Effects of Lime and NPSB Fertilizer Rates on Yield Attributes and Yield of Wheat, and Soil Properties in Harbagona District of Sidama Region, Ethiopia

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Abstract

Wheat is a crucial global cereal crop, particularly vital for Ethiopian highlanders. However, its production is often influenced by various environmental factors, notably soil acidity. This field experiment was carried out in Harbagona, Sidama Region of Ethiopia, during the main cropping season of 2022, aimed to evaluate the effects of combined lime and NPSB fertilizer applications on wheat yield and soil properties. The experiment was designed in a randomized complete block with ten factorial combinations involving five rates of NPSB fertilizer (0, 50, 100, 150, and 200 kg ha^{-1}) and two lime levels (with and without) replicated thrice. Results showed that combining lime with NPSB fertilizer significantly increased wheat grain and biomass yields, with the highest yields achieved at 150 kg ha^{-1} NPSB application rate. Furthermore, the integrated application of lime and NPSB improved soil pH, reduced exchangeable acidity, and increased cation exchange capacity, thereby enhanced nutrient availability. Economic analysis revealed that lime integrated with 100 kg ha^{-1} NPSB fertilizer provided the highest net benefit and marginal rate of return. Additionally, lime application extended days to heading, but accelerated days to maturity, while NPSB fertilization reduced both heading and maturity durations. Moreover, the combined application of lime and NPSB fertilizer enhanced various yield attributes of wheat, including tiller count, plant height, spike length, seed weight, and harvest index. In conclusion, the application of 100–150 kg ha^{-1} NPSB fertilizer combined with lime not only enhanced soil properties, but also optimized yield and economic benefits. These findings emphasize the importance of nutrient management and soil amelioration practices in optimizing wheat yield and soil health in acidic soil conditions.

Keywords: lime application, NPSB fertilizer, Soil acidity, Wheat, yield attributes and yield

Introduction

For nearly one-third of the world's population, wheat (*Triticum aestivum* L.) stands as a vital staple food source (Cakmak, 2009). With an estimated 2.1 million hacultivated under both rain-fed and irrigated systems, Ethiopia emerges as the second-largest producer of wheat in sub-Saharan Africa(Hei, Shimelis, & Laing, 2017). In comparison to the genetic potential of wheat varieties released by the research system, the national average wheat productivity, recorded at 3.1 t ha^{-1}, is notably very low (Agegnehu et al., 2021). Contributing factors to low yield include the use of unimproved cultivars, inadequate weed control techniques, the prevalence of aggressive crop diseases, depletion of soil minerals, limited chemical fertilizers usage, and the absence of contemporary crop management practices.(Belachew, Maina, Dersseh, Zeleke, & Stoddard, 2022)

The degradation of soil quality is hastened by diverse factors such as soil types, geography, climatic conditions, and land use patterns, resulting in wheat yields falling below the potential of more than 6.0 t ha^{-1}. Numerous studies including Klink (2014) highlight the role of improper land use in exacerbating the deterioration of soil properties, including physical, chemical, and biological aspects. Land use profoundly impacts essential processes such as erosion, soil structure, nutrient cycling, leaching, carbon sequestration, and other related physical and biological processes (Tully et al., 2015).

Soil acidity poses a significant challenge to achieving profitable and sustainable agricultural productivity across various regions worldwide. This issue is exacerbated by a growing trend in soil acidity and exchangeable aluminum in both arable and abandoned lands, largely attributed to intensive agricultural practices and persistent application of inorganic fertilizers, which contribute to acidification (Behera & Shukla, 2015). The complexity of soil acidity stems from a combination of factors, including nutrient/element toxicities, insufficient activity of beneficial microorganisms, and restricted plant root growth, thereby limiting nutrient and water absorption (Agegnehu & Amede, 2017).

The predominant soil factor influencing plant development, crop productivity, and profitability is the soil pH, a concern prevalent across regions with sufficient precipitation to leach exchangeable bases from the soil surface (Yirga, Erkossa, & Agegnehu, 2019). Numerous studies have shown that soil pH levels below 5.5, exacerbated by high levels of aluminum and manganese and deficiencies in essential nutrients such as phosphorus, nitrogen, and sulfur, significantly impede crop growth(Havlin, 2020).

