Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Integrated Aglime, Vermicompost, and Rotation Cropping Enhanced Crop Yield and Soil Quality in Acid Soils of Arsi Zone, Oromia Region

Dawit Habte

dawithabte99@yahoo.co

Ethiopian Institute of Agricultural Research

Dugasa Gerenfes

Ethiopian Institute of Agricultural Research

Kassu Tadesse

Ethiopian Institute of Agricultural Research

Geremew Taye

Ethiopian Institute of Agricultural Research

Temesgen Desalegn

Ethiopian Institute of Agricultural Research

Getahun Dereje

Ethiopian Institute of Agricultural Research

Samuel Lindi

Ethiopian Institute of Agricultural Research

Dawit Habte Haile

Ethiopian Institute of Agricultural Research

Research Article

Keywords: Integrated lime-vermicompost, aglime, Rotation Cropping, Soil Quality

Posted Date: September 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10688694/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Integrated Aglime, Vermicompost, and Rotation Cropping Enhanced Crop Yield and Soil Quality in Acid Soils of Arsi Zone, Oromia Region

Dawit Habte[1], Dugasa Gerenfes[1], Kassu Tadesse[1], Geremew Taye[2], Temesgen Desalegn[3], Getahun Dereje[2], Samuel Lindi[1]

[1]Kulumsa Agricultural Research Center, [2]Holeta Agricultural Research Center, [3]Ethiopian Institute of Agricultural Research Soil and Water Management Research Directorate

dawithabte999@gmail.com, dgerenfes2017@gmail.com, kasstad96@yahoo.com, geremewtayen@yahoo.com, temesgen2015@gmail.com, getahundereje2016@gmail.com, samuellindi5@gmail.com
Corresponding Author: Dawit Habte;
e-mail: dawithabte999@gmail.com

Abstract

A two-year (2023–2024) field trial in Arsi Zone evaluated the effects of full lime and partial lime combined with vermicompost (VC) under rotational cropping on bread wheat and malt barley productivity and soil chemical properties. Lime-based treatments significantly increased plant height, grain yield, and biomass, while most yield components were unaffected. Full aglime + recommended NP (RNP) produced the highest yields, whereas 50% lime + VC + RNP also significantly improved yields over RNP alone, providing a viable lower-input option for resource-limited farmers. Treatment effects were generally consistent across years, with wheat showing additional yield improvement in the second year, suggesting residual lime and rotation benefits. Soil analyses revealed increased pH and cation exchange capacity and reduced exchangeable acidity following lime application. Crop type and crop × treatment interactions influenced several soil properties, indicating crop-specific rhizosphere effects. Soil organic carbon showed no significant change, likely because of the short experimental period. Residual soil total nitrogen was highest in control plots and lowest in limed treatments, possibly reflecting improved crop uptake and yield-related nutrient dilution. Economic analysis showed that aglime + RNP generated the highest net present value across crops, while 50% lime + VC + RNP provided favorable marginal benefits for faba bean. Overall, lime application was most effective when integrated with legume-based rotations. Full lime + RNP is recommended where resources permit, while the 50% lime + VC + RNP approach offers a practical, sustainable, and lower-input alternative.

Keywords: Integrated lime-vermicompost, aglime, Rotation Cropping, Soil Quality

1. Background and Justification

Soil acidity is a major soil health constraint that limits the capacity of agricultural lands in Ethiopia to sustain crop productivity. Its wide spatial extent and increasing severity demand focused efforts to restore and improve productive soils [1, 2]. Acid soils are commonly associated with aluminum (Al^{3+}) toxicity and low phosphorus (P) availability, which restrict root development, nutrient uptake, and overall crop performance [1, 3]. Improving crop productivity under such conditions requires soil health–centered management practices, including the use of lime, fertilizers with liming effects, and organic soil amendments [2, 1]. Organic fertilizers contribute to improved soil health by supplying nutrients and enhancing soil physical, chemical, and biological properties. In Ethiopia, the combined application of lime and organic fertilizers, particularly with appropriate P fertilization, is an effective approach for ameliorating acidic soils, improving nutrient availability, and restoring crop productivity [4, 5]. The incorporation of organic matter can further improve soil chemical properties, increase soil pH, reduce exchangeable Al and acidity, enhance nutrient availability, and contribute to sustainable management of acid soils [4, 5]. However, recent evidence suggests that lime should be strategically targeted to soils where Al toxicity is a significant constraint, while integrated soil fertility management should address associated nutrient deficiencies, particularly P deficiency [6].

To address the challenges posed by acid soils, there is increasing emphasis on regenerative agricultural strategies that go beyond maintaining current soil conditions and instead aim to improve soil health and system productivity. Such strategies include conservation agriculture and integrated soil fertility management approaches that combine inorganic and organic soil amendments. Several studies conducted in central and western Shewa have demonstrated that the integrated application of lime and vermicompost can substantially improve the productivity of faba bean and wheat, with the best multi-year results achieved using 50% of the recommended lime rate combined with 50% vermicompost. However, for these technologies to be promoted at scale, their performance have to be validated across different agroecologies and cropping systems.

In response, the Soil and Water Management Research Directorate of the Ethiopian Institute of Agricultural Research (EIAR), in collaboration with the Agricultural Transformation Institute (ATI), initiated a field validation trial to evaluate integrated acid soil management practices. Unlike previous studies, this trial combined lime and vermicompost applications with rotational cropping. The objective of this study was to validate the integrated use of lime and vermicompost for improving faba bean, malt barley, and wheat production under rotation cropping on acidic soils of Ethiopia. The specific objectives were to: (i) compare the effectiveness of integrated lime and

vermicompost applications on the yield and yield components of wheat, faba bean, and malt barley in the Arsi zone; (ii) evaluate the residual effects of sole lime application and lime–vermicompost integration under rotational cropping; (iii) assess treatment effects on key soil quality indicators; and (iv) analyze the economic feasibility of the different management options.

2. Materials and Methods

2.1. Location Description

The field trials were executed across two consecutive seasons (2023 and 2024) at sites located in Arsi zones. The total number of sites were 13 for faba bean; 8 for wheat and another 8 for malt barley over the trial period. The geographic coordinates of the sites lie between 7.420° – 7.907° N and 39.115° - 39.300° E, with altitudes ranging from 2400 to 3100 m.a.s.l. The long term (30 years) mean annual rainfall across the study areas is about 1100 mm. Mean monthly minimum temperatures range from 6.5 – 8.5°C and mean monthly maximum temperatures range from 16 – 21°C. The agroecology is described by “cold to very cold humid sub-afroalpine”. However, most of the highlands can be described as “tepid to cool humid mid-highlands” (Ethio-Italian Development Project, 2001).

2.2. Experimental Design and procedures

The study employed a single-block design, utilizing multiple farmer fields (locations) as replicates. The trial consisted of three treatments: 1) 100% recommended lime + 100% recommended NP Fertilizer; 2) 50% recommended lime + 50% recommended vermicompost + 50% RNP; 3) RNP Only (control).

