil amelioration measures that include applying agricultural lime and compost in addition to nitrogen and phosphorus fertilizers aimed at increasing barley yields, which is the most dominant crop in this area. However, the effects of various acid soil amelioration measures on crop yield and soil properties remain inadequately assessed.

Therefore, this study aims to evaluate the effects of different acid soil amelioration measures on soil properties and barley yields in Jeldu district. By addressing these critical factors, it can be possible to contribute valuable insights into sustainable agricultural practices that enhance productivity while mitigating the adverse effects of soil acidity.

Materials and Methods

Description of the study area

The study area, Jeldu district, is located in the West Shewa zone of the central Ethiopian highlands, defined by geographic coordinates of 9.8’0” – 9.30’0” N and 37.58’30” – 38.9’30” E, covering a total area of 139,389 ha (Figure 1).

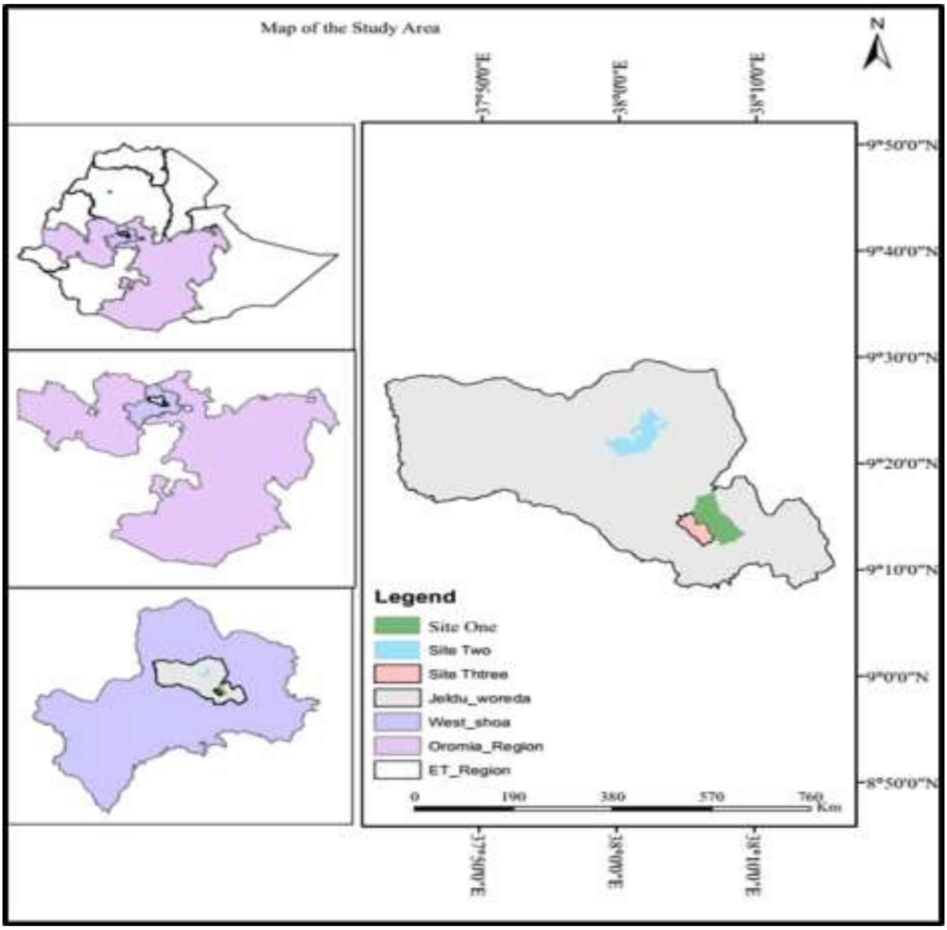


Figure 1. Location map of the study area showing farm fields where sampling was conducted

The topography of the district is largely undulating, with an average elevation of 2952 meters above sea level. According to the records from the Jeldu metrological station spanning from 1987 to 2018, the area receives a mean annual rainfall of 1323 mm, characterized by a unimodal rainfall pattern. The monthly mean temperatures range from a minimum of 8.4°C to a maximum of 19.65°C, with an average temperature of 14.02°C. Based on the scientific agroecological zonation and Köppen climate classification, Jeldu district falls within the cold sub-moist mid-highlands (Figure 2).