Liming stands as a widely adopted and effective practice for boosting crop productivity in acidic soils while enhancing their physical, chemical, and biological attributes (Zingore, Mutegi, Agesa, Tamene, & Kihara, 2015). The acidic nature of the soil contributes to low yields of main cereal crops, notably wheat, often reaching as low as 0.5 Mg ha^{-1}. Studies indicate a tripling of yields upon ameliorating soil pH through lime, nitrogen, and phosphorus additions (Dereje, Tamene, & Anbesa, 2019). When coupled with other advantageous agricultural methodologies or inputs, lime application exhibits significant yield improvements. Yield enhancements ranging from 34% to over 252% have been documented in wheat, barley, and tef under moderate to severe acidic soil conditions(Desalegn, Alemu, Adella, & Debele, 2017), 111–182% in maize (Opala, Odendo, & Muyekho, 2018), and 45–103% in Mucunain Kenya (Agba et al., 2017). To realize substantial yield increments, the combined application of nitrogen and phosphorus, and fertilizers with lime and other improved management techniques is recommended.

This research was conducted to assess the effectiveness of lime application, in combination with nitrogen and phosphorus containing fertilizers, in mitigating soil acidity and augmenting wheat productivity. By targeting soil acidity, a pivotal factor influencing soil pH levels and nutrient accessibility, the study aims to overcome a significant obstacle to wheat production. The primary objective of this study was to comprehensively dissect the multifaceted challenges impeding wheat productivity in the study area, with a specific emphasis on soil acidity and its consequences on wheat yield. Additionally, this work endeavored to uncover the promise of lime application, in tandem with nitrogen and phosphorus containing fertilizers, as a feasible approach for mitigating soil acidity and increasing wheat yields. By scrutinizing results obtained from field experiments, the aim was to evaluate the effectiveness of combined applications of lime with NPSB and urea fertilizers in enhancing soil quality, nutrient availability, and ultimately, wheat productivity.

Materials and Methods

Description of study site

This study was conducted in Harbagona district, southern Ethiopia, during the main cropping season of 2022. The geographical coordinates of the study site are06°26'59" N latitude and 38°27'44" E longitudes, situated at an altitude of 2648 meters above sea level. Harbagona experiences a sub-humid climate characterized by a bi-modal pattern of rainfall, with a mean annual precipitation ranging from 1000 to 1300 mm. The major rainy season lasts from June to September, typical of the highland regions in Ethiopian agro-ecological categorization. The main cereal crops produced in the area include wheat and barley. The prevailing soil type of the study area is Nitiosls (IUSS Working Group WRB, 2014).

Treatments and experimental design

The experiment was designed in a randomized complete block (RCB) with three replications. The experiment evaluated ten factorial combinations involving two lime levels (with and without)with five NPSB fertilizers levels (0, 50, 100, 150, and 200 kgha^{-1}).The experimental field was prepared using a native plough (Maresha), and plots were randomly assigned within the layout according to the experimental design specifications. Each plot measured 1.6 m in length and 1.5 m

in breadth, totaling2.4 m^2. The full doses of NPSB fertilizers, as per the treatment setup, were applied in rows as a basal placement immediately before sowing. The wheat seeds were manually drilled with in a row spaced at 0.20 m intervals between each row, encompassing all eight rows of wheat that were sown. Urea was applied at the recommended rate of 100 kg ha^{-1}, 45 days after the sowing.
According to Nelson and Su (2010), the exchangeable acidity of the soil (Al^{3+}+ H^{1+}) was used as the basis to determine the required amount of lime as shown in equation

$$\mathrm{LR, CaCO_3 (kg\ ha^{-1})} = \frac{\mathrm{EA} * 0.15\ \mathrm{m} * 10^4 m^2 * \mathrm{BD} * 1000}{2000}$$

Where:
LR is the lime requirement in kg ha^{-1}
EA is the exchangeable acidity of the soil in cmolekg^{-1}
BD is the bulk density of the soil Mgm^3
The lime requirement (LR) was calculated based on the acidity level of the experimental field, which exceeded the critical level for wheat production. Thus, employing equation 1, the total amount of lime required to neutralize the acidity of the experimental soil was found to be 4.8 t ha^{-1}.High-grade agricultural limes ($CaCO_3$) with a neutralizing value of 98% was utilized. A month before the sowing of wheat, lime was evenly distributed by hand across plots based on the treatments setup, and thoroughly incorporated into the soil using oxen plows. All other agronomic practices, including weeding, cultivation, and pest control, were carried out in accordance to the established guidelines for wheat production in Ethiopia.

