Research Article

The Effect of Phosphorus Fertilizer Sources and Lime on Acidic Soil Properties of Mollic Rhodic Nitisol in Welmera District, Central Ethiopia

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The soil acidity problem is intensified by improper utilization of synthetic fertilizers in addition to other naturally existing causes; thus, it is important to consider effects on soil health beyond seasonal crop productivity. Most widely used sources of soluble phosphate fertilizers cannot perform effectively on acidic soil due to its fixation. Field experiments were conducted on the acidic nitisols of Welmera District in two locations to determine the effects of using lime and different phosphorus fertilizer sources on the soil acidity attributes and nutrient use efficiency of barley crops. Treatments include a factorial combination of 4 different phosphate fertilizer sources (PARP, MOHP, NPSB, and NAFAKA) with 2 application rates (34.5 kg P_2O_5 ha^{-1} and 69 kg P_2O_5 ha^{-1}) and 2 lime application rates computed from soil exchangeable acidity result 404.25 kg·ha^{-1} and 563.9 kg·ha^{-1} for on-station and on-farm sites, respectively, with no lime application (1/4th of LR and 0 lime). Partially acidulated rock phosphate as a phosphorus fertilizer significantly improves soil acidity attributes such as exchangeable acidity, present acid saturation, and plant available phosphorus, and also another soil nutrient status is significantly affected by using different phosphorus sources with the lime application. Application of PARP phosphate sources significantly improves soil exchangeable acidity and present acid saturation by 42% and 41%, respectively, over the commonly used NPSB standard sources of phosphorus fertilizer. Using lime with alternative phosphate sources also contributes to more effective nutrient use efficiency and barely yields improvements with a productive acid soil amendment option. Maintaining soil health by using those integrated approaches improves the efficient utilization of scarce unrenewable resources on sustainable bases.

1. Introduction

Soil acidity is one of the major constraints in highly weathered soils for the production and productivity of crops worldwide; it is also chronic in high-rainfall areas of Ethiopia. According to EthioSIS [1], acid soil is estimated to be covering more than 43% of the arable land in Ethiopia. Soil acidification is a natural process that might be aggravated by human agricultural activities such as the removal of plant and animal products and leaching of excess nitrate addition of some nitrogen-based fertilizers [2]. Soil acidification leads to Al and Mn toxicity plus a deficiency of macro- and microplant essentials, which lead to a lack of or reduced response to fertilizer application due to high P fixation by Al and nutrient deficiency which can result in 50% and above yield reduction [3].

The application of different lime materials such as calcium carbonate ($CaCO_3$) is known to affect reducing the effect of Al by releasing fixed phosphorus within it [4]. So, it is important to consider the application of phosphorus fertilizer with lime to obtain effective nutrient use efficiency of crops under acidic soil conditions. According to Bekunda et al., the tropical acidic soils contain slight or no weatherable minerals and have a clay fraction dominated by

kaolinite, oxides, and hydroxides of Fe and Al which are known by their low cation exchange capacity (CEC) and low inherent fertility so they require balanced fertilization with several essential nutrients [5]. To enhance the lime amendment efficiency for acidic soil productivity it is essential to follow integrated approaches of soil management with balanced fertilization. The soil pH was markedly increased by lime addition, and thus the toxic effect of soil acidity was reduced consequently nutrient availability and crop growth were improved[6]. As reported by Boke and Fekadu [7], half a dose of recommended lime application with NPK fertilizer significantly increased barley yield on different soil types of Chencha and Hagere Selam which signifies that balanced fertilization of acidic soils is critical [8].

The EthioSIS soil fertility map has provided basic data for balanced fertilization research in major Ethiopian soils. Research results also indicated that yields could be doubled, in some cases tripled, with P application [9] on the acidic soil of the central highlands of Ethiopia. But, the high costs of high-grade, water-soluble P fertilizers, coupled with the strong P fixing capacities of acid soils, present agronomic and economic constraints to crop production [10]. There are different sources of phosphatic fertilizers appropriate for acid soil which has been appropriate through their efficiency in providing applied P to crops under low soil pH and high rainfall conditions; this fertilizer combined with lime and other essential nutrients can correct the nutrient availability, thereby enhancing the nutrient uptake and use efficiency [11]. Studies indicated that in some acidic soil of the western parts, application of lime with conventional fertilizer cannot enhance crop productivity, so it is mandatory to look for alternatives and investigate the effect on soil. So, the efficiency of those different fertilizer types with lime application was not widely studied under Ethiopian acidic soil condition. The objective of this study is to fill the research gap on alternative uses of different phosphorus fertilizers with liming to enhance potential crop production by optimizing yield-limiting soil acidity attributes. Different sources of phosphate fertilizer vary in their nature of availability with optimal lime application to enhance sustainable soil and crop productivity.

2. Materials and Methods

2.1. Description of Study Area.
Those field experiments were conducted in Welmera District in two locations at Holeta Agricultural Research Center (on-station (OnS) which is one of the research centers under Ethiopian Institute of Agricultural Research (EIAR)) and nearby farmer's field at Rob Gebeya PA (on-farm (OnF) based on a contractual agreement with respective farmers for the cropping season), in the central highland of Ethiopia, 35 km and 56 km, respectively, to the west direction of Addis Ababa. The experimental sites were located at DMS 9° 03′ 15″ N latitude and 38° 30′ 07″ E longitude with an altitude of 2365 m.a.s.l. and on-farm site at 9° 8′ 24″ N latitude and 38° 26′ 07″ E longitude with an altitude of 2625 m.a.s.l, respectively. The Welmera District is part of the Oromia Special Zone surrounding Addis Ababa. It is bordered in the south by Sebeta Hawas, in the west by the West Shewa Zone, in the north by Mulo District, in the northeast by Sululta, and in the east by the Addis Ababa City.

2.1.1. Soil Property.
The Welmera area is low in soil pH and deficient in available P [8]. Thus, the amount of available P in the soil is, by far, insufficient to meet the requirements of barley production which is the most widely grown cereal crop in the highlands of Ethiopia. This soil was characterized as mollic rhodic nitisol (aric, feric, and humic) according to the classification in [12] . The soil fertility map of EthioSIS [1] described the study area as acidic soil and having a limitation/deficiency of essential elements such as nitrogen, phosphorus, sulfur, and boron. It was widely affected by soil acidity problems, and the textural class of this area is dominated by clay particles.

Nitrogen, phosphorus, sulfur, and boron nutrients' availability for crop uses was more limited in the specific soil type than any other essential mineral nutrients (Figure 1), whereas the remaining essential nutrients are found relatively in higher and sufficient levels which were also revealed on EthioSIS [1], soil fertility map of Welmera District's specific experimental site.