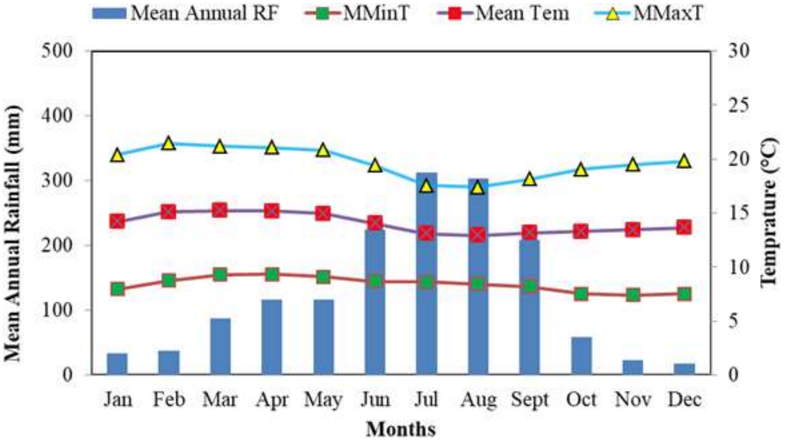
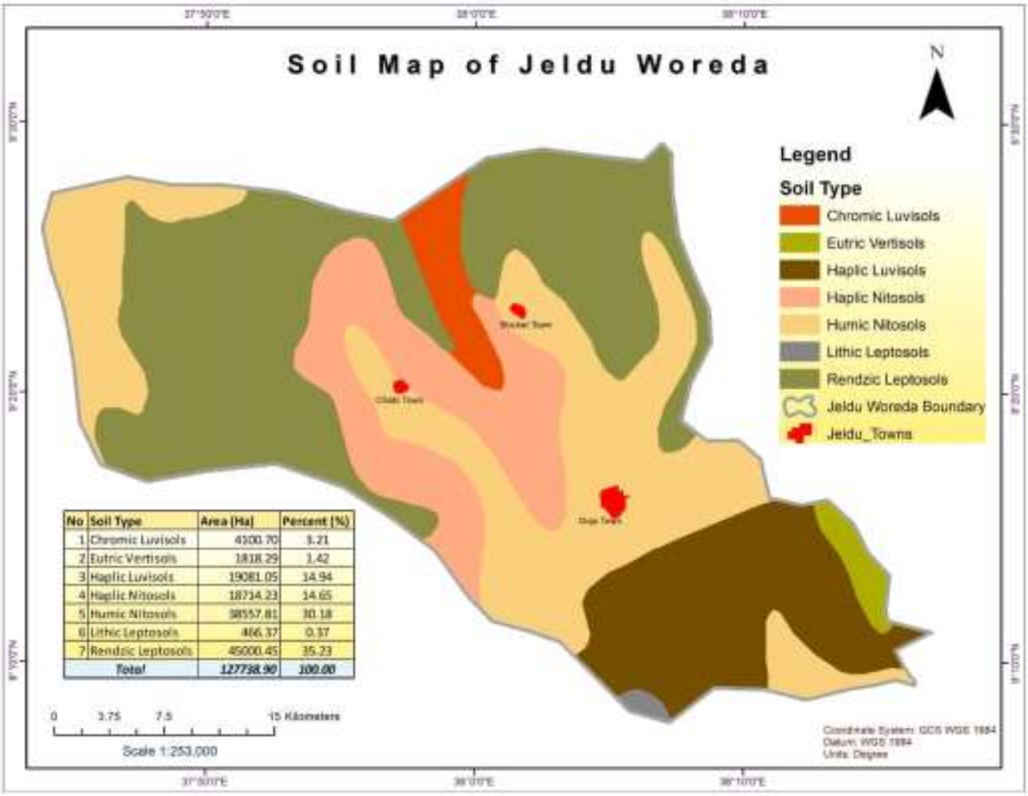


Figure 2. Monthly average rainfall and mean minimum and mean maximum temperature of Jeldu district (NMSA, 2021)

The study area is primarily characterized by subsistence farming, which integrates mixed crop-livestock systems. Major crops grown include food barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor*) and highland maize (*Zea mais*), while zebu cattle and sheep are the predominant livestock raised by farmers. Crop rotation practices observed in the district involve alternating cereals crops (wheat-barley-teff) with legumes (faba bean, pea) at intervals of two to three years in the highlands, and rotating sorghum-maize with teff or oilseeds at similar intervals in the lowlands (Oduol and Nang, 2012). According to the FAO (1984) soil map at a scale of 1:2 million, the dominant soil types in the study area include Nitisols (45%), Leptosols (35.23%), Luvisols (18%) and Vertisols (1.42%) (Figure 3).



No	Soil Type	Area (Ha)	Percent (%)
1	Chromic Luvisols	4100.70	3.21
2	Eutric Vertisols	1818.29	1.42
3	Haplic Luvisols	19081.05	14.94
4	Haplic Nitosols	18714.23	14.65
5	Humic Nitosols	38557.81	30.18
6	Lithic Leptosols	466.37	0.37
7	Rendzic Leptosols	45000.45	35.23
	Total	*127738.90*	*100.00*

Figure 3: Soil map of the study area (FAO, 1984)

Treatments and experimental design

This study involved soil and crop sampling from selected farm fields that hosted GIZ acid amelioration trials established in a 100^2 area (10 m by 10m). The GIZ integrated soil fertility management project applied acid soil amelioration treatments once in 2018, with evaluations conducted during the growing seasons from 2018 to 2021. The treatments evaluated are presented in Table 1. The experiment was laid out in a randomized complete block design, with three farmers' fields considered as replicates.