Data collection

Soil physico-chemical properties

Initial composite surface soil samples were collected from five randomly selected locations diagonally across the experimental field using an auger sampler at a depth of 0–20 cm, aiming to characterize the soil. Subsequently, these collected soil samples were combined to create one composite sample. Furthermore, post-harvest soil samples were also collected from the 20 treatment-based locations within the experimental field to assess the impact of treatment application on soil properties. The collected soil samples were air-dried and ground using a mortar and pestle, then sieved through a 2 mm mesh. The prepared soil samples were analyzed to organic carbon (OC), total nitrogen (N), pH, available phosphorous (P), exchangeable acidity, cation exchange capacity (CEC), calcium and magnesium in Hawassa University of Agriculture College. Particle size distribution was determined using the hydrometric Bouyoucos method, following the accepted approach. The available soil P was determined following the procedure set by (Olsen, 1954). Soil pH was measured using a glass electrode connected to a digital pH meter, with a soil-to-water dilution ratio of 1:2.5. Total

N was determined using Kjeldahl method (Bremner, 1961). OC content of the soil was determined through wet chemistry, following the procedure outlined in the Walkley method (Walkley, A., Black, I. A. 1931.), exchangeable acidity was determined with buffer pH method (Mehlich, 1976). Cation exchange capacity was determined with ammonium acetate method (Schollenberger & Simon, 1945) and calcium and magnesium was determined with simple titrimetric method (El Mahi, Ibrahim, Abdel Magid, & Eltilib, 1987).

Phonological data

The days to emergence were determined by counting the number of days between sowing and the point when 50% of the plants displayed visible emergence. Similarly, the days to heading were calculated based on visual observation by calculating the duration from seeding to the moment the plants attained heading stage. Additionally, the days to maturity were assessed through ocular observation, marking the interval from sowing to the plant's full maturity. Senescence of the leaves and the ability to threshing grain from the glumes by pressing them in between the forefinger and thumb were relied upon as indicator of physiological maturity.

Growth and yield attributes data

At physiological maturity, the height of each plant from the ground surface up to the tip of the panicle was measured for ten randomly chosen plants from each plot. The spike length was determined by averaging measurements taken from five randomly chosen plants per plot, measuring the distance between the node where the first spike branches appear and the spike's tip. The number of seed per spike was calculated by averaging three chosen spikes from each plot. The number of tillers per square meter was determined by placing a 1 m^2 quadrant in the center of each plot, and tallying the total number of tillers within the designated area. Just before harvest, five randomly selected ears from each plot were selected, and kernel number per spike was measured.

To determine the total above-ground biomass yield, harvesting was conducted from three central rows to minimize border effects. The harvested samples were air-dried and weighed using a digital balance. Manual threshing was performed to separate seeds from straw, followed by cleaning and measurement for grain yield determination. Both the above-ground total biomass yield and grain yield were converted to tons per hectare for statistical analysis. Prior to statistical analysis, grain yield was adjusted to a standard moisture content of 12.5%.Harvest index was calculated by dividing grain yield by the total above-ground air-dry biomass yield. Grains were carefully counted and weighed using a digital balance to determine the weight of 1000 seeds.

Data analysis

The data collected were subjected to an analysis of variance (ANOVA) using SAS software version 9.0 as described by (Littell, Stroup, & Freund, 2002). Means separation was performed following the guidelines by (Gomez & Gomez, 1984) using the least significant difference (LSD) test at either a 5% or 1% probability level depending upon the results of the ANOVA.

Economic analysis

The partial budget analysis was conducted according to the procedure outlined in (Alimi, 2000) to evaluate the economic viability of the tested treatments. Total variable costs (TVC) in this study comprised expenses for procuring NPSB and urea fertilizers, as well as lime, and labor costs for lime application at the experimental site. Lime and fertilizers application labor costs were computed based on the required number of days, expressed in Ethiopian Birr (ETB).Urea and NPSB fertilizers were priced at 13.38 and 12.30 ETB kg^{-1}, respectively, while lime and its application cost amounted to 12,500.00 ETB kg^{-1}.Total benefits (TB) considered the revenue generated by the farmer, calculated by multiplying the farm gate selling price of wheat grain by the total harvested yield. The farm gate price of wheat grain stood at 17.25 ETB kg^{-1}.The net benefit was determined by subtracting the TVC from the TB. Grain yields obtained in this study was downscaled by 10% to represent the actual harvestable yield according to local farming practices. Treatments were then arranged based on their increasing TVC. Treatments with marginal costs exceeding marginal benefits were excluded from further analysis as they were deemed dominated. The acceptable marginal rate of return (MRR) considered in this study was equal to or greater than 100%.