During the first year, the treatments containing lime and vermicompost were applied three weeks prior to planting and incorporated into the plow depth. The lime material was ground limestone (Calcium carbonate) and the lime requirements (LRs) for each trial site was estimated from the LR map developed for acid soils of Arsi zone. The amount of Vermicompost was calculated based on the nitrogen equivalence from the recommended N. Newly released varieties of wheat, faba bean, and malt barley were used. Gross plot size was 10m*10m. All recommended cultural practices were properly implemented.

The second year trial was designed to evaluate the residual effect of the initial amendments and the rotational effect of legume-cereal sequence on crop yield and soil properties. Thus, no lime and vermicompost treatments was applied in the second season. However, the NP fertilizer was applied at the rate used in the previous year.

Treatment 1 and 3 received the full dose of N and P, while treatment 2 received 50% of the recommended N and P from Urea and NPS/DAP. To see the interaction of lime * VC * rotation, wheat and malt barley were planted on plots used for faba bean in the previous year while the wheat and malt barley fields were planted with faba bean.

2.3. Agronomic Data Collection

The yield and yield component data collected for wheat and malt barley include: plant height (PH), spike length (SL), number of seeds per spike (NSPS), above ground biomass yield (AGBM), grain yield (GY), and thousand seed weight (TSW). The agronomic data for faba bean include: number of pods per plant (NPPP), number of seeds per pod (SPP), AGBM, GY, and TSW.

2.4. Soil Sampling and Laboratory Analysis

Prior to treatment application, composite soil samples were collected from the surface 0–20 cm depth. Post-harvest soil samples were collected 2 weeks before harvest using random sampling method from 5 sampling points and bulked to make 1 kg composite sample per plot. The collected samples were taken to Kulumsa Agricultural Research Center (KARC) Soil and Plant Nutrition Laboratory for air drying, sample preparation and chemical analysis. The air-dried samples were ground using mortar and pestle; sieved through a 2 mm sieve before being analyzed for selected physico-chemical properties.

The laboratory analysis included soil pH, organic carbon (OC), total N, available P, cation exchange capacity (CEC), and exchangeable acidity. Soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension using a digital pH meter; OC by the[1] wet digestion method, total N by the Kjeldahl procedure [7, 8], CEC by saturating the soil with neutral 1M NH_4OAc at pH 7, followed by displacement of adsorbed NH_4^+ with 1M KCl, and measured using Kjeldahl distillation [9]. Available P was determined using Bray II method [10].

2.5. Agronomic and Soil Data Analysis

Both the soil and crop data were managed using MS EXCEL computer software and analyzed using linear mixed-effects models in SAS (PROC MIXED) to account for fixed treatment effects and random variability among farmers' fields. In order to account the variability by rotation effects in year 2, two separate analysis of variance models were used. The following statistical model (Eq. 1) was applied for combined analysis of year 1 and 2, but excludes rotation effect.

$$Yield = \mu + T_i + C_j + (T * C)_{ij} + R_k + \epsilon_{ijk} \quad \text{..... Eq. 1}$$

Where: Yield = observed yield, T_i = fixed effect of treatments (i = 1,..., n_times), C_j = fixed effect of crop (j = 1,...,2; $(T * C)_{ij}$ = treatments*crop interaction, R_k = random effect of location (k = 1,..., n locations), ε_{ijk} = residual error.

This model evaluates the overall effect of treatments, which mainly contain lime and integrated lime and vermicompost, and crop type, including their interaction, across multiple locations. Location variability is treated as random. The year effect is absorbed into the residual since no temporal structure is considered in this model. The effect of crop rotation in year 2 was evaluated by incorporating interaction terms among treatments, crop type, and rotation.

$$Yield = \mu + T_i + C_j + Rot_k + (T * C)_{ij} + (T * Rot)_{ik} + (C * Rot)_{jk} + (T * C * Rot)_{ijk} + R_l + \epsilon_{ijkl} \ldots\ldots \text{(Eq.2)}$$

Where: Yield = observed yield, μ = overall mean yield, T_i = fixed effect of treatments (i = 1,..., n_times), C_j = fixed effect of crop (j = 1,...,2), Rot_k = fixed effect of rotation; $(T * C)_{ij}$, $(T * Rot)_{ik}$, $(T * Rot)_{jk}$, and $(T * C * Rot)_{ijk}$ are all interaction terms; R_i = random effect of location (i = 1,..., n locations), ε_{ijkl} = residual error.

The model captures the specific influence of previous crop on current yield responses and assesses whether lime and integrated lime and vermicompost effects vary by rotation or crop type. The use of multiple interaction terms enables the analysis of complex agronomic relationships such as whether lime interacts differently with wheat and faba bean depending on the previous crop used.

Statistical analyses were performed using both SAS (v9.4) and R software (v4.x). Mixed models were primarily fitted using the PROC MIXED procedure in SAS, applying the REML (Restricted Maximum Likelihood) estimation method. The Kenward-Roger approximation (ddfm=kr) was used to adjust degrees of freedom for the fixed effects. To cross-validate model results using the lme4 packages and generate quality graphs, R software was used. Least Squares Means (lsmeans) were calculated and pairwise comparisons among treatments using Tukey's HSD adjustment (pdiff=all adjust=tukey) was conducted in SAS. Location was used as a random variable. In some instances, Location and Year was used as random variable. For soil data analysis using mixed effects model, Equation 1 was applied, while the GLM procedure of SAS was applied for analysis of fixed effects.

2.6. Calculation of lime and rotation effects

The lime (lime type) effect was calculated vertically (between treatments) to get the yield gains from the three lime treatments against the control (RNP only treatment). The yield gain from the rotation effect was calculated horizontally (across time) using the following simple formula:

$$YG_{RotEff} = Yield\ at\ year\ 2 - Yield\ at\ year\ 1$$

$$adjYG_{RotEff} = (Y_{trt}, year\ 2 - Y_{trt}, year\ 1) - (Y_{cont}, year2 - Y_{cont}, year1)$$

Where: YG_{RotEff} = Yield gains from rotation effect, $adjYG_{RotEff}$ = adjusted yield gain from rotation effect, Y_{trt}= yield from a treatment, cont = control treatment.

2.7. Economic Analysis

The economic feasibility and comparative advantage of the treatment options were evaluated using a cost-benefit analysis (CBA) approach. The CBA framework is a preferred approach for a more comprehensive assessment of total costs and total returns associated with each treatment across years, enabling comparison based on net present value (NPV), benefit–cost ratio (BCR), and marginal benefits (MB).