Table 1. Treatments description and their application rates

Treatments No.	Treatments description	Application rate (kg ha^{-1} | t ha^{-1})
T1	No input application (control)	-
T2	NPS and urea	100 kg NPS ha-1 + 100 kg urea ha-1
T3	Conventional compost	2.5 t ha-1
T4	Ag-lime (from Guder site)	7 t ha-1
T5	Lime + NPS and urea fertilizers	7 t lime ha-1 + 100 kg NPS ha-1 + 100 kg urea ha-1
T6	Lime + conventional compost	7 t lime ha-1 +2.5 t ha-1 compost

Soil sampling and analysis

Composite soil samples were collected from six on-farm plots replicated across farmers' fields using a two-way diagonal methods, resulting in a total of 18 composite samples were taken at a depth of 0 - 20 cm using an Edelman Auger. Additionally, a total of 18 undisturbed soil samples were collected using core samplers with volumes of 100 cm^3 (5.03 cm diameter and 5.03 cm height). Bulk density was determined following Lu et al. (2019) as expressed in equation 1.

$$\rho_b = \frac{M_{dry\,soil}}{V_{total}} \qquad (1)$$

where, ρ_b is the bulk density of the soil (g cm^{-3}), M_{dry} soil is the mass oven dry soil, and V_{total} is the total volume of the core samplers (cm^3).

Soil water content was determined at the soil and plant analysis laboratory of Debrezeit Agricultural Research Center employing a gravimetric method. The collected soil cores were weighed on an electric balance (precision = 0.01 g), oven-dried for 24 hours at 105°C, and then reweighed to determine water content as the difference between wet and dry masses. The water content at field capacity (measured at 1 bar), permanent wilting point (measured at 15 bar) and plant available water content (PAWC) were measured using a pressure plate apparatus technique (Gupta, 2004). The PAWC was computed from PWP and FC values according to Van Reewijik (2002).

Particle size distribution was measured using the modified sedimentation hydrometer procedure (Bouyoucos, 1951), while particle density was determined by the pycnometer method as outlined by Tan (1996). Soil porosity was computed using bulk and particle densities as shown in equation 2.

$$Porosity\ (\%) = \left(1 - \frac{Bulk\ density\ (g\ cm^{-3})}{Particle\ density\ (g\ cm^{-3})}\right) * 100 \qquad (2)$$

Chemical property analysis were undertaken at the national soil research center of EIAR. Soil pH was determined using a pH meter with a soil-to-water solution ratio of 1:2.5 to measure hydrogen ion concentration. Exchangeable acidity and exchangeable aluminum were determined using potassium chloride leachate method, as described by Thomas (1982). This method involves extracting soil samples with a neutral 1 mol L^{-1} KCl solution, which effectively displaces exchangeable ions from the soil matrix. The resulting leachate allows for the determination of both exchangeable acidity and exchangeable aluminum content. Available phosphorus content was analyzed using sodium bicarbonate extraction solution (pH 8.5) spectrophotometric measurement at 882 nm as described by Olsen and Sommer (1982). Organic carbon content was determined using the wet combustion method of Walkley and Black (1934), while total nitrogen was analyzed thorough the wet-oxidation procedure of the Kjeldahl method as described by Bremner and Hauck (1982). Exchangeable basic cations and cation exchange capacity were determined using ammonium acetate extraction at pH 7 (Van Reeuwisk, 1992), with atomic absorption spectrophotometry (AAS) employed for measuring exchangeable cations (Ca and Mg). Available micronutrient contents (Fe, Mn, Zn, and Cu) were extracted via diethylene triamine pentaacetic acid (DTPA) method as outlined by Tan (1996) and quantified using AAS.

Data collection

Total biomass yield of barley was harvested from a net plot area of 9m^2 (3m * 3m) located within the central plots at physiological maturity. Harvested samples were air-dried to constant moisture content before measuring dry biomass through manual threshing. Grains were carefully separated from straw and weighed using digital balance, with the grain yield adjusted to a standard moisture content of 12.5% for statistical analysis.

Data analysis

Soil and agronomic parameter data were subjected to analysis of variance using the General Linear Model procedure within statistical analysis software (SAS, 2004) to determine statistical differences among soil properties and yields across various amendments. Pearson correlation coefficients were computed to assess linear relationships among measured variables related to soil properties and barley yield. This analysis was conducted using OriginPro software (version 2024, OriginLab Corporation, Northampton, MA, USA). Results are presented as means, with least significance difference tests at a 5% significance level employed to establish the differences among means. The results are presented in Figures and Tables.