Results and Discussion

Physico-chemical properties of the experimental soil before sowing

The initial characteristics of the experimental soil are presented in Table 1. The soil texture revealed that the experimental area primarily consisted of clay-based soil, with composition of31% sand, 32% silt, and 37% clay, indicative of a clay loam texture. These textural characteristics influence various soil properties such as water holding capacity, aeration, and root penetration. The initial pH of the soil was measured at 4.47, indicating a very strong acidic soil reaction according to (Chimdi, 2015).The cation exchange capacity (CEC) of the soil was determined to be 19.76 cmol $_{(+)}$ kg^{-1}, categorizing it as medium fertility soil based on Landon's classification(Landon, 2014). The organic carbon (OC) and total nitrogen (N) contents of the experimental soil, measured at 2.36% and 0.14% respectively, indicate medium statuses for both OC and total N content according to Murphy (1968) classification. The soil also exhibited a very low level of available phosphorus (P; 3.53 mg kg^{-1}) according to (Olsen, 1954)Olsen et al. (1954) classification (Table 1).

Table 1: Selected physico-chemical properties of the experimental site soil before sowing

Soil properties	Unit	Value
Sand	%	31
Silt	%	32
Clay	%	37
Texture class		Clay loam
Soil reaction (pH)		4.47
Organic carbon	%	2.36
Total nitrogen	%	0.14
Available phosphorous	mg kg^{-1}	3.53
Boron	mg kg^{-1}	0.46
Cationexchange capacity	$Cmole_{(+)}$ kg^{-1}	19.76
Exchangeable acidy	$Cmole_{(+)}$ kg^{-1}	0.91
Calcium	$Cmole_{(+)}$ kg^{-1}	1.54
Magnesium	$Cmole_{(+)}$ kg^{-1}	2.24
Potassium	$Cmole_{(+)}$ kg^{-1}	1.91
Bulk density	g cm^{-3}	1.14

Effects of lime combined with NPSB fertilizer on selected soil properties

The results indicated that the combined application of lime and NPSB fertilizer significantly improved the chemical properties of the soil, as evidenced in Table 2.The combined application of lime with NPSB fertilizer notably raised the pH levels of the experimental soil from 4.48 (without lime or other external inputs) to 4.76, 4.79, 4.82, 4.81, and 4.65 with increasing doses of NPSB (ranging from 50 to 200 kg ha^{-1}), indicating a pH increment of 0.14–0.29 units. Additionally, this combined treatment effectively reduced the exchangeable acidity of the soil from 0.93 $cmo_{l(+)}$ kg^{-1} to 0.65, 0.51, 0.47, 0.57, and 0.62 $cmol_{(+)}$ kg^{-1} with corresponding NPSB doses, showcasing a reduction of 0.09–0.28 $cmol_{(+)}$ kg^{-1} (Table 2).
The rise in pH and subsequent decline in exchangeable acidity resulted in an enhanced CEC of the soil and increased availability of P, Ca, and Mg as outlined in Table 2. The combined application of lime and NPSB fertilizer increased the CEC and available P levels from 21.55 cmol (+) kg^{-1} and 3.51 mg kg^{-1} (without lime and other external inputs) to 22.2–24.63 cmol(+) kg^{-1} and 9.5–10.5 mg kg^{-1}, respectively, across the range of NPSB doses. These changes represented increments of 0.64–2.37 cmol (+) kg^{-1} and 5.09–6.1 mg kg^{-1} due to the effects of the combined treatment. Furthermore, the integration of lime with NPSB fertilizer led to a notable increase of 0.05–5.44 cmol(+) kg^{-1} in Ca content and 0.07–0.36 cmol(+) kg^{-1} in Mg content of the soil. The results also indicated a rise in total nitrogen (N) content from negligible levels to 0.02%, accompanied by a reduction in soil OC content ranging from 0.51% to 0.089% (Table 2).