For all inputs and outputs, farm gate prices were used to reflect realistic economic conditions for farmers. Both grain and straw yields were included in the estimation of total revenues. To account for annual changes in input prices, especially the rising costs of fertilizers and transport of lime, the 2025 input prices were applied uniformly over the two years data. Yield prices vary highly, rising and falling within a season and across years. Hence, the yield prices that most frequently appear in the market was selected to represent the economic viability of the treatments under the prevailing market trends. Economic indices: NPV, BCR, and MB were calculated using equations 1, 2, and 3. A discount rate of 15% was applied for all PV calculations.

$$\mathrm{NPV} = \frac{(\mathrm{Benefits_{t1}} - \mathrm{Costs_{t1}})}{(1+\mathrm{r})^1} + \frac{\langle \mathrm{Benedits_{t2}} - \mathrm{Costs_{t2}} \rangle}{(1+\mathrm{r})^2} \qquad \text{Equation 1}$$

$$BCR = \frac{Present\ Value\ (PV)\ of\ Total\ Benefits}{Present\ Value\ (PV)\ of\ Total\ Costs} \qquad \text{Equation 2}$$

$$MB = Net\ Benefit\ of\ Treatment_i - Net\ Benefit\ of\ Control \qquad \text{Equation 3}$$

The NPV measures the absolute total profit in today's money value generated by each treatment. The treatment with the highest NPV is the one that adds the most total values to the management option. However, the relative economic efficiency of each treatment

option is measured using BCR. Any ratio with BCR > 1 is economically worthwhile. The marginal benefit relative to the control is measured using MB. For any management option to be feasible and comparatively acceptable, the MB should be positive.

3. Results and Discussion

3.1. Mean Response of Crops to Integrated Acid Soils Management

The ANOVA results of treatment effects on the yield and yield components of wheat, barley, and faba bean are presented in Table 2. Combined analysis across years and crops showed that treatments had high and very high significant effect on plant height (PH), grain yield (GY) and above ground biomass/biological yield (AGBM/BY); but no statistically significant effect on the number of plants/m^2 (NSPM) or plant density for the three crops. The combined analysis also showed that crop types differed strongly in GY and BY. All treatment effects did not differ significantly between the two years, showing the consistence of treatment effects over years, which can be described by the carryover effect of aglime and aglime + VC.

Crop types strongly differed (significantly) in GY, BY, and PH responses to the treatments. However, Crop*treatment interaction effect was significant on plant height (PH) only, showing that the treatments affect PH differently in wheat, malt barley, and faba bean. On the other hand, the non-significance of Crop*treatment interaction effect on GY and BY shows that the direction of treatment effects on both yields is largely similar for the three crops. It also implies that while treatments improve yields, the relative ranking of treatment effects remained fairly consistent across crops. In other words, the management practices did not differentially benefit one crop more than another, even if absolute yield levels differ significantly by crop type. This is consistent with meta-analysis findings from acid soils research in Ethiopia (not published), which show that lime and integrated nutrient management consistently improve crop productivity, but the magnitude of the effect varies more with crop sensitivity to acidity (faba bean > barley > wheat) rather than differences in treatment effectiveness across crops.

Year*treatment interaction effect was non-significant on all measured parameters, showing that the mean response of wheat, malt barley, and faba bean to treatments did not differ significantly between the two years, or there is no strong evidence that the treatment by year interaction can affect crop responses differently. Since the 2024 yield result did not show any reduction, the non-significant effect of years and year*treatment interaction shows the consistence of the treatment effect across years, strengthening the argument that lime and lime+VC effect can last for more than one or two years.

The results of analysis of variance disaggregated by year showed significant or highly significant treatment effect on plant height (PH) differed significantly between treatments in 2024 only.
However, combined analysis across years showed highly significant treatment effect on PH. Treatment effects also differed by crop type in 2023 and 2024, but the combined analysis over years showed otherwise, suggesting the presence of high variability the treatment effect across locations. There is also statistically no strong evidence that crop*treatment interactions significantly affected all measured yield and yield component parameters in both years, suggesting that the trend of treatment affects is similar across the three crops.

Table 1: Results of ANOVA for yield and yield components of wheat and barley

Period	*Sources of Variability*	*PH*	**SPL**	**NSPS**	**NPPM**	*GY*	*BY*
Combined across years	Treatment	**	NS	*	NS	*	***
	Crop type	NS	NS	NS	NS	***	***
	Year	NS	NS	NS	NS	NS	NS
	Crop*Treatment	*	NS	NS	NS	NS	NS
	Year*Treatment	NS	NS	NS	NS	NS	NS
2023	Treatment	NS	NS	*	NS	*	*
	Crop type	***	NS	NS	NS	***	***
	Crop*Treatment	NS	NS	NS	NS	NS	NS
2024	Treatment	*	NS	--	NS	**	**
	Crop type	***	NS	--	***	***	***
	Crop*Treatment	NS	NS	--	NS	NS	NS

Note: PH = plant height, SPL = spike length, NSPS = number of seeds per spike, NSPM = number of plants per m^2, GY = grain yield, BY = biological yield

The mean grain yield response of three major crops tested (wheat, malt barley, and faba bean) to different integrated lime and organic inputs across two years are demonstrated in Figure 1. The treatments were compared against the recommended rate of Nitrogen and Phosphorus (RNP), which served as the control and had a mean GY of 3645.4 kg/ha. The Aglime + RNP (Recommended Lime + Recommended NP) treatment recorded the highest mean GY of 4118.2 kg/ha, suggesting that Aglime is the most effective management option for crop production. The superior performance translated into a significant annual GY advantage of 472.9 kg/ha over the control, (13% increase/ year). The cumulative yield gains from the Aglime + RNP = 945.7 kg/ha.

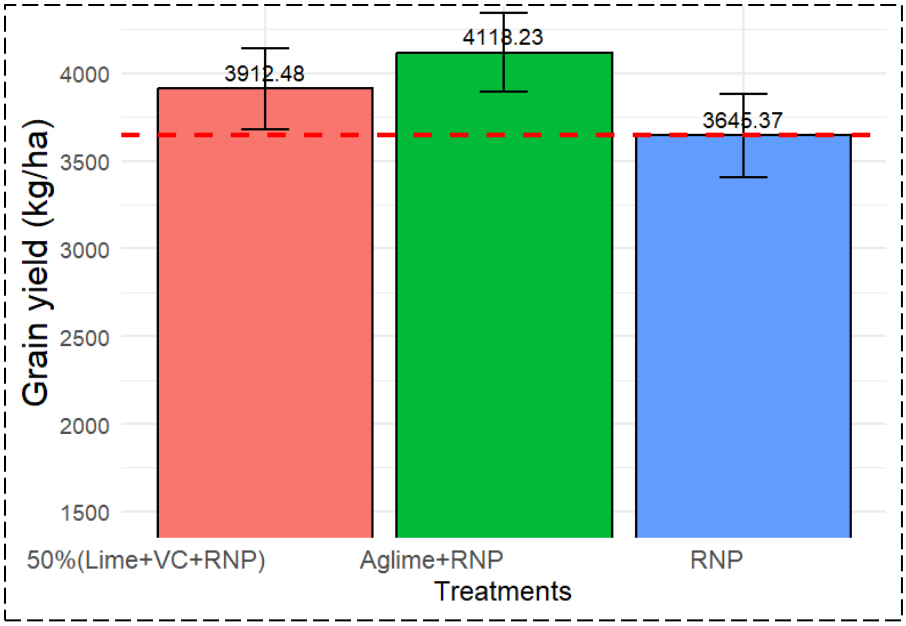


Figure 1: Mean grain yield response to treatments across all crops

The 50% (aglime + VC + RNP) treatment, which is an integrated approach at reduced rates also performed well resulting to mean GY of 3912.48 kg/ha, a notable mean grain yield advantage of 267.1 kg/ha over the RNP control. This represents an annual yield increase of approximately 7.3%. Over the two-year period, the total yield gain achieved by this integrated, reduced-input approach was 534.22 kg/ha. The results are in agreement with [11-12].