2.1.2. Climate.
The recent seven years' (from 2013 to 2019 inclusive) weather records of Holeta Agricultural Research Center mean result showed that a mean annual air temperature of 14.7°C that varies from 6.1°C minimum monthly average up to 23.5°C monthly mean maximum temperature. The absolute monthly mean maximum of 28.8°C and minimum of −0.6°C occurred in Jan and March 2013, respectively. The average sunshine hours are 6.8 hours/day in a year, and this varies between 2.7 hours/day in July and 9.1 hours/day in November. Holeta or Welmera District receives an average total rainfall of 1102.4 mm annually (Figure 2), whereas in the study year (2017), a total of 1071.6 mm of rain was received. This is spread over all months except December and ranges from the lowest of 0 mm in December to the highest of 311 mm in August 2017.

2.2. Experimental Design.
The experiment was conducted by using a factorial RCB design which has three experimental factors comprising four different types of phosphorus fertilizer sources PARP, MOHP, NPSB, and NAFAKA plus; two phosphorus fertilizer rates (PR1 = 34.5 kg P_2O_5 ha^{-1} and PR2 = 69 kg P_2O_5 ha^{-1}). The amount of 69 kg was established based on the findings ofthe previous fertilizer rate study conducted at a specific site and for thecorresponding crop type. P_2O_5 ha^{-1}is the full recommended rate. Two lime application rates, i.e., no lime and 1/4th of lime, required computation from the soil exchangeable acidity result for each experimental location, with three replications (Table 1). Different sources of P fertilizers used are listed below with their nutrient compositions.

> P1. PARP (granular partly acidulated rock phosphate): P_2O_5 = 49% (20% soluble in mineral acid, 18% soluble in water and neutral ammonium citrate, and 11% soluble in water), S = 7%, B = 0.6%, and Zn = 2%.
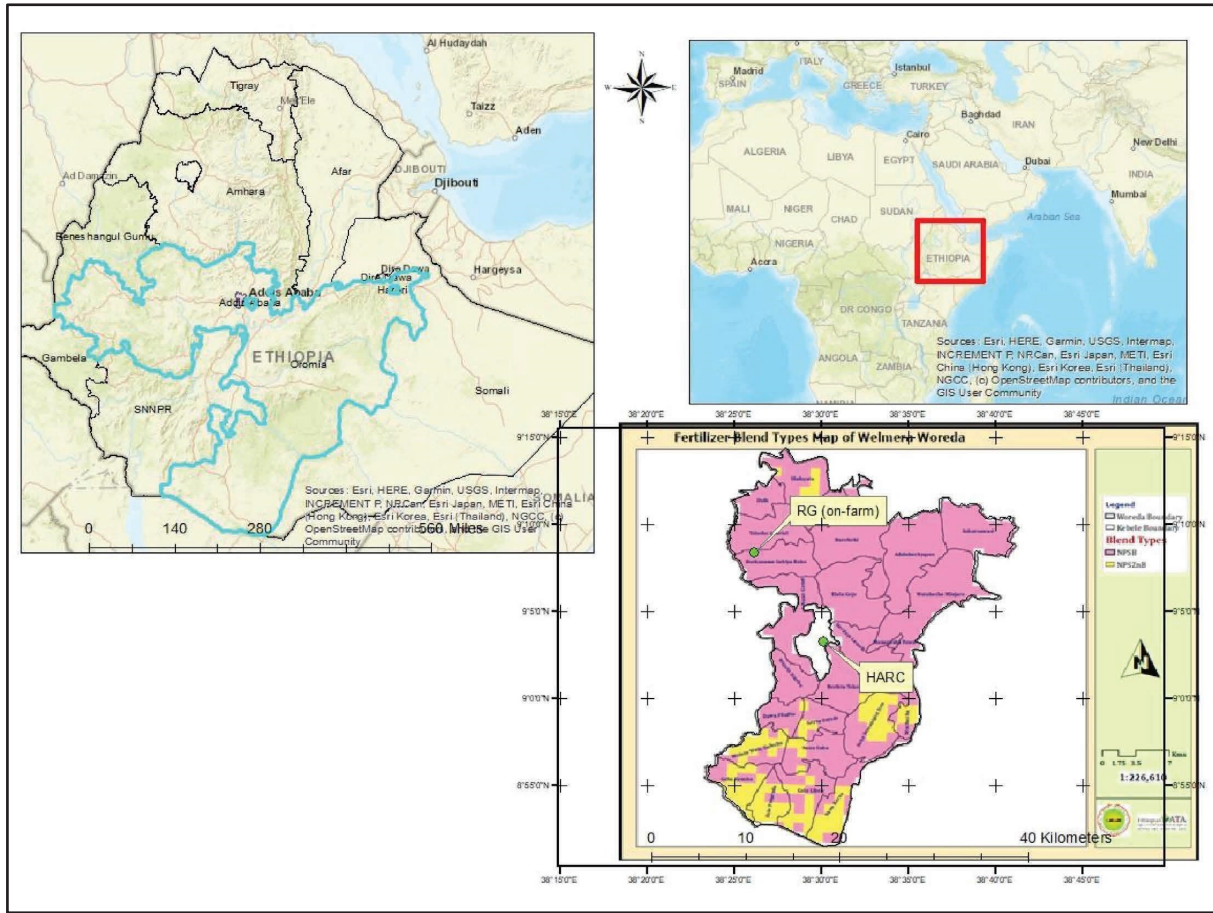
FIGURE 1: Study area with Ehiosis 2015 soil fertility map of Welmera district for on-station and on-farm trial sites.
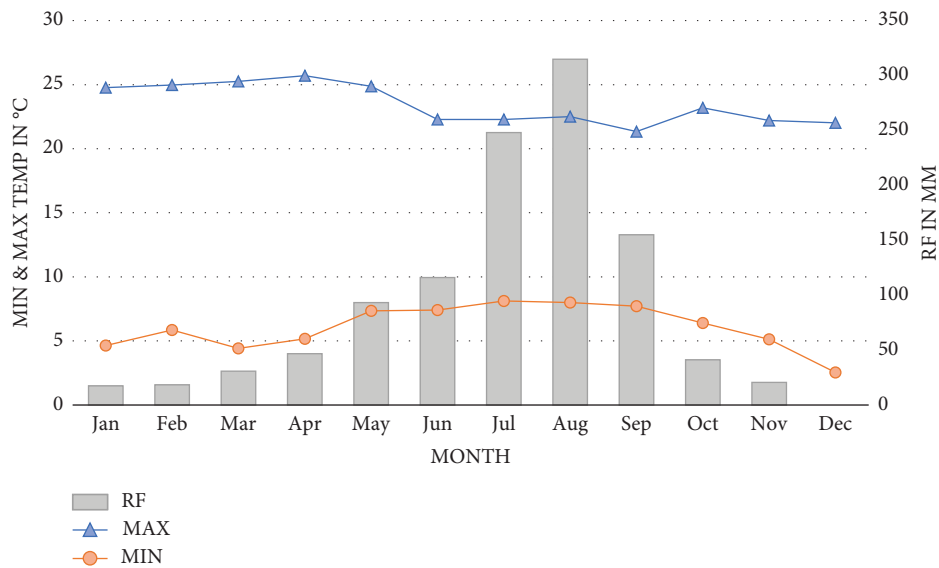

FIGURE 2: Seven years (2013–2019) of mean climatic data for the Holeta agricultural research center taken from its weather station. Where the major axis is for max and min temp, the minor axis is for rainfall.