Results and Discussion

Effect of soil amendments on selected soil physical properties

The integrated application of lime and compost significantly improved the physical properties of soil. This enhancement is evidenced by a reduction in bulk density, an increase in total porosity, and an improved ability of the soil to retain plant-available water, both at field capacity and permanent wilting point.

The bulk density of the untreated soil was 1.16 g cm^{-3} (Table 2). However, treatment with a combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1} decreased its bulk density to 1.02 g cm^{-3}. (Table 2). Similarly, the integrated application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} also reduced the bulk density to 1.04 g cm^{-3}. These treatments resulted in reductions of 12% and 10%, respectively, in bulk density compared to the untreated soil. Whereas the bulk densities of the soils amended with 7 t lime ha^{-1} alone and 2.5 t compost ha^{-1}

alone were 1.06 and 1.09 g cm^{-3}, respectively (Table 2), reflecting reductions of 7% and 6%, respectively. The highest bulk density (1.46 g cm^{-3}) was observed with the application of 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} (Table 2).

The combined application of lime and compost decreases bulk density and increases porosity and soil water content through several interconnected mechanisms. Lime and compost both contribute to the reduction of soil bulk density by altering the soil structure. Lime raises soil pH and promotes flocculation of soil particles, leading to the formation of stable aggregates that reduce soil compaction; thereby enhancing air and water movement through the soil matrix (Frank *et al*., 2021; Ejigu *et al*., 2023). Additionally, lime neutralizes soil acidity, improving root growth and nutrient availability, which further enhances soil structure through increased microbial activity (Frank *et al*., 2021; Iticha *et al*., 2024). Furthermore, compost, rich in organic matter, supports soil aggregation and improves structure by binding soil particles together (Sweeney and McCarthy, 2023; Zhang *et al*., 2023). The synergy of lime and compost results in a less compact, more porous soil structure compared to untreated soils.

These findings align with those of Frank *et al*. (2021), who reported a 10% reduction in bulk density following lime and compost application, and Ejigu *et al*. (2023), who observed reductions of 5%, 12%, and 18% in bulk density at varying application rates. Similarly, Dejene *et al*. (2023) found that the application of 2 t lime ha^{-1} combined with compost decreased bulk density by approximately 12%, improving soil aeration and water retention capabilities. These results further support the effectiveness of combining lime and compost as a strategy for improving soil physical properties.

The total porosity of the soil was significantly affected by soil amendments ($p < 0.0001$) (Table 2). The highest porosity (56.2%) was achieved with the combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, followed closely by the integration of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} (55.3%). These treatments resulted in 12% and 10% increases in porosity compared to untreated soil (50.2%) (Table 2). The application 7 t lime ha^{-1} alone and 2.5 t compost ha^{-1} alone resulted in porosities of 54.5% and 53.2%, respectively, demonstrating 9 and 6% increases compared to the untreated. The lowest soil porosity (37.3%) was recorded in soils treated with 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} (Table 2).

Reducing in bulk density and increasing porosity offer benefits, including improved soil aeration, reduced compaction, easier root growth, and enhanced water and nutrient availability These benefits positively impact agricultural productivity, as improved porosity facilitates the movement of water, nutrients, and gases within the soil (Blanco-Canqui, 2017; Omondi et al., 2016).

Both lime and compost contribute to increased porosity. Lime enhances the availability of calcium ions, which help bind soil particles into larger aggregates, creating more pore spaces within the soil (Ejigu *et al*., 2023; Iticha *et al*., 2024). Lime also increases soil pH, reducing the dispersion of clay particles and improving soil structure (Haynes and Naidu, 1998). Compost further improves porosity through its fibrous nature and its ability to retain moisture, while also providing a habitat for beneficial microorganisms that enhance soil structure (Sweeney and McCarthy, 2023; Zhang *et al*., 2023). Compost, with its high organic matter content, also contributes to soil aggregation by providing binding agents that help soil particles stick together (Six *et al*., 2000; Annabi *et al*., 2011; Zhang *et al*., 2023). Both amendments stimulate microbial activity, leading to the production of substances that bind soil particles together, further enhancing soil structure and porosity (Haynes and Naidu, 1998).

Previous studies corroborate these findings. For example, Frank *et al*. (2021) reported a 10% increase in soil porosity following the application of lime and compost, while Dadi and Tolossa (2024) observed a 35% increase in porosity with the combined application of lime and compost compared to untreated soils. Similarly, Ejigu *et al*. (2023) reported increases in soil porosity of 5%, 12%, and 18% at different application rates. Furthermore, Dereje *et al*. (2023) found that combining 8.44 t lime ha^{-1} with 10 t compost ha^{-1} resulted in a 40% increase in soil porosity, highlighting the synergistic benefits of lime and compost in improving soil structure.