The incorporation of lime to acidic soil exerts a neutralizing effect, which is responsible for these changes in soil chemical properties, a phenomenon well-documented by (Yang, Mitchell, & Howe, 2018). This process elevates the soil pH while concurrently reducing its exchangeable acidity, as evidenced in our study. The reduction in exchangeable acidity can be attributed to the enhanced displacement of Al^{3+} ions by Ca^{2+} ions at exchange sites, leading to the subsequent precipitation of Al^{3+} as $Al(OH)_3$ upon liming (Alemu, Selassie, & Yitaferu, 2022). Moreover, the increase in soil pH prompts the precipitation of exchangeable and soluble Al^{3+} ions as insoluble Al hydroxides, thereby diminishing the concentration of Al^{3+} in the soil solution. This pH adjustment facilitates the release of phosphate ions previously complexed with Al^{3+} and Fe $^{2+}$ ions, rendering P more accessible for plant uptake (Ghosh & Devi, 2019). By encouraging the mineralization of soil organic phosphorus, liming can raise the availability of phosphate (Dereje et al., 2019).

The shift in pH and the release of the variable charged minerals and functional groups within humus compounds by Ca^{2+}ions likely underlie the observed rise in CEC following liming. This elevation in CEC stems from the augmented availability of negative charges on mineral surfaces. Consistent with our findings, (Frank, Zimmermann, & Horn, 2020) reported similar changes in soil CEC up on application of 3.75 t ha^{-1}, preceding the sowing of common beans by 60 days.
Similarly, in agreement with our results, (Mkhonza, Buthelezi-Dube, & Muchaonyerwa, 2020)observed heightened total N levels upon treating acidic soils with lime. Moreover, applications of N and P fertilizers resulted in higher N contents in both light and heavy fractions compared to unbalanced applications, particularly in barley production on acidic soils (Hameso, Worku, & Ayalew, 2022).The decline in OC contents of the experimental soil after harvest may be attributed to soil tillage, which enhances aeration, thereby, stimulating microbial activity and accelerating the decomposition rate of soil OC(Kibet, Blanco-Canqui, & Jasa, 2016).

Table 2: Effects of lime combined with various rates of NPSB fertilizer on selected chemical properties of acidic soils of Harbagona

Lime	NPSB rate (kg ha^{-1})	pH	OC%	TN%	Av. P (mg kg^{-1})	CEC (cmol$_{(+)}$ kg^{-1})	EA (cmol$_{(+)}$ kg^{-1})	Ca (cmol$_{(+)}$ kg^{-1})	Mg (cmol$_{(+)}$ kg^{-1})
Without	0	4.48	2.37	0.13	3.51	21.55	0.93	1.57	2.37
	50	4.51	2.36	0.16	3.62	22.43	0.78	1.61	2.53
	100	4.53	2.37	0.19	4.46	23.15	0.56	1.68	2.57
	150	4.52	2.35	0.18	4.46	23.63	0.67	1.65	2.55
	200	4.51	2.36	0.16	4.42	22.56	0.83	1.62	2.52
With lime	0	4.76	1.86	0.14	9.49	22.19	0.65	6.55	2.73
	50	4.79	1.57	0.18	9.56	24.66	0.51	6.68	2.82
	100	4.82	1.48	0.21	10.54	25.52	0.47	7.12	2.86
	150	4.81	1.51	0.18	10.56	25.17	0.57	7.08	2.83
	200	4.65	1.53	0.16	9.51	24.63	0.62	1.67	2.59

The effects of lime and NPSB fertilizer on phenology of wheat

The effects of lime on phenology of wheat

The application of lime and NPSB fertilizer had a significant ($p< 0.0001$) influence on both the days to heading and maturity. Nevertheless, the interaction effects between lime and NPSB fertilizer applications did not prove to be statistically significant, as illustrated in Table 3.The application of lime resulted in an extension of the days to heading, with a mean value of 73 compared to 71 in the unlimed treatments. Conversely, liming the soil accelerated the days to maturity, with a mean value of 116 compared to 118 in the treatment without lime, as depicted in Table 3.