TABLE 1: Treatments setup for evaluation of different phosphorus sources for Barley production on acidic Nitisols soils of Welmera.

No.	P sources	P_2O_5 rates	Lime application
1	$P1$ = PAPR	PR1 = 34.5 kg·ha^{-1}	$L0$ = No lime
2	$P2$ = MOHP	PR2 = 69 kg·ha^{-1}	LM2 = ¼ split
3	$P3$ = NPSB		
4	$P4$ = NAFAKA +		

P2. MOHP (organic hyperphosphate): P_2O_5 28% and CaO 36%

P3. NPSB (formula II blend fertilizer): N = 18.1%, P_2O_5 = 36.1%, S = 6.7% +, and B = 0.71%.

P4. NAFAKA +: N = 9%, P_2O_5 = 16%, K_2O = 16%, CaO = 25%, S = 5% MgO = 2%, Zn = 0.5%, and B = 0.1%.

Major essential nutrients were kept constant for all treatment sets except phosphorus (P_2O_5) to reduce the cofound effects from varied nutrient compositions from different phosphorus sources by using a single nutrient fertilizer. Nitrogen, potassium, sulfur, and boron are kept at the same rate for all treatments by using fertilizer sources such as urea CO $(NH_2)_2$ 46% N, muriate of potash (MOP) KCl 60% K_2O, ammonium sulfate $(NH_4)_2SO_4$ 21% N and 24% S, and borax $(Na_2B_4O_7.10H_2O)$ 11% B sources of fertilizer, respectively. From previous studies in those experimental sites, recommended phosphorus and nitrogen fertilizer rates for barley production on nitisol were 69 kg·P_2O_5 ha^{-1} and 60 kg·N ha^{-1}, respectively. Other major essential nutrients' (except N and P) application was determined according to the recommended rate of NPSB blended fertilizer composition based on P content based on [1] fertilizer type recommendation. It determines that the blended fertilizer rate combination for the Welmera District-specific study site was obtained from a combination of NPSB with 69 kg P_2O_5 ha^{-1} from 191 kg ha^{-1} NPSB application, which has a nutrient composition of N = 34.6 kg ha^{-1} (plus 55 kg ha^{-1} urea for 60 kg N ha^{-1}), P_2O_5 = 69 kg ha^{-1}, S = 12.4 kg ha^{-1}, and B = 1.4 kg ha^{-1} so other P fertilizer source rates were fixed accordingly.

Lime rate (LR) determination was done by using the exchangeable acidity method which was defined by the authors in [13]. The required lime rate was computed based on exchangeable acidity for on-station and on-farm experimental sites. We use 1/4th of LR so the final amount of lime applied is 275.1 kg ha^{-1} and 422.9 kg ha^{-1}, respectively. It was incorporated into the soil before planting by using $CaCO_3$ as a lime source. All fertilizer treatments were applied in the band application method at planting except nitrogen sources from urea which are applied into two splits (i.e., 1st at planting and the 2nd at the tillering growth stage of the barley). Planting was done by using the row planting method with a spacing of 20 cm between rows on a plot size of 2 m × 3 m and 100 kg·ha^{-1} seed rate was used for both experimental sites. Spacing between treatments and replications was kept at 0.5 m and 1 m, respectively. All other crop management practices were kept as per recommended for specific crop production uniformly for all experimental

units. The test site was georeferenced to generate area-specific micronutrient deficiency information [14].

2.3. Data Collection

2.3.1. Soil Sampling and Analysis.
150 cm by 200 cm pit was dug to a 200 cm depth for soil profile description for the Holeta on-station study site with standard soil characterization procedures using WRB's [12] soil classification system, and all identified soil horizon samples were taken for physicochemical characterization purpose, whereas composite surface soil samples were taken at 0–20 cm depth at each experimental site to assess the physicochemical properties and fertility status of the study soils at the surface. Fifteen random samples were collected before treatment application and homogenized into one for soil analysis. Finally, after harvesting soil, samples were collected treatment-wise to assess the residual effect of the treatments and to compute nutrient use efficiency.

2.3.2. Soil Property Determination.
Soil samples were prepared and examined for their textural class by using the hydrometer method of soil textural class determination. For characterization purposes, bulk density was analyzed on a dry weight basis from pF-ring undisturbed core soil samples. After drying the soil samples for 24 hours at 105°C, the bulk density was computed from its volume and weight. To calculate the soil availability water holding capacity, moisture volume at field capacity (1/3 atm) and the permanent wilting point (15 atm) by pressure plate extraction were determined, while particle density was determined by the pycnometer method [15]. Determination of soil pH is done by the H_2O method with a 1 : 2.5 ratio of soil to water suspension. The exchangeable acidity (EA) of the study area soil sample was determined by using Van reeuwij k, L.p 1N KCl leaching titration method [16]. Organic carbon (OC %) was determined by using the Walkley–Black chromic acid wet oxidation method [16]. Total nitrogen (TN) was determined by using Kjeldhal Bremner and Mulvancy methods. Available P was determined by using the Brey II method. Cation exchange capacity (CEC) was determined by using the ammonium acetate extraction method; soil available sulfate-sulfur (SO_4-S) was determined by using the turbidimetric method.

The composite soil sample from both experimental locations was analyzed for their basic cations, i.e., exchangeable potassium (K^+), magnesium (Mg^{2+}), sodium (Na^+), and calcium (Ca^{2+}), by using the ammonium acetate method of extraction which is appropriate for acidic to slightly alkaline soil types. Subsequently, the concentration of extracted nutrients was assessed using specific instruments. Flame emission spectrophotometer (FESP) was employed to measure K+ and Na+, while an atomic absorption spectrophotometer (AASP) was utilized to determine the levels of Ca2+ and Mg2+. Boron (B) was determined by using a dilute hydrochloric acid method which is most suitable for acidic soil types [16]. Other

micronutrients Fe, Zn, Mn, and Cu were determined by using the Mehlich-III extraction procedure followed by atomic absorption spectrophotometer (AASP) instrumental reading.