Analysis of variance showed that the PAWC was significantly influenced by the application of soil amendments ($p < 0.0001$). The soil water contents at field capacity (-0.33 bar) ranged from 32% to 38%, while the permanent wilting point (-15 bar) ranged from 24.4% to 29.9%, and the plant available water content (PAWC) varied from 6.6% to 8.6% (Table 2). The highest water content at field capacity (38.3%) was recorded with combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, followed by the sole application of 7 t lime ha^{-1} (37%).The highest soil water content at permanent wilting point (29.9%) was observed with the sole application of 7 t lime ha^{-1}, followed by the combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1} (29.7%). Consequently, the highest PAWC (8.6%) was recorded in soils treated with 7 t lime ha^{-1} combined with 2.5 t compost ha^{-1}, followed by the sole application of 7 t lime ha^{-1} (7.13%) (Table 2). The lowest PAWC (6.58%) was recorded in soils treated with 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} (Table 2). The combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1} increased the soil's water retention capacity by 30%, while the sole application of 7 t lime ha^{-1} increased it by 8% compared to the untreated soil. The integrated application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} as well as the sole application of 2.5 t compost ha^{-1} resulted in modest increases of 5% and 3% in PAWC, respectively (Table 2).

The enhanced water retention capacity of soils amended with lime or compost can be attributed to the high specific surface area and porosity of organic materials, which improve soil structure and water absorption. Additionally, the chemical interactions between $CaCO_3$ from lime and the oxidized organic matter in compost further enhance the aggregation of soil particles, improving soil structure and water-holding capacity (Blanco-Canqui *et al.*, 2006).

Liming also improves the chemical properties of the soil, such as cation exchange capacity (CEC), which enhances the soil's ability to retain water and nutrients (Ejigu *et al.*, 2023). Lime increases soil pH, reducing clay particle dispersion, and promoting the formation of larger aggregates that enhance water infiltration and retention (Ayalew *et al.*, 2023; Orton *et al.*, 2023). The incorporation of compost increases the soil's water-holding capacity due to its high organic matter content, which absorbs and retains water more effectively than mineral soils (Abiven *et al.*, 2018; Zhang *et al.*, 2020).

These findings are consistent with previous studies. Dadi and Tolossa (2024) observed a 30% increase in water retention with the combined application of lime and compost resulted. Similarly, Frank *et al.* (2021) found a 12% increase in soil water content following lime and compost application, while Ejigu *et al.* (2023) reported increases of 8%, 20%, and 35% at varying application rates. Dereje *et al.* (2023) also observed a 18% increase in water content with the combined application of lime and compost, emphasizing the potential of these amendments to improve soil water retention.

Results further showed that soils treated exclusively with chemical fertilizers having 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} fertilizers exhibited lowest PAWC (6.6%) and porosity (37.3%), along with the highest bulk density (1.46 g cm^{-3}), which can adversely affect soil health and barley yields. These results indicated that the reliance on chemical fertilizers leads to soil compaction, limiting root growth and nutrient availability. Thus, adopting integrated nutrient management practices that combine lime and compost with chemical fertilizers is essential for improving soil health and agricultural productivity.

Table 3. Effects of soil amendments on soil bulk density, porosity, and soil water content in the Jeldu district

Treatment	Bulk density (g cm^{-3})	Total porosity (%)	Water content at field capacity (%)	Water content at permanent wilting point (%)	Plant available water content (%)
No application (control)	1.16	50.18	34.35	27.75	6.60
100 kg NPS ha^{-1} + 100 kg urea ha^{-1}	1.46	37.29	32.00	25.42	6.58
2.5 t compost ha^{-1}	1.09	53.19	35.84	29.06	6.78
7 t lime ha^{-1}	1.06	54.47	37.00	29.87	7.13
7 t lime ha^{-1} + 100 kg NPS ha^{-1} + 100 kg urea ha^{-1}	1.04	55.33	32.85	25.92	6.93
7 t lime ha^{-1} + 2.5 t compost ha^{-1}	1.02	56.19	38.32	29.71	8.61
Standard error	0.04	0.01	0.54	0.43	0.17
LSD (5%)	0.071	0.034	0.20	0.18	0.03
CV(%)	3.41	3.63	0.31	0.36	0.20

Note: water content at field capacity and permanent wilting point were measured at 0.33 and 1500 bar.

Effects of integrated lime and compost application on soil chemical properties

Soil amendment with the integrated application of lime and compost significantly improved the chemical properties of the soil ($p < 0.0001$) (Table 3). The soil reaction varied from 4.44 in the untreated control soils, which is very strongly acidic, to 5.6 with the combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, which is moderately acidic (Tekalign, 1991). Similarly, exchangeable acidity decreased from 4.14 meq 100g^{-1} in the untreated soil to 0.13 meq 100g^{-1} with the combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1} (Table 3).