In summary, while the full recommended rate of Aglime with RNP maximized yield, the integrated treatment achieved a substantial yield gain with potentially lower amendment costs and environmental impact, demonstrating a viable option for sustainable management. However, the yield advantage varied by crop type and years.

3.2. Temporal Changes in Grain Yield Response to Amendments

The mean GY of the three crops, disaggregated by treatment and year, is illustrated in figure 2. The relative ranking of the treatment effects remained consistent across the two years, with the Aglime + RNP yielding the highest in both years. A notable observation is the difference in response magnitude between the years, which ranges from 150 to 172 kg/ha depending on the treatment. The overall yield trend for the limed plots was positive in the second year.

The plots that initially received Aglime + RNP in 2023 and RNP only in the following year (to measure residual effect), showed increased mean GY in 2024 (4220.2 kg/ha) which represents an increase of 172.1 kg/ha (4.2%), mainly attributed to the residual effect of

lime and rotation Similarly, the 50% (aglime + VC + RNP) plots, which also received 50% RNP only in 2024 had the GY increased by 150.1 kg/ha in 2024, about 3.9% yield gain.

The fact that the limed plots experienced a yield increase in 2024, despite not receiving any new aglime or vermicompost amendments in the second year, suggests a strong residual effect from the initial aglime application. Aglime works by slowly neutralizing soil acidity, and the second year often captures the peak of this beneficial chemical effect, leading to better nutrient availability and uptake. Conversely, the control treatment, which received RNP only in both years, experienced a reduction in yield by 160.5 kg/ha. The decline in the control group is an important result, likely indicating the progressive negative impact of acid soil stress and lack of pH correction over time, increasing the gap to 670 kg/ha between the control and aglime + RNP and 451 between the control and integrated lime and VC, furthering the necessity of the soil amendment strategies.

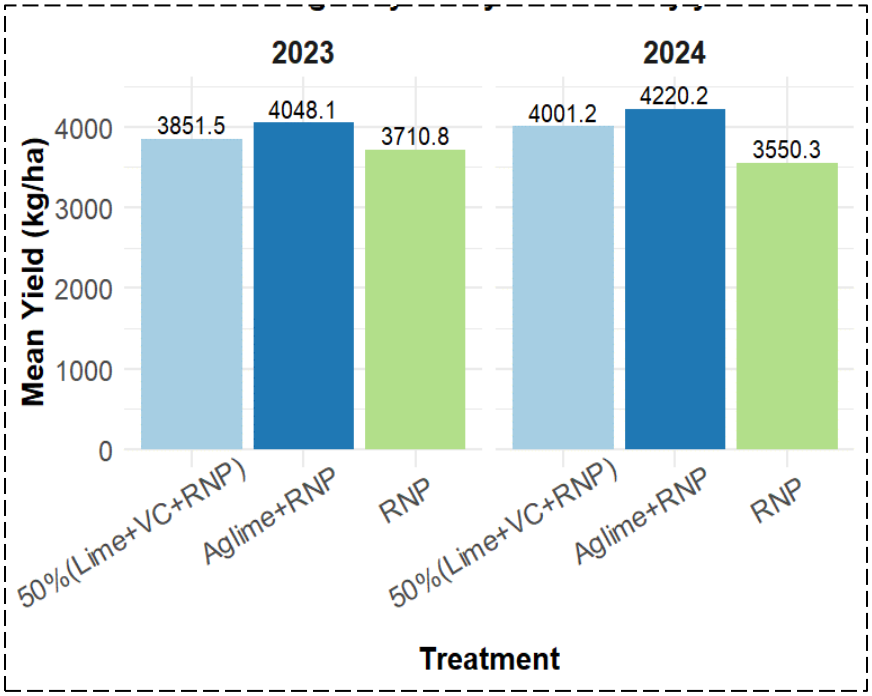


Figure 2: mean GY of crops by treatment and year

Despite the observed differences in magnitude between the years for individual treatments, the Year effect was statistically insignificant for the combined analysis of all crops. This statistical finding supports the conclusion that the treatment effect was the dominant factor influencing the results, with the overall year-to-year environmental variation being insufficient to cause a significant change in the total mean crop yield.

3.3. Carryover effect of aglime, vermicompost and rotation cropping

The mean grain yield response, differentiated by treatment, year, and crop type, is presented in Table 3. A detailed analysis reveals a highly contrasting inter-annual yield response between the two cereal crops, wheat and malt barley, demonstrating the critical role of both the residual effect of the amendments and the rotation effect of the legume used.

For wheat, yields rose sharply in 2024 across all treatments. The Aglime + RNP treatment reached 6166 kg/ha, over 1056 kg/ha higher than the 2023 result, while 50% (aglime+VC+RNP) gained 728 kg/ha. These increases reflect the combined benefits of residual lime and rotation cropping. But, the gain is most likely attributed to the nitrogen contribution from the preceding faba bean crop. Wheat, with its high N demand, responded strongly. Even the GY from control (RNP only) rose by 1062.9 kg/ha (22.5%), demonstrating that the legume effect alone is substantial. The dual effect of pH correction and rotation produced the highest wheat yield, confirming that integrating aglime with crop rotation is the most effective strategy for sustainable productivity of wheat.

Barley yield, however, showed the opposite trend, with yields declining in 2024 under all treatments. The GY from aglime plots dropped by mean of 560 kg/ha (from 4497.9 to 3935.8 kg/ha), while the GY from control also fell. But, the yields from the 50% (aglime+VC+RNP) remain nearly the same for the two years. This suggests that barley was less able to benefit from the residual lime and legume N inputs or was negatively influenced by other factors.

Table 2: Mean yield response by treatment, by year, and crop type

Treatment / Crop type	50%(aglime+VC)		Aglime		RNP	
	2023	2024	2023	2024	2023	2024
Wheat	4902.8	5631.3	5110.0	6166	4726.9	5789.8
Barley	3642.9	3621.8	4497.9	3935.8	3808.5	3464.0
Faba bean	2988.0	3140.9	3151.0	3253.9	2781.3	2658.6

Figure 3 illustrates how wheat and barley respond differently to faba bean based rotation across the three amendments (RNP, Aglime + RNP, 50% Lime + 50% VC + 50% RNP). Wheat consistently outperformed in the rotation system (faba bean–wheat) compared to no rotation. The large separation between the Rotation_Wheat and the No-Rotation_Wheat lines confirms effective use of legume-derived N by wheat, especially under Aglime+RNP application. This highlights the synergy between soil acidity correction and rotational N supply.