Percent acid saturation (PAS) of the soil was determined from the ratio of exchangeable acidity (EA) to the CEC multiplied by 100, which is part of the cation exchange site occupied by the H^+ and Al^{3+} ions which contribute to the EA properties of soil [17]. Percent base saturation (PBS) was computed from the exchangeable basic cations, i.e., K^+, Ca^{2+}, Mg^{2+}, and Na^+, and the CEC value of each sample which was from direct lab analysis result by using the equation offered by Fageria et al. [17]: BS% = $100 \times \sum$ (Ex. Ca, Mg, Na, K)/ CEC. On the other hand, a stratified soil sample was taken at harvesting from each experimental unit to determine the treatment effects on the soil's physicochemical properties.

2.3.3. Plant Sample Preparation and Analysis.
The plant sample was collected finally at threshing and winnowing which includes grain and all the remaining aboveground plant parts (straw) in a separate sample from each experimental treatment. The straw and grain samples were milled and sieved through a 0.5 mm size sieve and analyzed under the HARC plant and soil analysis laboratory for their phosphorus and other primary macroessential minerals such as nitrogen and sulfur contents by using the ashing method.

2.3.4. Determination of Phosphorus Recovery, Use Efficiency, and Harvest Index.
Phosphorus uptake in straw and grains was calculated by multiplying the P content by the respective straw and grain yields per hectare. Phosphorus uptake, by the whole plant, was determined by summation of the respective grain and straw P uptake on a hectare basis. Apparent fertilizer P recovery was calculated by the procedure described by the authors in [18]. Agronomic efficiencies (AE) and physiological efficiencies (PE) of P were calculated using the procedures described by Craswell and Godwin [19].

$$AE = \frac{(G_n - G_0)}{n},$$
$$PE = \frac{(G_n - G_0)}{(U_n - U_0)},$$

(1)

where "G_n" is the grain yield of the fertilized plot, "n" is the fertilizing rate, "G_0" is the grain yield of the unfertilized plot, and "U_n and U_0" are the nutrient uptakes on fertilized and unfertilized plots, respectively.

The phosphorus harvest index (PHI) was computed by taking the ratio of P uptake in grain yield to P uptake in total plant biomass and then multiplying the result by 100%.

2.4. Statistical Analysis.
Data on the soil and plant sample analysis results were subjected to analysis of variance (ANOVA) using Statistical Analysis software (SAS version-9.0) to evaluate the impact of different P fertilizer sources with different lime and fertilizer application rates on acid soil productivity attributes such as pH, exchangeable acidity,

available P, and others. Results were presented as means with the least significance difference (LSD) at the $P < 0.05$ probability level [20]. Over location, combined data of some parameters were computed since the largest standard error SE to least SE ratio was below 3 which indicates its homogeneity across experimental locations [21].

3. Results and Discussion

3.1. Soil Profile Description and Characterization of the Study Area.
According to Tefera et al. [22], the geology of the study area belongs to the Middle Miocene-aged transitional and alkaline basalt. Characterization results showed that these soils have rapid permeability and have evidence of significant weathering. This unit is used for crop production in cereal-pulse-based crop rotation which is mostly used for different field trials under several crops and soil and is currently under the harvested field of cereals.

The profile has an AP-B1-B2-B3 top-down horizontal sequence. This location's soil was characterized as mollic rhodic nitisol (aric, feric, and humic) according to the classification in [12] (updated 2015). This soil profile represents well-drained soils that occur on a sloping land (5–10% slope) in the middle slope of the farm. The soils of this mapping unit are generally very deep (>150 cm). The surface soil is dark reddish brown with a hue of 5 YR, a value of 2.5, and chroma of 2 when moist and reddish brown with a hue of 5 YR, a value of 4, and chroma of 4 when dry; and the subsurface horizons are dark reddish brown with a hue of 2.5 YR, value of 2.5 to 3, and chroma of 3 when moist and dark reddish brown with a hue of 2.5 YR, value of 3, and chroma of 3 to 4 when dry, whereas the on-farm (OnF) site has a 10 YR 5/6 light olive brown color at the dry condition and read as 10YR 4/3 "olive brown" while moist soil condition at the surface.

The soil texture is clay at the surface and heavy clay in the subsurface soils. The surface soils have sticky and slightly plastic, friable, and hard consistency when wet, moist, and dry, respectively, and sticky and plastic, friable, and hard consistency when wet, moist, and dry, respectively, in subsurface horizons. It has a strong coarse subangular blocky structure at the surface with clear and smooth boundaries and closely spaced medium surface cracks, and strong coarse subangular to angular blocky and strong coarse prismatic structure, common to many and medium hard manganese mineral concretion, pronounced strong angular blocky structure breaking into polyhedral or flat-edged or nut-shaped elements with common shiny aggregate faces at a moist state, with clear and gradual and smooth boundary in the subsurface soils.

Bulk density: As a major soil physical property influencing lime application rate and overall productivity of the studied soil, bulk density (apparent density) of the experimental site at the surface (depth <20 cm) result was 1.14 and 1.09 g·cm^{-3} for OnS and OnF sites, respectively; they are categorized under low (1.0–1.3 g·cm^{-3}) rating of soil bulk density according to Hunt and Gilkes [23]. This was influenced by frequent plowing methods and other farm management techniques used there.

The pH of the soil is strongly acidic (5.1) on the surface and strongly acidic to moderately acidic (5.5–5.8) in 40 subsurface horizons according to USDA/NRCS [24] rating, while for the OnF, the average surface soil pH was 4.24, which is virtually the same rating category with the OnS experimental site (Table 1) according to their soil pH results which were used as primary criteria to select study location in a specific district. The soil is generally nonsaline as it is acidic.

Exchangeable acidity: Mean exchangeable acidity (Al^{3+} and H^+) results for both locations' soil samples were 0.98 and 1.367 Meq 100^{-1} gram of soil for OnS and OnF sites, respectively (Table 2), which are quite representative for soil acidity [14]. The OnS site EA level exceeds 1 meq 100^{-1} gram of soil. As reported by several authors, soil pH values <5.5 usually have problems of Al toxicity or acidification, but they can be improved by amendment practices such as the application of lime, compost, or organic manure [25]. Up on liming, Álvarez et al. [26] reported decrease of Al^{3+} in the soil solution as well as in the exchangeable complex which creates a conducive soil environment for potential crop production.

The OC content in the surface horizon is low (1.134%) and also low to moderate, increasing and decreasing with depth (0.630–1.066%) in the subsurface horizons, while on-farm (OnF) OC content was found to be 1.76% on average. Soil organic matter contents were 1.95% and 3.03% for the two experimental sites, respectively, which were categorized under low levels of OC or SOM according to Brook's [27] rating.