The combined application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} also raised the soil pH to 5.43, and reduced the exchange acidy to 1.37 meq 100g^{-1}, values comparable to those achieved with lime and compost. These treatments resulted in a 26 and 22% increase in soil pH, and a 97 and 67% reduction in exchangeable acidity, respectively compared to the untreated soil. The combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, and the integrated application of lime and mineral fertilizers, also increased soil pH by 21% and 17%, respectively, and reduced exchangeable acidity by 97% and 64% compared to the use of sole mineral fertilizers (100 kg NPS + 100 kg urea ha^{-1}). Although compost alone did not significantly improve soil acidity, its combined application with lime was effective in ameliorating soil pH and reducing exchangeable acidity. The highest rates of lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}) were most effective in sustainably reducing soil acidity, increasing nutrient availability, and improving crop yields compared to other treatments. Thus, it is important note that the application of the recommended rate of chemical fertilizer alone did not significantly improve soil acidity compared to its integration with lime and compost (Table 3).

The available phosphorous (av. P) content ranged from 0.74 mg kg^{-1} in the untreated soils to 9.69 mg kg^{-1} with the combined application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1}, which was significantly higher than the untreated control treatment, and conventional practice with only mineral fertilizers (3.21 mg kg^{-1}) (Table 3). The combined lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}) treatment increased the av. P content to 8.97 mg kg^{-1}, while the sole application of lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}) resulted in values of 5.79 and 5.25 mg kg^{-1}, both significantly higher than the untreated soil and the mineral fertilizer treatments. These findings indicate that the integrated application of lime and compost raised the av. P status of the soil from very low to medium, as classified by Olsen et al. (1954).

Soil amendment with lime and compost significantly increased the organic carbon (OC) and total nitrogen (N) contents (Table 3). OC and total N levels ranged from 1.55% and 0.16% in the untreated soil to 3.74% and 0.37% with the combined lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}) application. The integrated application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1} also resulted in comparable OC (3.02%) and total N (0.32%) levels. The sole application of lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}) resulted in OC contents of 2.86% and 2.97%, and total N contents of 0.23% and 0.27%, respectively. These treatments led to an 85%–141% increase in OC compared to the untreated soil, and a 34%–74% increase compared to the conventional mineral fertilizer practice (100 kg NPS + 100 kg urea ha^{-1}). The increases in N were 44%–131% relative to the untreated soil and 10%–76% relative to the conventional practice. Based on Tekalign’s (1991) classification, the untreated soil was low in OC, while the combined application of lime and compost significantly improved OC to high levels, demonstrating the beneficial effects of integrating lime and compost in agricultural systems.

Soil amendment with lime and compost also significantly increased the cation exchange capacity (CEC), exchangeable calcium (Ca), and exchangeable magnesium (Mg). The CEC, exchangeable Ca, and Mg ranged from 21.03, 4.52, and 2.83 $cmol_{(+)}$ kg^{-1} in the untreated soil to 26.98, 12.35, and 4.82 $cmol_{(+)}$ kg^{-1} in soils treated with 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, respectively (Table 3). The combined application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1}, and the sole application of lime (7 t ha^{-1}) also resulted in comparable CEC (25.81 and 24.12 $cmol_{(+)}$ kg^{-1}), exchangeable Ca (11.55 and 11.19 $cmol_{(+)}$ kg^{-1}), and exchangeable Mg (3.75 and 3.61 $cmol_{(+)}$ kg^{-1}). Compared to the untreated soil, the sole or combined application of lime and compost increased CEC, exchangeable Ca, and exchangeable Mg by 15%–28%, 33%–173%, and 24%–70%, respectively. Relative to the conventional mineral fertilizer treatment, the increases were 14%–27%, 32%–172%, and 22%–67%, respectively. Higher CEC values indicate that the soil has a greater capacity to hold cations, which is essential for improving nutrient availability and reaching an optimal soil pH.

The untreated soil exhibited the lowest values for pH (4.44), av. P (0.74 mg kg^{-1}), OC (1.55%), total N (0.16%), CEC (21.03 $cmol_{(+)}$ kg^{-1}), exchangeable Ca (4.52 $cmol_{(+)}$ kg^{-1}), and Mg (2.83 $cmol_{(+)}$ kg^{-1}), but the highest exchangeable acidity (4.14 meq $100g^{-1}$), indicating that conventional practices without amendments are depleting soil fertility.