Barley, in contrast, showed little to no benefit from rotation. Except the 50% (Lime+VC+RNP), the No-Rotation_Barley line remained above the Rotation_Barley line, suggesting that barley does not capitalize on legume residues or that other limiting factors override the benefit.

The combined wheat and barley mean effect (Rotation_WhtBry) further illustrates the system's efficacy. Across all treatments, the Rotation_WhtBry line sits above the barley line, showing the same optimal response pattern. Yield is maximized by the Aglime+RNP treatment, followed by the 50% (Lime+VC+RNP) treatment. Thus, pH correction via liming remains the most critical management factor for maximizing system performance for cereal production under a legume rotation, though integrated approaches still provide a viable alternative option.

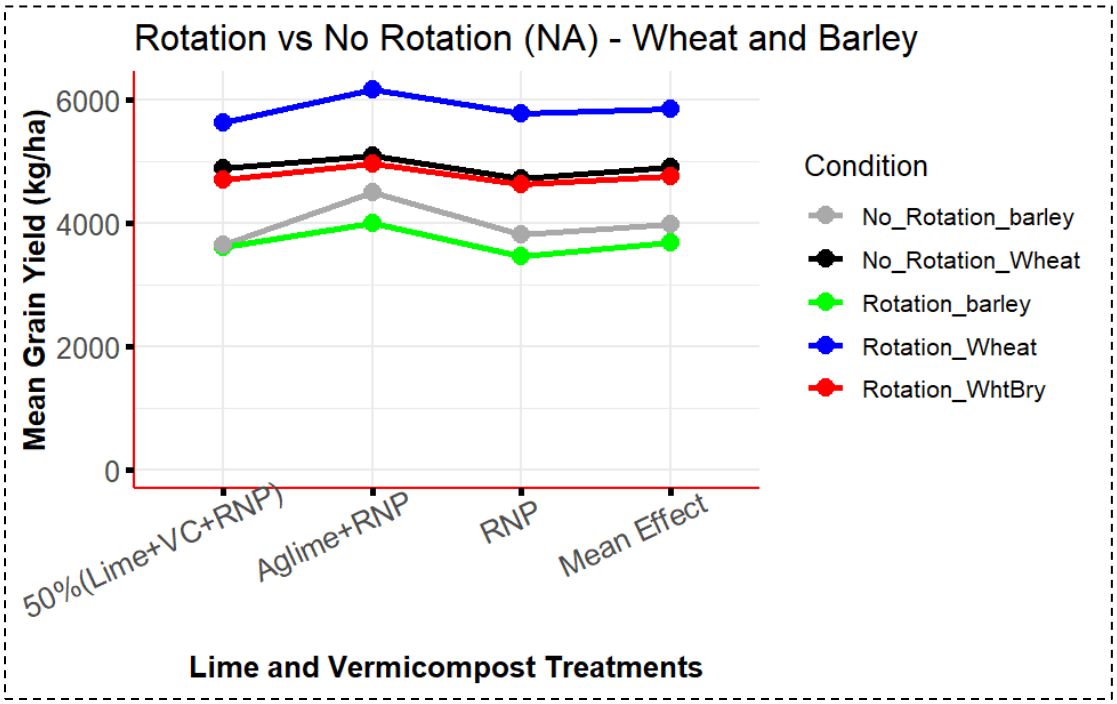


Figure 3: effect of rotation cropping on grain yields of wheat and barley

3.4. Effect of integrated acid soils management options on soil properties

The results of combined analysis of variance of treatment effects on soil properties using mixed effects model are shown in Table 4 and 5. Soil pHw, exchangeable acidity (ExAc), cation exchange capacity (CEC), available phosphorus (AvP), and total nitrogen (TN) were highly significantly affected by the treatments. This indicates that the applied treatments (aglime + vermicompost + RNP and Aglime + RNP) substantially altered soil

acidity parameters and nutrient availability, but did not significantly change soil organic carbon (OC) in the short term. Crop type significantly differed in their effects on soil pH, AvP, and TN, but not on ExAc, CEC, or OC. This shows that different crops influenced soil reaction and nutrient availability differently, likely due to their varied nutrient uptake and rhizosphere processes. Treatment effects also differed significantly between years, particularly for ExAc, CEC, AvP, and TN; likely reflecting the residual effect of treatments and crop sequence on soil properties. The crop*treatment interaction effect was significant for pHw, CEC, and OC, indicating that the effect of lime and Aglime+VC treatments on pHw, CEC, and OC differ depending on whether the preceding crop was wheat, barley, or faba bean. Similarly, the Year*Treatment interaction was significant for pHw and ExAc, implying that treatment effects changed between the two years, which is expected given that lime and vermicompost applied only in Year 1; and their effect maintained or amplified in the second year due to the additional reaction time.

Table 3: results of ANOVA for treatment effects on soil properties, results based on years

Year	Effect	pHw	ExAc	CEC	OC	AvP	TN
2023	Treatment	***	NS	**	NS	NS	*
	Crop	*	NS	NS	NS	NS	NS
	Crop*Treatment	NS	NS	NS	NS	NS	NS
2024	Treatment	**	***	*	NS	*	*
	Crop	NS	NS	NS	NS	*	**
	Crop*Treatment	NS	NS	NS	NS	NS	NS
Combined across years and crops	Treatment	***	***	***	NS	**	***
	Crop	*	NS	NS	NS	**	***
	Year	NS	***	***	NS	***	***
	Crop*Treatment	**	NS	*	*	NS	NS
	Year*Treatment	*	***	NS	NS	NS	NS

3.4.1. Soil pH and Exchangeable Acidity

Treatment effects on soil pH and exchangeable acidity were consistent with expected liming responses. Both aglime + RNP and 50% (aglime + VC + RNP) treatments significantly increased soil pH compared to the control in both year 1 and 2, showing the residual effect of the treatments. Correspondingly, exchangeable acidity was significantly reduced under both lime-based treatments relative to the RNP (control). These results align with established findings that liming neutralizes exchangeable Al^{3+} and H^{+}, raising soil pH and base saturation [14, 15].

Table 5 shows how the mean effect of main treatments (aglime + RNP and 50% (aglime + VC + RNP)) compared to the control (RNP) across key soil quality indicators: pH,

Exchangeable Acidity (ExAc), and Cation Exchange Capacity (CEC), grouped by crop and combined across two years. Based on the mean effect of the treatments across crops and years showed that aglime increased soil pH by 0.52 units compared to the baseline or control (RNP), while 50%(Lime+VC+RNP) treated plots increased by 0.27 units only. Aglime was the more effective at neutralizing acidity, resulting in the highest mean pH (5.42). The 50%(Lime+VC) resulted in to the lowest mean Exchangeable Acidity (0.97 Cmolc/kg), showing that it is slightly more effective at reducing active acidity (ExAc) likely due to the buffering effect and Al-complexing role of organic matter.