The soil total nitrogen content is generally medium (0.142%) on the surface horizon and it is low (0.080%) in subsurface horizons. OnS and OnF study sites had an average total N value of 0.142% and 0.134%, respectively; both of them are categorized under the medium range of soil total N level according to Brook's [27] soil total nitrogen rating.

The CEC of the surface soils is moderate (19.6 cmol (+)/kg soil) with high BSP (74.8%) and that of the subsurface soils is low to moderate CEC (10.7–14.5 cmol (+)/kg soil) with high to very high BSP (66.6–87.5%). The mean CEC result for the on-farm experimental sites was recorded as 27.4 cmol (+)/kg soil of soil, which is categorized under a medium and high level of CEC rating which is the most common value for heavy texture soils. These might be strongly associated with their pH buffering and other chemical properties. Percent base saturation (PBS) of the experimental site has computed mean results of 84.4 and 75.5 meq 100^{-1} gram of soil for OnS and OnF experimental sites which are categorized as under 'high' levels of PSB [28] ratings.

Available P (AP ppm) is generally very low (4.34 ppm) in the surface soils and is also very low, decreasing with depth (3.929–4.391 ppm) in the subsurface horizons for OnS. OnF sites were 7.85 ppm; the level of AP in each study site can be categorized as low since their results were far below 15 ppm [29], or for <5 ppm and 6–12 ppm range, they were categorized as very low and low AP ratings, respectively. So, we can generally categorize the experimental sites as deficit based on their available soil P level.

Extractable sulfate (S-SO_4) is very low and very low to low in both surface and the subsurface horizons, (5.14 ppm and 3.91-10.76 ppm, respectively), while a specific study area has extractable sulfate/sulfur (SO_4/S) results of marginal to medium ranges (according to [28]) with their average values of 5.41 ppm and 3.52 ppm for OnS and OnF sites, respectively.

Most of soil extractable micronutrient contents except boron are generally sufficient; its content is 77.530 ppm (high), 1.900 ppm (high), 67.760 ppm (very high), and 2.700 ppm (medium) for Fe, Zn, Mn, and Cu, respectively, in the surface soils and ranges between 12.430 and 30.290 ppm for Fe (high), 0.250 to 0.430 ppm for Zn (very low to low), 29.020 to 39.620 ppm for Mn (high), and 0.750 to 1.600 ppm for Cu (low) in the subsurface horizons. Boron (B) results showed it was 0.428 and 0.473 ppm for OnS and OnF, respectively, which is categorized under the marginal level [30].

3.2. Effects of Different Phosphorus Sources and Lime Application on Soil Property.

Soil test results revealed that the application of different sources of P fertilizers significantly ($P < 0.05$) influenced soil exchangeable acidity (EA), available P (AP), total nitrogen (TN), and acid saturation (AS) of the soil, whereas the remaining considered soil properties were not significantly ($P < 0.05$) affected. The lime application showed a significant ($P < 0.05$) effect of organic carbon (OC), TN, potassium (K), cation exchange capacity (CEC), and sulfate-sulfur (SO_4/S) soil chemical properties as compared to nonlimed plots, whereas application of different P fertilizer rates does not show any significant difference in considered soil analysis results at crop harvesting.

3.2.1. pH.

From the final soil pH result collected at harvesting possible to attain a statistically significant ($P < 0.05$) difference in the location source of variability, the on-farm site has a lower soil pH result than the preliminary test which is probably from the acidifying effects of impute used and crop cultivation practices within specific soil property. On the other sources of variability in the aggregate MOHP P source can give the highest soil pH result with 5.03 (Table 3), while comparing to other sources of fertilizers, when looking at each experimental site result independently. OnS results have shown the highest pH value from P sources NAFAKA+ with pH value 5.3, whereas the OnF site shows the higher soil pH values on fertilizer treatment P2 (MOHP) and P1 (PARP) with a pH value of 4.88 and 4.87, respectively. From this result, active acidity or pH results were varied through using different P sources of fertilizers on acidic soils, which give a varied final soil pH result.

Related to P fertilizer rate, soil pH result from 69 kg·ha^{-1} P_2O_5 rate (PR2) showed the least pH value. The pH result was significantly ($P < 0.05$) influenced in the OnF site in which a higher soil pH value was obtained from P fertilizer 34.5 kg·P_2O_5 ha^{-1} rate PR1. Lime application variability in all locations could not show a significant ($P < 0.05$) difference between treatments; however, based on mean soil pH value application of lime, it could show better soil

TABLE 2: Preliminary soil physicochemical properties of experimental sites soil samples before planting.

Location	BD (g·cm^{-3})	pH	EA cmol (+) kg^{-1}s	CEC (meq/100 g soil)	OC (%)	AP (ppm)	TN (%)	SO$_4$/S (ppm)	B (ppm)	K cmol (+) kg^{-1}s	Ca cmol (+) kg^{-1}s	PBS (%)
OnS	1.14	5.14	0.98	19.6	1.13	4.36	0.14	5.41	0.428	1.262	6.8	84.4
OnF	1.09	4.24	1.37	27.4	1.76	7.86	0.13	3.52	0.473	1.978	8.3	75.5

TN= total nitrogen, AP= available P, OC = organic carbon, EA= exchangeable acidity, PBS= percent base saturation, meq 100 g^{-1} soil = cmol (+) kg^{-1} of soil.

Table 3: Effects of different phosphorus fertilizer sources, rate, and lime application on the major soil properties of Welmera at harvesting.

Source of var.		pH	EA cmol·kg⁻¹s	AP ppm	PAS%	OC%	TN%	Mg cmol·kg⁻¹s	Ca cmol·kg⁻¹s	K cmol·kg⁻¹s	CEC cmol·kg⁻¹s	SO₄/S ppm
Location	OnS	5.21A	0.13B	4.38B	0.64B	1.24B	0.095B	3.94B	7.85B	0.86A	20.8B	7.48
	OnF	4.79B	1.32A	7.62A	4.92A	1.63A	0.141A	4.79A	9.96A	0.69B	27.1A	4.82
LSD		**0.09**	**0.21**	**0.76**	**0.83**	**0.15**	**0.014**	**0.32**	**1.78**	**0.106**	**1.14**	**Ns**
P sources	P1	4.98	0.49C	6.84A	1.86C	1.51	0.121AB	4.27	9.15	0.81	24.4	6.53
	P2	5.03	0.62BC	6.02AB	2.34BC	1.38	0.129A	4.36	9.88	0.76	24.0	6.23
	P3	5.01	0.85AB	5.5B	3.16AB	1.45	0.104B	4.28	8.22	0.74	24.2	5.57
	P4	4.99	0.94A	5.63B	3.77A	1.41	0.118AB	4.56	8.36	0.79	23.2	6.31
LSD		**0.14**	**0.29**	**1.1**	**1.17**	**0.22**	**0.02**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**
P ferz. rate	PR1	5.01	0.66	5.78	2.61	1.44	0.119	4.46	8.60	0.77	24.2	6.97
	PR2	5.00	0.77	6.21	2.95	1.43	0.117	4.26	9.21	0.78	23.7	5.35
LSD		**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**
Lime	LM1	4.99	0.77	5.92	3.11A	1.36B	0.107B	4.51	9.18	0.65B	24.5A	8.36A
	LM2	5.02	0.68	6.08	2.45B	1.51A	0.129A	4.22	8.62	0.89A	23.4B	3.96B
LSD		Ns	Ns	Ns	0.15	Ns	0.014	Ns	Ns	0.11	1.14	2.79
Mean		5.00	0.72	5.998	2.78	1.44	16.64	4.36	8.9	0.78	23.9	6.16
CV %		2.6	7.46	17.7	20.9	14.5	0.118	10.02	27.51	18.78	6.51	32.2