Our findings indicated the profound impact of acidic soils amendment using lime on wheat phenology and growth, as demonstrated in Table 3. The application of lime mitigated the detrimental effects of soil acidity, leading to improved wheat performance. Specifically, lime-treated crops generally attained physiological maturity earlier compared to untreated plots. These results align with previous findings suggesting that wheat's vegetative growth is hindered in the presence of aluminum in nutrient solutions (Asresach, 2021). Acidic soils often contain high levels of aluminum, which can be toxic to plants and inhibit root development. Lime neutralizes soil acidity, reduces the availability of toxic aluminum ions and allows roots to function more effectively. As a result, plants may reach maturity sooner due to improved nutrient uptake and healthier root systems (Asresach, 2021). Lime application also raises the pH of acidic soils, making essential nutrients more available to plants. This enhanced nutrient availability can promote faster growth and development, leading to earlier maturity. Overall, lime application to acidic soils can positively influence various factors contributing to plant growth and development, ultimately resulting in faster days to maturity.

The effects of NPSB on phenology of wheat

Our results also revealed a notable trend where the days to heading and maturity decreased as the rates of NPSB increased, as illustrated in Table 3. The longest periods to heading (75 days) and maturity (120 days) were observed in the treatment with no NPSB input. As the NPSB rate increased to 50, 100, 150, and 200 kg ha^{-1} the days to heading decreased by 3, 4, 4, and 5 days, respectively. Similarly, except for the 200 kg ha^{-1} NPSB treatment, the same trend was observed for the days to maturity. This may be increased N prolongs the vegetative growth period, delays maturity(Anas et al., 2020). With NPSB rates of 50, 100, and 150 kg ha^{-1}, the days to maturity decreased by 6, 11, and 16 days, respectively, as depicted in Table 3. The unusually longer period required for maturity with the 200 kg ha^{-1} NPSB treatment could not be justified.

The application of various rates of NPSB greatly impacted wheat phenology, likely due to balanced nutrition and the physiological actions of N and P.N promotes vegetative growth,but delays maturity, whereas P hastens maturity. This balance is reflected in our findings and supported by (Abdeta, Tulu, & Berecha, 2022) and (Dugassa, Belete, & Shimbir, 2019), who noted that NPSB applications accelerated heading and maturity by enhancing nutrient availability and photosynthesis. NPSB provides readily available N and P, stimulating photosynthesis and carbohydrate production, which fuels growth and development. Adequate nutrient availability reduces stress on plants, such as nutrient deficiencies, soil acidity, and aluminum toxicity, enabling efficient progression through growth stages. In summary, NPSB applications promote faster heading and maturity by ensuring nutrient availability, reducing stress, enhancing photosynthesis, and improving overall plant health. Hameso et al. 2022.

Table 3: Effects of lime and NPSB fertilizer treatments on days to heading and physiological maturity under acidic soil condition

Treatments	Day to heading (No)	Day to maturity (No)
Lime		
Without lime	70.8^{b}	118.3^{b}
With lime	72.7^{a}	116.3^{a}
LSD	1.36	1.67
NPSB (kg ha^{-1})		
0	74.7^{a}	119.8^{a}
50	72.0^{b}	113.5^{b}
100	71.2^{bc}	108.8^{c}
150	71.2^{bc}	103.8^{d}
200	69.8^{bc}	114.3^{b}
CV (%)	**2.48**	**1.94**
LSD (0.05)	**2.16**	**2.64**

Notes: Means within a column followed by the same letter are not significantly different at 5% probability level

The effects of lime and NPSB fertilizer on yield attributes of wheat

The effects of lime on yield attributes of wheat

The analysis of variance revealed that the applications of lime and NPSB fertilizer significantly ($p < 0.0001$) impacted all measured yield attributes of wheat, including tiller count, plant height, spike length, seeds per spike, seed weight, and harvest index. However, the results indicated that the interaction effects between lime and NPSB fertilizer were not significant for any of the measured variables (Table 4).