3.4.2. Available Phosphorus (AvP)

Combine analysis across years and crops (Table 5) shows that application of aglime results to the lowest mean available phosphorus content (av P) of 16.34 mg/kg. The RNP and 50% (Lime + VC + RNP) treatments resulted in higher mean available P (17.38 and 17.90 mg/kg, respectively). Crop and year based evaluation of soil data (Table 6) showed similar results. This is unexpected, as raising soil pH should generally increase availability of P in highly acidic soils by reducing aluminum and iron fixation. Although the differences are relatively small, the result warrants further investigation. And yet, the lower available P exhibited in the lime treated plots can be explained by enhanced yield-induced P removal (or a “dilution effect”). The higher biomass yield in the aglime treated plots compared to the remaining two treatments, results to higher amount of nutrient extraction and utilization, thus reducing the available P content after harvest. In the soils were well supplied above the crop/s’ requirement, the results could have been different.

3.4.3. Cation Exchange Capacity (CEC)

CEC showed the clearest and most consistent positive response to treatments. Integrated 50% (aglime + VC + RNP) achieved the highest CEC increases, followed by Aglime + RNP, while RNP alone had the lowest values. This pattern reflects the restoration of negative charge sites through pH correction and the contribution of organic matter functional groups [16]. The residual effect in year 2 was also evident, especially under lime treatments, confirming the longer-term benefits of liming on soil charge properties [17].

3.4.4. Soil Organic Carbon and Total N

The application of aglime and the combined aglime + vermicompost (VC) treatment did not result in a significant change in soil organic carbon (SOC). This outcome is consistent with the well-established understanding that SOC accumulation is a slow and long-term process, driven by the gradual stabilization of organic inputs through humification and the

formation of mineral–organic complexes [18, 19]. Short-term amendments, even when they include organic materials, often fail to produce measurable increases in SOC because the majority of the added carbon is rapidly decomposed by soil microorganisms, especially under improved pH conditions that enhance microbial activity [20]. Sustained SOC buildup typically requires continuous application of organic residues over several years, combined with practices that promote residue retention, reduced disturbance, and long-term carbon stabilization mechanisms.

Table 6, 7, 8, and 9 show the ANOVA results by crop, year, or combined across crops and years. TN (total N in the soil) was highest in the RNP-only plots and lowest in the aglime + RNP treatment. This contrast reflects the interplay between N mobilization and crop removal (yield). In the RNP-only plots, this has the lowest pH and highest exchangeable acidity, the higher TN likely stems from the native organic N pool being suppressed from decomposition and less N being removed by the crop. In essence, much of the organic N becomes “acid-locked,” resisting mineralization when pH is low. Microbial activity (especially nitrification) is sensitive to acidity, so conversion of organic N to NH_4^+ and NO_3^- is hindered under low pH [21]. Because root growth is constrained by Al/Fe toxicity, crops in these plots likely had lower biomass and less N removal, leaving more residual N in the soil.

In contrast, the lower residual TN in the limed plots (aglime and 50 % lime + VC), can be explained by yield-induced N removal. Raising soil pH stimulates microbial mineralization, converting the locked organic N into forms accessible to plants. The crops under these conditions produce greater biomass and thus take up more N, exporting it with the harvest, with the amount of N removed in harvested material increasing with increased yields. Thus, residual TN tends to be lower per unit soil, consistent with what is sometimes referred to as the dilution effect. This mechanism is consistent with [22, 23]. who showed that enhanced yield and N uptake due to improved soil conditions effectively increases N removal by the crop.

Table 4: mean effect of treatments on soil chemical properties combined across two years

Crop	Treatment	pHw	ExAc	CEC	OC	AvP	TN
F/bean	50%(Lime+VC)	5.36	1.00	21.87	2.32	18.28	0.23
	Aglime	5.78	0.97	21.83	2.50	16.42	0.21
	RNP	4.98	1.24	20.78	2.30	17.48	0.24
barley	50%(Lime+VC)	5.14	0.99	21.89	2.66	17.13	0.26
	Aglime	5.12	1.06	23.97	2.26	14.61	0.25
	RNP	4.83	1.28	22.30	2.30	16.15	0.27
Wheat	50%(Lime+VC)	5.1	0.92	19.13	1.95	18.37	0.22

	Aglime	5.45	1.04	21.89	2.30	17.94	0.22
	RNP	4.99	1.28	19.77	2.52	18.59	0.24
Mean	50%(Lime+VC)	5.17	0.97	20.86	2.32	17.9	0.24
of three	Aglime	5.42	1.02	22.43	2.36	16.34	0.22
crops	RNP	4.90	1.27	20.84	2.37	17.38	0.25

3.5. Crop by Treatments interaction effects on soil properties

Significant interaction effects were observed between crop type and soil amendments for key chemical properties, particularly soil pH, exchangeable acidity (ExAc), and cation exchange capacity (CEC). Among the three crops, faba bean showed the strongest response to lime-based treatments (Table 5). Under Aglime + RNP, soil pH on faba bean plots increased by 0.8 units, compared to 0.45 units for wheat and 0.3 units for barley. Similarly, the reduction in ExAc was greatest under faba bean, with a fall by 0.27 Cmol(+)/kg for Aglime + RNP and 0.24 Cmol(+)/kg for 50% (aglime + VC + RNP), indicating that legume cultivation enhanced the effectiveness of liming (Table 6). This response reflects the dual contribution of lime and faba bean to improving soil chemical conditions. Legumes can raise rhizosphere pH through nitrate uptake and organic acid exudation, which accelerates lime reactions and reduces exchangeable acidity [18]. Their nitrogen-fixing capacity further stimulates microbial activity, promoting rapid amelioration of soil acidity.

For CEC, wheat fields recorded the largest increase by aglime application (2.12 Cmol(+)/kg), followed by malt barley (1.65 Cmol(+)/kg) and faba bean (1.05 Cmol(+)/kg). This pattern may be attributed to differences in rooting systems, nutrient uptake dynamics, and residual effects. Wheat benefited substantially from both the residual lime effect and preceding legume crop, leading to improved soil chemical properties even in the second year.

In contrast, malt barley showed the weakest response across all indicators, particularly in pH increase and reduction of ExAc. This suggests malt barley is less able to modify its rhizosphere environment or take advantage of improved soil chemical conditions compared to faba bean. Barley's relatively shallow root system and limited biological nitrogen input may further constrain its interaction with amendments [24]. Wheat showed intermediate responses, reflecting its capacity to benefit from both rotation and residual liming, though not as strongly as faba bean in the application year. Overall, these crop-specific differences highlight that the effectiveness of soil acidity management depends not only on amendment type but also on crop physiology and soil–plant interactions. Incorporating faba bean into rotations with cereals enhances liming benefits, leading to

greater improvements in soil pH, reduced exchangeable acidity, and sustained gains in CEC.