Means with the same letters have no significant difference, Ns: not significant, *significant @ $P < 0.05$ **highly significant @ $P < 0.01$, and ***significant @ $P < 0.001$. EA: exchangeable acidity, AP: available P, PAS: percent acid saturation, OC: organic carbon in %, TN: total nitrogen, CEC: cation exchange capacity, SO4/S: sulfate-sulfur. cmol kg⁻¹ of soil = meq 100⁻¹ gram of soil.

pH improvement results with 5.2 on average (Table 3) which supplements the result reported by Sanchez et al. [31] through the application of lime. It is possible to improve the soil pH property of acidic soil.

3.2.2. Exchangeable Acidity (EA).

The least result in EA (meq 100^{-1}g of soil) is considered an improved soil property since it measured as a negative attribute for soil productivity. Each experimental site shows a statistically significant difference ($P < 0.05$) in exchangeable acidity ANOVA result. Among different P sources of fertilizer, PARP shows a significant ($P < 0.05$) respectable improvement in the aggregate. In both experimental sites, the best soil EA result was obtained from P1 and P2 sources of fertilizers with 0.49 and 0.62 meq 100^{-1}g of soil, respectively. As studied by Sikora [32], PR sources of P fertilizers from Minjingu (MPR) have to contain 6.9% $CaCO_3$ on average, contributing to liming effects of acidic soil by reducing the EA which neutralizes acidity and Al^{3+} toxicity on the P fertilizer rate source of variability. However, in all experimental sites' separate and combined analyses, the result was not significantly affected by treatments and the least soil EA mean result was obtained from LM2 application with 0.68 meq 100^{-1}g of soil.

In general, from all sources of variability, using treatment combination PARP, 34.5 kg P_2O_5 ha^{-1} rate with lime gives better soil EA improvement results. As studied by Moir and Moot [33], application of lime coupled with P fertilizer on acidic soil improves productivity through increased soil pH and significantly reduces the concentration of exchangeable Al^{3+} in the soil. The reduction in exchangeable acidity with liming is explained by the increased replacement of Al^{3+} by Ca^{2+} in the soil exchange site and by the subsequent precipitation of Al as $Al(OH)_3$ [6, 34]. Phosphorus additions in different forms which contain CaO or other lime materials also increased the exchangeable Ca content of the soil, and thus the exchangeable Al form insoluble $Al(OH)_3$ pH at high pH [35].

3.2.3. Available P (AP).

Application of different sources of P fertilizer significantly ($P \leq 0.05$) influences the soil AP level at the final/harvesting stage in which from different sources of P fertilizer, a set of treatments which receives PARP were given superior AP result on the residual level of soil AP with 6.84 ppm in the soil immediately after harvesting, and the least AP result (5.5 ppm) is obtained from NPSB of the same location (Table 3) which reviles that using less soluble sources of P fertilizer such as PARP and MOHP on acidic soil improved AP status in long-term crop P supplies. Several authors studied that the increase in the dissolution of the PRs when treated with soils may also be attributed to the neutralization of the OH^- ions released on hydrolysis of the phosphate ions due to soil acidity [36]. Hart et al. [37] also investigated the slower release of P from PRs and partly acidulated PR sources of P fertilizers than water-soluble fertilizers such as TSP reduces the risk of P pollution (eutrophication) of the aquatic environment, and their $CaCO_3$ content improves soil acidity which in turn improves their soil AP content.

Comparatively, the experimental site was a significant difference ($P \leq 0.05$) in their residual extractable P level, and their soil AP status was like the preliminary soil analysis result. On the other hand, each experimental site soil AP result individually recorded as the highest level (5.7 ppm) was obtained from the same set of treatment P1. The least AP result was recorded from P4 at OnS and P3 at OnF experimental sites with 3.4 ppm and 6.79 ppm, respectively. It supplements the research results of Rajan's [38] application of PARP which improves soil AP levels in the long run by supplying water-soluble P_2O_5 slowly to acidic soil for sustainable crop uses.

The application rate of P fertilizer cannot show a statistically significant difference, but there is a corresponding tendency on their mean comparison in both aggregate and distinct results. Comparatively, the superior soil AP mean result was obtained from 69 kg·P_2O_5 ha^{-1} rate. Likewise, the lime-treated set of treatments LM2 were given higher mean soil AP results. In general, from over location combined analysis result (Table 3), superior ones were obtained from P1, PR2, and LM2 sets of treatment combined with soil AP of 6.84 ppm, 6.21 ppm, and 6.08 ppm, respectively, at harvesting. This important soil property majorly contributed to crop productivity as revealed in the research result of Sinirkaya et al. [39] which contributes to efficient nutrient use efficiency by enhancing plant root development which in turn facilitates the water and nutrient uptake and optimizes the physiological activities of the crop.

A different source of P fertilizer and lime application was significantly ($P < 0.05$) influenced by percent acid saturation (PAS). The mean separation result showed that minimal PAS (2.01%) on the soil exchangeable site was observed from the PARP source. A study about sources of P fertilizer indicates that using such a source of fertilizer is also an alternative way to amend soil acidity in addition to the lime application. However, the ANOVA results showed no significant difference between treatments, using the PR1 (34.5 kg·ha^{-1} P_2O_5) rate with an average of all types brought minimal PAS on the soil exchange site, whereas using lime brought minimal acid saturation (2.45%) on the soil exchange site. As observed in the EA and CEC results in each experimental location, there was a significant difference in b/n PAS result, thus larger acid saturation mean result was recorded from the OnF experimental site.

ANOVA results showed a significant difference ($P \leq 0.05$) in the extractable soil sulfate-sulfur (SO_4/S) due to the application of lime. Hence, the set of treatments with no lime have got higher concentration of extractable SO_4/S 8.36 mg·kg^{-1} on average, which was related to the nutrient use efficiency of the crop since all of the entries were treated equally with the application of S fertilizer; thus, it might be from vigor plant growth which can utilize more soil available S than poor performing crops. Finally, the remaining soil nutrient levels were reveling the abovementioned assertion of Bolan et al. [40].