Corroborating our findings, previous studies have also demonstrated that the combined application of lime and compost significantly enhances various soil chemical properties. Our findings are consistent with those of Biruk *et al*. (2017) and Kisinyo (2016), who reported that integrated amendments of lime and compost reduced P fixation, enhanced soil pH, and promoted phosphate mineralization. Similarly, Kisinyo *et al*. (2014) and Geremew *et al*. (2020) highlighted the positive effects of lime and organic fertilizers in improving soil chemical conditions and nutrient availability. Dadi and Tolossa (2024) reported that the application of 8.44 t lime ha^{-1} combined with 10 t compost ha^{-1} resulted in a significant increase in soil pH, from 4.69 to 6.53, and a notable improvement in av. P, which rose from 1.63 to 5.27 mg kg^{-1}. Similarly, Dereje *et al*. (2023) found that the combined application of lime and compost enhanced OC levels and total N content, with total N increasing from 0.19% to 0.24%. The study also revealed a marked increase in CEC, which rose from 27.18 to 31.58 $cmol_{(+)}$ kg^{-1}, and a significant increase in exchangeable Ca, from 3.56 to 8.43 $cmol_{(+)}$ kg^{-1}. Additionally, the lime and compost treatment effectively reduced exchangeable acidity, from 0.73 $cmol_{(+)}$ kg^{-1} to trace levels, indicating a substantial improvement in soil quality and its potential for agricultural productivity. Collectively, these studies underscore the effectiveness of lime and compost application as a sustainable strategy for enhancing soil fertility.

Effects of integrated lime and compost application on barley yield

The results of this study indicated that barley yield was significantly affected by soil amendments ($p< 0.0001$) as summarized in Table 4. The highest grain yield of 5.3 t ha^{-1} and biomass yield of 8.23 t ha^{-1} were obtained with the combined application of 7 t lime ha^{-1} and 2.5 t compost ha^{-1} during the 2021 cropping season, due to lime materials react slowly after three years of application, and compost helps retain soil organic carbon. This treatment was closely followed by the integrated application of 7 t lime ha^{-1}, 100 kg NPS ha^{-1} and 100 kg urea ha^{-1}, which resulted in a grain yield of 4.65 t ha^{-1} and a biomass yield of 7.21 t ha^{-1}. Notably, the grain and biomass yields from both the combined application of lime (7 t ha^{-1}) and compost (2.5 t ha^{-1}), as well as the integrated application of lime (7 t ha^{-1}) with mineral fertilizers (100 kg NPS ha^{-1} and 100 kg urea ha^{-1}), were nine and eight times higher than those of the control treatment, respectively, and nearly double that of the conventional treatment composed of mineral fertilizers alone (Table 4).

Table 3. Effects of combined application of lime and compost on chemical properties in the Jeldu district

Treatment code	**pH (H_2O)**	**Exchangeable acidity (meq 100g^{-1})**	**Organic carbon (%)**	**Total nitrogen (%)**	**Available phosphorous (mg kg^{-1})**	**Cation exchange capacity (cmol$_{(+)}$ kg^{-1})**	**Calcium (cmol$_{(+)}$ kg^{-1})**	**Magnesium (cmol$_{(+)}$ kg^{-1})**
No input application (control)	4.44^{def}	4.14^{a}	1.55f	0.16^{f}	0.74^{f}	21.03^{ef}	4.52^{ef}	2.83^{de}
100 kg NPS + 100 kg urea ha^{-1}	4.64^{de}	3.80^{ab}	2.14^{de}	0.21^{e}	3.21^{e}	21.18^{e}	4.54^{de}	2.89^{d}
2.5 t compost ha^{-1}	4.90^{d}	3.50^{bc}	2.97^{abc}	0.23^{cd}	5.25^{cd}	24.12^{d}	5.99^{d}	3.52^{abc}
7 t lime ha^{-1} alone	5.24^{abc}	1.80^{d}	2.86^{cd}	0.27^{c}	5.79^{c}	25.81^{abc}	11.19^{abc}	3.61^{bc}
7 t lime ha^{-1} + 100 kg NPS ha^{-1} + 100 kg urea ha^{-1}	5.43^{ab}	1.37^{de}	3.02^{ab}	0.32^{ab}	9.69^{a}	26.55^{ab}	11.55^{ab}	3.75^{ab}
7 t lime ha^{-1} + 2.5 t compost ha^{-1}	5.60^{a}	0.13^{f}	3.74^{a}	0.37^{a}	8.97^{b}	26.98^{a}	12.35^{a}	4.82^{a}
LSD (5%)	0.074	0.0471	0.1488	0.0147	0.0985	0.086	0.3386	0.5365
CV (%)	0.41	0.99	2.96	3.12	1.02	0.13	0.99	0.92

Table 4. Effect of combined application of lime and compost on grain and biomass yields of barley in the Jeldu district