Table 5: ANOVA results by crop type for treatment effects on soil properties

Crop	Sources of variability	pHw	ExAc	CEC	OC	AvP	TN
Faba bean	Treatment	***	***	NS	NS	**	*
	Year	NS	***	NS	NS	***	***
	Year*Treatment	NS	***	NS	NS	NS	NS
Barley	Treatment	*	**	**	NS	*	*
	Year	NS	*	*	NS	***	***
	Year*Treatment	NS	*	NS	NS	NS	NS
wheat	Treatment	**	**	**	NS	NS	*
	Year	NS	NS	**	NS	***	***
	Year*Treatment	NS	NS	NS	NS	NS	NS

Table 6: mean effect of treatments on soil chemical properties, separated by years and crop type

Crop type	**Treatment**	**pHw**		**ExAc**		**CEC**	
		2023	2024	2023	2024	2023	2024
F/bean	50%(Lime+VC)	5.34	5.38	1.17	0.82	21.09	22.60
	Aglime	5.80	5.76	1.15	0.78	21.49	22.13
	RNP	5.01	4.93	1.20	1.28	20.37	21.15
barley	50%(Lime+VC)	5.05	5.22	1.13	0.86	21.58	22.08
	Aglime	5.07	5.17	1.18	0.95	23.01	24.80
	RNP	4.89	4.78	1.24	1.34	21.62	22.85
Wheat	50%(Lime+VC)	5.04	5.16	1.05	0.80	18.33	20.40
	Aglime	5.43	5.47	1.14	0.95	21.17	23.09
	RNP	4.99	4.98	1.24	1.33	18.68	21.34

3.6. Economic Analysis

The results of the cost–benefit analysis (Table 7) clearly demonstrate that the application of agricultural lime (Aglime) in combination with the recommended nitrogen and phosphorus fertilizers (RNP) provides consistent economic advantages across the three crops evaluated: wheat, barley and faba bean. In all cases, Aglime + RNP generated higher net present values (NPV) and marginal benefits (MB) compared to the sole application of RNP. This indicates that liming effectively enhances soil conditions, improving nutrient availability and crop productivity, which ultimately translates into higher revenues. The improvement in profitability across both years further confirms that liming

is not only agronomically beneficial but also economically justified for acid soil management.

The combined application of vermicompost (VC), Aglime, and RNP at 50% of the recommended rates of each resulted in mixed economic outcomes. This approach yielded a small Marginal Benefit (MB) for wheat but a negative MB for barley. This low profitability is attributed to the fact that the integrated input rates likely failed to satisfy the nutrient demands of the crops during the first year. The sharp decline in barley yield during the second year further underscores this deficiency, suggesting that the residual nutrient supply from the previous year's vermcompost application and the second year's application of 50% RNP only was significantly below the crop's requirements. Conversely, faba bean exhibited a clear positive economic response to the combined Aglime+VC treatment. As a legume, faba bean benefited substantially from both the improved soil chemical environment and the biological advantages and organic nutrient cycling provided by the vermicompost, leading to a favorable economic return. It also indicates sufficiency of the nutrient inputs from the external supply.

Comparison of the two-year NPVs indicate that wheat production can generate the highest income. However, the high NPV for wheat is also partially attributable to the beneficial nutrient carryover provided by the faba bean rotation. Conversely, the higher MB observed for faba bean and barley compared to wheat suggests that their production costs are inherently lower. This difference is due to faba bean and barley being relatively lower-input crops, esp. for post-plant management costs.

Overall, the economic analysis consistently confirms the superiority of the Aglime + RNP treatment across all three crops. Lime application serves as a sound investment for farmers by effectively increasing the efficiency of applied fertilizers and supporting stable yield improvements. Conversely, vermicompost appears to be more suitable for specific crops, particularly legumes, when applied at existing recommended rates. The success of integrating vermicompost with lime and RNP at 50% of each recommended rate may be contingent on the initial soil fertility status and the quality of the organic product. In general, the analysis highlights that while organic amendments offer valuable complementary benefits, lime remains the most economically reliable intervention for correcting soil acidity and enhancing crop productivity on a broader scale. Hence, further work is required to optimize the use the recommendations for integrated use of organic inputs with lime and inorganic fertilizers.

Table 7: Cost benefit analysis of lime and lime + Vermicompost relative to sole application of recommended N and P

Crop type	Treatments	Revenue		Total Cost (fixed + TCV)/ha		Discounted values		Economic Indices		
		2023	2024	2023	2024	PV (b)	PV (C)	BCR	NPV	MB
Wheat	RNP	304,670	384,190	97,605	101,325	555,434	161,490	3.4	393,944	…..
	Aglime + RNP	331,018	410,610	113,945	102,641	598,322	176,694	3.4	421,628	27,684
	50%(glime+VC+RNP)	318,142	372,811	110,191	90,239	558,544	164,051	3.4	394,493	549
Barley	RNP	289,043	259,833	84,988	83,784	447,813	137,255	3.3	310,557	…..
	Aglime + RNP	337,748	291,079	102,403	85,436	513,791	153,648	3.3	360,143	49,586
	50%(aglime+VC+RNP)	275,255	273,469	98,331	75,757	446,134	142,788	3.1	303,345	-7,212
F/bean	RNP	241,316	229,357	81,744	81,317	383,267	132,568	2.9	250,699	…...
	Aglime + RNP	270,425	280,416	98,039	83,399	447,188	148,313	3.0	298,875	48,176
	50%(aglime+VC+RNP)	255,826	270,633	97,402	75,438	427,094	141,739	3.0	285,355	34,657

Note: PV (b)= present value of total benefits, PV (c) = present value of total costs, BCR= benefit-cost ratio, MB = marginal benefits. The total cost included total costs that vary (TCV), and revenue = sum of grain and straw yield economic values

4. Conclusions and Recommendations

4.1. Conclusions

Aglime and integrated lime + vermicompost (VC) treatments had strong positive effects on plant height, grain yield, and biological yield, with stable responses across 2023 and 2024. Although Year × Treatment interactions were not significant, yield improvements in the second year indicated a clear residual effect of lime and VC, as well as benefits from the preceding crop. In rotation, wheat benefitted notably from preceding faba bean under limed conditions, while malt barley showed less consistent gains, possibly due to lower responsiveness to residual nitrogen. The highest yields were obtained from the full Aglime + RNP treatment, but the 50% (Aglime + VC + RNP) treatment also performed well, suggesting that a half-rate integrated approach offers a cost-effective and sustainable option for acid soil management.