This fact is also observed in other experimental factors such as different P sources and their application rates. The

better performing treatment to crop performance was left with minimal residual soil extractable sulfur at the final soil analysis result; it was also confirmed on the plant tissue analysis result (Table 4). The soil % OC results in a different set of treatments at crop harvesting showed a nonsignificant difference ($P < 0.05$). These values were expected from such P fertilizer sources.

3.3. Effects of Lime and P Sources on Plant Nutrients' (P, N, and S) Concentration and Uptake.

Phosphorus concentration in the biomass and grain of barley were nonsignificantly ($P < 0.05$) influenced by P sources, rates, and lime application (Table 4); phosphorus uptake in the biomass and grain of barley was significantly affected by different phosphorus sources application and location variables. Nitrogen and sulfur concentration and uptake in the biomass and grain of barley were nonsignificantly influenced by P sources, rates, and lime application. From the analysis result, P uptake in plant biomass and grain was significantly ($P < 0.05$) affected by the application of different phosphorus sources. The better result, i.e., 3.27 and 9.45 kg P ha^{-1}, was obtained from biomass and grain P uptake, respectively, by applying the P3 (NPSB) phosphorus source. In the study by Mengel and Kirkby [41], direct relationship was obtained from soil available phosphorus concentration and plant tissue nutrient uptake. Thus, phosphorus availability to plants is determined by the phosphorus fertilizer source and chemical property of the soil [34]. Hammond et al. [42] can establish a strong correlation between phosphorus uptake and the available P from various fertilizers sources. Significantly, the highest P concentration and uptake in barley biomass and grain were obtained from the on-station experimental site. The percentage of P concentration in plant biomass was majorly affected by different phosphorus sources of fertilizers. The maximum percent of P concentration has resulted from P3. The application of lime variable obtained a statistically significant difference ($P \leq 0.05$) between treatments at P uptake in the aboveground plant biomass. Apart from grain yield, it achieved more favorable outcomes within the group of lime application treatments. Other parameters also exhibited corresponding responses, particularly in terms of biomass phosphorus concentration, which was a significant factor (Table 4). The level of nutrient fertilization affects the nutrient availability in soil, and at high contents of soil nutrients and their availability of more nutrients might be taken up by plants [43] which in turn improve the productivity of the crop by supplementing or providing essential nutrients with the required level which is primarily constrained by competition from Al and Fe oxides in low pH soil, especially for phosphorus nutrient.

3.4. Effects of Lime and Different P Source Application on Barley Yield.

Limed set of treatments obtained 8.7% aboveground biomass yield advantage over untreated set of treatments (Table 5); application of lime markedly increased the yield of barley by improving soil pH and plant nutrient availability, especially P as reported by Beyene [44]. Likely, Desalegn et al. [45] also approve using lime with P application on acidic soils of Ethiopia improves barley productivity by increased phosphorus availability for the crop uses.

Use of NPSB sources of phosphate fertilizer at 69 kg P$_2$O$_5$ ha^{-1} application rate with lime in combination enables maximum yield of barley under acidic soil condition, whereas PARP sources of phosphate fertilizer at 69 kg P$_2$O$_5$ ha^{-1} application rate with lime produced comparable grain and biomass yield advantage. Likely, Shiferaw and Anteneh [7] also obtained results on half a dose of recommended lime application with balanced fertilizer utilization significantly increasing barley yield under acidic soil conditions in the southern part of the country. Uses of different phosphate fertilizer sources significantly ($P < 0.05$) affect barley grain yield at both locations; the maximum average grain yield (3601 kg·ha^{-1}) was obtained from the NPSB source followed by PARP source of the phosphate fertilizer (Table 5) with 2888.9 kg·ha^{-1} grain yield. The least result was 1906.6 kg·ha^{-1} which is from the control treatment. NAFAKA + phosphate source only improves grain yield by 34.4% over the control which is far below 88.9% grain yield improvement from the application of the NPSB source which support the finding of Ester et al. [46] which indicated different crop performances in response to different sources of P fertilizers' application. Indeed, the available/soluble P$_2$O$_5$ content varied to provide immediate use and gradual release of P in available forms to plant uptake. The comparable result obtained from the PARP phosphate source supports the findings of Chen and Menon [47] which resulted PARP at 40–50% acidulation with H$_2$SO$_4$ or at 20% by H$_3$PO$_4$ as alternative approaches the effectiveness of high-grade water-soluble phosphate sources in certain tropical soil and crop types. Lime application can provide significantly ($P < 0.05$) higher grain yield results 3025.2 kg·ha^{-1} as compared to the unlimed set of treatments; Meng et al. [48] also reported significant yield increment was obtained by using lime on acidic soils.

3.5. Effects on Agronomic Efficiency, Apparent Recovery, and Physiological Efficiency.

The application of different phosphate sources significantly ($P < 0.05$) improves the agronomic efficiency, phosphorus recovery in both biomass and grain, and total P uptake barely (Table 6). Agronomic nutrient use efficiency of barley significantly ($P < 0.05$) influenced the difference between treatments, in which the amount of yield obtained in kg 1 kg^{-1} applied fertilizer. Accordingly, higher agronomic efficiency resulted from using NPSB and PARP sources with computed values of 12.54 and 10.19 kg kg^{-1} of the phosphorus fertilizer source, respectively, which is highly correlated with the effectiveness of the applied fertilizer, concerning its economic and/or biological product with minimal loss. Fageria and Baligar [49] also reported that high agronomic efficiency is obtained if the yield increment per unit of nutrient applied is high

TABLE 4: Plant tissue P, N, and S concentrations are affected by the application of lime, P sources, and P rates.

Source of var.		Biomass P (%)	Grain P (%)	P Bs (kg·ha⁻¹)	P Gy (kg·ha⁻¹)	PHI (%)	N (%)	S (%)
	PARP	0.063	0.255	2.405B	7.37B	76.6	1.206	0.088
	MOHP	0.066	0.232	2.554B	6.598B	73.8	1.198	0.098
P sources	NPSB	0.071	0.252	3.276A	9.45A	74.6	1.221	0.090
	NAFAKA	0.070	0.228	2.376B	6.13B	72.9	1.239	0.095
LSD		**Ns**	**Ns**	**0.61**	**1.68**	**Ns**	**Ns**	**Ns**
Ferz. rate	PR1	0.067	0.2417	2.549	7.13	74.7	1.204	0.089
	PR2	0.068	0.2418	2.757	7.69	74.2	1.229	0.096
LSD		**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**	**Ns**
Lime	LM1	0.065	0.242	2.33B	7.028	75.4	1.175	0.091
	LM2	0.070	0.241	2.97A	7.79	73.5	1.257	0.094
LSD		**Ns**	**Ns**	**0.42**	**Ns**	**Ns**	**Ns**	**Ns**
Location	OnS	0.094A	0.288A	3.89A	9.92A	71.6A	1.198	0.078
	OnF	0.041B	0.195B	1.42B	4.89B	77.4B	1.234	0.108
LSD		**0.006**	**0.021**	**0.43**	**1.19**	**3.17**	**Ns**	**Ns**
Mean		0.0674	0.242	2.65	7.41	74.5	1.21	0.093
CV %		12.9	11.9	22.18	22.08	5.84	12.14	24.1

Means with the same letter do not have significant differences from each other, PHI: phosphorus harvest index, N%: nitrogen concentration, and S%: sulfur concentration. P. Bs P uptake in plant biomass, P. Gy P uptake in barley grain yield.