Treatments	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})
No input application (control)	0.52^{f}	0.81
100 kg NPS ha^{-1} + 100 kg urea ha^{-1}	1.74^{de}	2.70
2.5 t compost ha^{-1}	2.43^{d}	3.77
7 t lime ha^{-1} alone	4.01^{bc}	6.22
7 t lime ha^{-1} + 100 kg NPS ha^{-1} + 100 kg urea ha^{-1}	4.65^{b}	7.21
7 t lime ha^{-1} + 2.5 t compost ha^{-1}	5.31^{a}	8.23
LSD (5%)	8.38	11.90
CV (%)	26.57	26.56
SE	4.1	5.82

Note: Means within a column with the same letter are not significantly different at $p<0.05$

The observed increases in barley yield, ranging from four to nine-fold compared with integrated soil amendments, can be attributed mainly to the improvements in soil properties, particularly the reduction in exchangeable acidity (Table 2) and the subsequent increase in nutrients availability, especially available phosphorus (av. P) in the soils (Table 2). The improved yields of barley in response to the combined application of organic and mineral amendments resulted from positive changes in soil characteristics, including increased soil pH, av. P, OC, total N, CEC, exchangeable bases (Table 5). These findings are consistent with previous research indicating that improved soil conditions lead to better crop performance (Agegnehu and Demissie, 2011; Agegnehu e*t al*., 2016; Kassu *et al*., 2018). The strong positive correlations observed between barley yield and soil properties such as pH (R^2 = 0.997), av. P (R^2 = 0.895), OC (R^2 = 0.92), total N (R^2 = 0.979), CEC (R^2 = 0.97), exchangeable Ca (R^2 = 0.96) and Mg (R^2 = 0.89) suggest that increases in these parameters correspondingly enhance barley yields. Conversely, a strong negative correlation was observed between exchangeable acidity and barley yield (R^2 = -0.98), indicating that as exchangeable acidity decreases; barley yield increases (Table 5). This suggests that reducing soil acidity is crucial for enhancing barley productivity, as lower levels of exchangeable acidity improve the overall soil environment, facilitating better nutrient availability and root development.

The increase in crop yield can also be attributed to the liming materials providing essential basic cations, especially calcium that mitigated the effects of acidic cations in the soil. This enhancement created a more favorable environment for the root development and nutrient uptake, particularly P, which is crucial for plant growth (Figure 4).

Table 5. Pearson correlation coefficients between chemical properties of the studied soil and grain yield of barley as influenced by the integrated application of lime and compost in the Jeldu district

	pH	Ex. A	Av. P	OC	TN	CEC	Ca	Mg
Grain Yield	0.997	- 0.981	0.895	0.92	0.979	0.97	0.96	0.89

Note: pH, Ex. A, Av. P, OC, TN, CEC, Ca and Mg are soil reaction, exchangeable acidity, available phosphorous, organic carbon, total nitrogen, cation exchange capacity, calcium and magnesium, respectively.

These results agreed with the finding by Desalegn *et al. (*2017), who reported that amending acidic soils with combined application of 1.65 t lime ha^{-1} and 30 kg P ha^{-1} led to 133% increase in grain yield of barley compared to the control treatments. This emphasizes that fertilizer application alone is insufficient for improving barley yields without also addressing soil acidity through liming and improving organic matter content using compost application.

Furthermore, previous studies have shown that relying solely on inorganic fertilizers or organic sources alone does not lead to sustainable yield increases in acidic soils (Abedi *et al*., 2010; Agegnehu *et al*., 2014). Thus, integrating both nutrient sources is essential for sustainable agricultural production. Shata *et al.* (2007) also suggested that integrating chemical and organic fertilizers not only increase production but also can maintain crop yields at optimal levels while reducing the amount of chemical fertilizers needed; thereby, minimizing negative environmental impacts and production costs. The study suggests that the yield increase, environmental benefits and soil quality with the application of lime and compost were higher based on the results.

Conclusions

Integrated application of lime and compost significantly enhances barley yield and improves key soil properties in acidic soils. The results of this study demonstrated that combining 7 t lime ha^{-1} and 2.5 t compost ha^{-1}, as well as the integration of lime with mineral fertilizers resulted in the highest grain and biomass yields, substantially outperforming both control treatments and conventional mineral fertilizers. These improvements can be attributed to the positive changes in soil quality, including increased pH, organic carbon, total nitrogen, available phosphorous, cation exchange capacity, and exchangeable bases, along with a reduction in exchangeable acidity. The strong correlations between these soil properties and barley yield emphasizes the importance of addressing soil acidity and nutrient availability for sustainable crop production. The findings also highlight that relying solely on inorganic fertilizer is not a viable long-term solution for enhancing soil fertility or crop yields; instead, these fertilizers must be integrated with organic amendments. Therefore, adopting practices that incorporate lime, compost and mineral fertilizers not only boosts barley yields but also contributes to long-term soil health and sustainability. Future agricultural strategies should prioritize such integrated approaches to optimize crop performance while minimizing environmental impacts. Further research across diverse locations is essential to validate these results and formulate robust recommendations for sustainable agricultural practices.

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