Treatments improved soil pH, reduced ExAc, and increased CEC, confirming rapid improvement of soil chemical properties. Significant Year × Treatment interactions for pH and ExAc demonstrated the persistence of lime and VC effects into the second year. Crop × Treatment interactions for pH, CEC, and OC indicated that crop biology and root processes influence treatment effectiveness. Although soil organic carbon did not change significantly likely due to the short study duration, TN showed a complex pattern, with higher residual TN in control plots and lower TN in limed plots, suggesting that liming mobilized previously unavailable nitrogen absorbed by crops. Overall, crop-specific sensitivity was evident, with faba bean plots showing stronger increases in pH and

reductions in ExAc, underscoring legumes' role in enhancing liming efficiency and acid soil management.

4.2. Recommendations

Applying the full lime + RNP dose gives maximum yield, but where resources are limited, the 50% lime + VC + RNP option remains effective and economical. As lime and VC effects last into the second year, annual reapplication is not be needed, reducing costs. The strong benefit of faba bean–wheat rotation under limed conditions also underscores the value of legumes in improving soil fertility, nitrogen supply, and wheat yields

4.3. Suggestion for future research and extension support

- Longer-term trials. Extend the experiment over 3–5 years to track how residual effects evolve under different application rates, and whether diminishing returns set in.
- There is also a need to study more legume crops for rotation cropping of cereals under limed soil conditions. Some crops or varieties can be more responsive to amendments, providing additional advantage for correction soil acidity and yield of the subsequent crop.
- There is also a need to optimize the integrated lime, chemical fertilizer and organic inputs. The variation in the amount of organic inputs needed is to strike a balance between lime+RNP and organic inputs.

5. Acknowledgement

This research was supported by the Ethiopian Institute of Agricultural Research (EIAR) and Agricultural Transformation Institute (ATI)- Ethiopia. We would like to thank them for their support to advance sustainable land management on acid soils of Ethiopia.

6. Declaration of conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

"Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors."

7. Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. Will also be available from the data base under Ethiopian Institute of Agricultural Research

8. References

[1] Gebrekidan, H. H. (2026). Soil acidification: Sources, processes, impacts on soil properties, nutrient dynamics, crop health, and yield: A review with evidence from Ethiopia and Sub-Saharan Africa. *EQA – International Journal of Environmental Quality*.

[2] Cherie, D. A., & Abeje, B. Y. (2022). Soil Acidity Formation and its Amelioration Methods in Ethiopia: A Review. *Asian Journal of Soil Science and Plant Nutrition, 8*(2), 23–31. https://doi.org/10.9734/ajsspn/2022/v8i230136.

[3] Takala, B. (2019). Soil Acidity and Its Management Options in Western Ethiopia: Review. *Journal of Environment and Earth Science, 9*(10).

[4] Bekele, S., et al. (2018). Effects of Lime, Vermicompost, and Chemical P Fertilizer on Selected Properties of Acid Soils of Ebantu District, Western Highlands of Ethiopia. *Applied and Environmental Soil Science*, 2018, 8178305.

[5] Regasa, A., Haile, W., & Abera, G. (2026). Synergistic effects of lime, vermicompost, and phosphorus fertilizer enhance maize productivity and soil quality in acidic soils of Ethiopia. *Discover Soil, 3*, 42.

[6] Gebrekidan, H. H., et al. (2026). Soil acidity in Ethiopia: Its causes, extent and management. *Geoderma Regional, 45*, e01092. https://doi.org/10.1016/j.geodrs.2026.e01092.

[7] Walkley, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37: 29–38.

[8] Bremner, J.M. and Mulvaney. C.S. 1982. Total nitrogen, In: Miller, AL., R.H. and Keeney, D.R. (eds). Method of Soil Analysis, Part 2, Agronomy Monograph No. 9. American Society of Agronomy, Madison, WI.

[9] Chapman, H.D. 1965. "Cation-Exchange Capacity." In *Methods of Soil Analysis, Part 2*, ed. C.A. Black, pp. 891–901. Agronomy Monograph no. 9. ASA and SSSA, Madison, WI.

[10] Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic and available forms of phosphorus in soils. Soil Sci., 59:39-45.

[11] Regasa, A., Haile, W., & Abera, G. 2025. Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils. *Scientific Reports*, *15*(1), 25544. https://doi.org/10.1038/s41598-025-02053-4

[12] Temesgen Desalegn, Getachew Alemu, Ayalew Adella, Tolessa Debele *and* Julián Gonzalo. 2016. Effect of Lime and Phosphorus Fertilizer on Acid Soils and Barley (*Hordeum Vulgare* L.) Performance in the Central Highlands of Ethiopia. *Expl Agric.*: page 1 of 13. https://doi.org/10.1017/S0014479716000491

[13] Temesgen Chimdessa. 2018. Effect of Lime and Vermicompost Amendments on Selected Soil Properties and Wheat (*Triticum aestivum* L.) Productivity on Nitisols of Negasa Area, East Wollega Zone, Ethiopia. MSc Thesis, Haramaya University, Haramaya.

[14] Fageria, N. K., Baligar, V. C. 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. Advances in agronomy. 99:345–399. https://doi.org/10.1016/S0065-2113(08)00407-0.

[15] Marschner, H. 1995. Mineral Nutrition of Higher Plants. 3rd ed. Academic Press. https://doi.org/10.1016/C2009-0-63043-9.

[16] Hue, N.V., & Silva, J.A. 2000. Organic soil amendments for sustainable agriculture: Organic sources of nitrogen, phosphorus and potassium. In Silva, J.A. & R. Uchida (Eds.). Plant nutrient management in Hawai's soils: Approaches for tropical and subtropical agriculture. pp. 133–146.

[17] Weil, R. R., and N. C. Brady. 2016. The Nature and Properties of Soils. 15th ed. Pearson, Columbus, OH.

[18] Six, J., Conant, R. T., Paul, E. A., & Paustian, K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil, 241(2), 155–176. https://doi.org/10.1023/A:1016125726789

[19] Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security.Science,304(5677), 1623–1627. https://doi.org.10.1126/science.1097396

[20] Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. 2016. Climate-smartsoils.Nature,532(7597), 49–57. https://doi.org/10.1038/nature17174

[21] Weier, K. L., and J. W. Gilliam. 1986. "Effect of acidity on denitrification and nitrous oxide evolution from two soils. Soil Science Society of America Journal, 50(5), pp. 1011–1014.

[22] Fageria, N. K., R. J. Wright, and V. C. Baligar. 2010. Low soil pH effects on dry bean production. Communications in Soil Science and Plant Analysis, 41(7), pp. 883–919.

[23] Fageria, N. K., & Barbosa Filho, M. P. (2008). Influence of pH on Productivity, Nutrient Use Efficiency by Dry Bean, and Soil Phosphorus Availability in a No-Tillage System. Communications in Soil Science and Plant Analysis, 39(7–8), 1016–1025. https://doi.org/10.1080/00103620801925422

[24] Tang, C., & Rengel, Z. (2003). Role of Plant Cation/Anion Uptake Ratio in Soil Acidification. In Z. Rengel, & Z. Rengel (Ed.), Handbook of Soil Acidity. USA: Marcel Dekker.