TABLE 5: Grain yield and some grain physical quality parameters of barley as affected by different P sources, P rate, lime application, and location.

Source of var.		GY (kg·ha⁻¹)	TSW (gm)	HLW (kg·hl⁻¹)	Msr (%)
Location	OnS	3403.2A	43.8A	65.6A	10.36B
	OnF	2491.4B	41.2B	63.9B	11.10A
LSD		**200.1 ****	**0.11 ***	**0.82 ****	**0.11 ***
	PARP	2888.9B	42.4B	64.83	10.74
P sources	MOHP	2737.4BC	41.9B	64.78	10.70
	NPSB	3601.4A	44.1A	65.33	10.64
	NAFAKA	2561.6C	41.5B	64.20	10.85
LSD		**282.9 *****	**1.0 ****	**Ns**	**Ns**
P. rate	34.5 kg·ha⁻¹	2854.1	42.6	65.2	10.72
	69 kg·ha⁻¹	3040.6	42.4	64.4	10.74
LSD		**Ns**	**Ns**	**Ns**	**Ns**
Lime	LM1	2842.5B	42.7	64.9	10.72
	LM2	3025.2A	42.3	64.6	10.74
LSD		**200.1 ***	**Ns**	**Ns**	**Ns**
Control		1906.6	38.27	60.85	10.70
CV (%)		16.6	4.2	3.09	2.57

Means with the same letters have no significant difference, Ns: not significant, *significant @ $P < 0.05$ **highly significant @ $P < 0.01$ and ***significant @ $P < 0.001$., GY: grain yield, TSW: Thousand seed weight, HLW: hectoliter weight, and Msr: gain moisture percentage.

because of reduced losses and increased uptake of nutrients. On the other hand, different P fertilizer rates also significantly ($P < 0.05$) affected the agronomic efficiency and P recovery but not the physiological efficiency PE. Accordingly, as the P rate increased from 34.5 to 69 kg·ha⁻¹, the AE and P recoveries decreased significantly. In this perspective, lower rates of P fertilizer obtained superior results. The application of lime did not significantly ($P < 0.05$) affect those parameters.

Physiological efficiency (PE) has no significant difference between different P sources of treatments although there is a considerable difference as shown on other parameters, which is supplementary to them. Sandana [43] showed that at high P uptake, the PE of crops decreases and the PE of P would depend on varieties. Nutrient use efficiency of plants depends on soil factor of production potential, chemical species of the fertilizer used, and plant factors interact with environmental factors and root microbe.

TABLE 6: Effects of lime and different sources of *P* fertilizers on NUE like agronomic efficiency, physiological efficiency, and *P* recovery of barley in Wolmera highlands, Ethiopia.

Source of var.		Total P uptake (kg ha^{-1})	BM PR (%)	GY PR (%)	Total P recovery (%)	AE (agronomic efficiency)	PE (physiological efficiency)
P sources	PARP	9.86B	4.72B	16.32AB	21.0B	10.19A	234 (15.9)
	MOHP	9.15B	4.75B	12.32B	17.0B	5.02B	277 (16.1)
	NPSB	12.73A	8.53A	24.76A	33.3A	12.54A	276 (17.3)
	NAFK	8.51B	4.48B	10.65B	15.1B	2.39C	199 (16.0)
LSD		2.03	2.97	7.65	9.14	2.59	Ns
P ferz. rate	34.5 kg·ha^{-1}	9.68	7.03A	20.12A	27.12A	9.29A	267 (16)
	69 kg·ha^{-1}	10.45	4.20B	11.90B	16.10B	5.78B	265 (15)
LSD		Ns	2.10	5.42	6.47	1.83	Ns
Lime rate	LM1	9.36	4.02B	14.6	18.6	7.14	238 (15)
	LM2	10.76	7.22A	17.4	24.6	7.93	293 (17)
LSD		Ns	2.10	Ns	Ns	Ns	Ns
Location	OnS	13.8A	7.11A	7.11A	19.3A	5.79B	130 (11)B
	OnF	6.31B	4.12B	4.12B	12.8B	9.27A	400 (20)A
LSD		1.44	2.10	5.4	6.5	1.82	51 (4.29)
CV %		19.61	20.6^{t}	19.5^{t}	17.14^{t}	26.3	26.9

Values in brackets represent data transformed by the square root method of data transformation. (1+√mean), BM PR biomass *P* recovery, GY PR grain *P* recovery, AE: agronomic efficiency, PE: physiological efficiency.

4. Conclusion and Recommendation

Using alternative nutrient sources of fertilizers can be the best approach to amend acidic soils integrated with liming application. According to our research finding, partiality acidulated rock phosphate sources of fertilizer can contribute for soil and barley productivity through improving most of acidic soil attributes and organic carbon of soils which even contribute to the proceeding crop for the succeeding season in the sustainable base. Subsequently, it is better to integrate these sources as an alternative means to improve the productivity issue of strongly acid-affected soils of the study area and similar agroecologic zones.

Lime application is well known as an amendment for acidic soils but using a full dose of the required lime amount specially for strong acidic soil is challenging to resource-poor farmers; thus, as an alternative split application with other preferable phosphorus sources, it can give better improvements of soil fertility-related chemical properties such as pH, exchangeable acidity, present acid saturation, organic carbon, nutrient uses efficiency, and other related attributes of soil and barley productivities. Application of the phosphate fertilizer at 69 kg P_2O_5 ha^{-1} rate could give better crop productivity with improved extractable soil phosphate in acidic soils.

Integrated uses of soil input utilization alternative were mandatory to challenge the ever-increasing soil acidity and fertility constraints which were currently aggravated by both natural and manmade impacts. As an alternative, looking for interaction effects of different nutrient sources with different soil health amendment approaches should get due attention to generate sustainable technologies which are environmentally safe and economically sound.

Data Availability

The data used to support this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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