Applications of NPSB fertilizer at various rates notably enhanced the yield attributes of wheat as described in Table 4. The highest rate of NPSB fertilizer application, at 200 kg ha^{-1}, yielded the maximum total tillers $plant^{-1}$ (5.9), effective tillers $plant^{-1}$ (5.6), plant height (78.8 cm), spike length (8.5 cm), grains $spike^{-1}$ (49.8), seed weight (63.5 mg), and harvest index (40.8%; Table 4). Similarly, applying 150 kg ha^{-1} of NPSB fertilizer resulted in comparable total tillers $plant^{-1}$ (5.9), effective tillers $plant^{-1}$ (5.5), plant height (77.8 cm), spike length (8.5 cm), grains $spike^{-1}$ (49.8), seed weight (63.3 mg), and harvest index (38.1%). Moreover, statistically equivalent effective tillers $plant^{-1}$ (5.2), spike length (8.2 cm), grains $spike^{-1}$ (47.4), seed weight (62.8 mg), and harvest index (39%) were observed with the application of 100 kg ha^{-1} of NPSB fertilizer (Table 4).

The improved yield attributes observed with the addition of lime can be attributed to changes in soil properties subsequent to lime application. As described in Table 3 and corroborated by the findings of (Ejigu, Selassie, & Elias, 2023),lime application, led to the neutralization of soil acidity, resulting in an increase of soil pH and reductions in exchangeable acidity and exchangeable Al^{3+}.These changes fostered enhanced soil fertility and created favorable conditions for agricultural production, thereby supporting increased yield attributes such as tillers, plant height and spike length.

Consistent with our findings, (Wubayehu, 2021)similarly documented that the application of lime significantly influenced the quantity of productive tillers $plant^{-1}$. Moreover, (Victoria, Ping, Yang, & Eneji, 2019) noted a significant impact of nitrogen and lime application on plant height throughout the growth stages, with the tallest plants observed when lime and N were applied at a rate of 180 kg N ha^{-1}. In accordance with our findings, (Dabesa & Tana, 2021) reported that lime application at a rate of 3.12 t ha^{-1}resulted in a significantly higher harvest index (41%) of soybean compared to no lime application (39%).This outcome may be attributed to the role of lime in neutralizing soil acidity, which in turn enhancing the availability of P. This increased phosphorus availability is crucial for initiating flowering and seed formation, thus contributing to the observed improvement in harvest index (Dabesa and Tana, 2021).(Victoria et al., 2019) further emphasized that in addition to raising soil pH and mitigating acidity's adverse effects on crop performance, the combined application of NPS fertilizer along with lime amendment plays a significant role in enhancing the availability of applied P. Likewise, according to (Megersa, 2022), the largest mean plant height, spike length, number of seeds $plant^{-1}$, biomass production, and thousand seed weight showed a progressive increase with higher quantities of lime application. This suggests that lime application positively influences various aspects of plant growth and development, ultimately contributing to improved crop productivity. In agreement to our current findings, (Y. Tesfaye, Alemu, Asefa, Teshome, &

Chimdesa, 2020) and (Hameso, Worku, & Ayalew, 2021) also observed that barley genotypes treated with the recommended NPSB and NPS rates produced more effective tillers on average per square meter compared to NP, with no significant differences between the two. They further noted that effective tillers were strongly influenced by the application of P. Similarly, (Ameyu & Asfaw, 2020) found that the plant height of soybeans significantly increased with combined application of lime and phosphorus to the soil. In line with our results, (Tilahun Abera, Lemma, Hundesa, Husen, & Firomsa, 2021)stated that spike length increased as the rates of both NPS and N increased from zero to the highest levels. They reported that the highest and lowest spike lengths were measured in response to combined applications of 100 kg NPS ha^{-1} with 92 kg N ha^{-1} and control treatments, respectively. In line with our results, (Kuma Megersa, 2019) also reported the largest number of grains per bread wheat spike (50.6) in acidic soil conditions with the In agreement to our current findings, (Y. Tesfaye et al., 2020) and (Hameso et al., 2021)also observed combined applications of NPS fertilizers at a rate of 150 $kgha^{-1}$ with 50 $kgha^{-1}$KCl, while the lowest number of grains per spike (16.33) was observed in the unfertilized treatments.

Additionally, (Mamo & Erkeno, 2022) reported the maximum kernel count per spike (76.78) with the application of blended fertilizers. Our results further corroborated with the findings of (Ishete & Tana, 2019), who noted a significant difference in the thousand kernel weight between the control mean and the NPS-treated mean in their study on durum wheat. The harvest index represents the coefficient of efficacy between the aboveground biomass yield to grain yield ratio. The balance between the plant's productive portion and its reserve, which together make up the economic yield, is represented by the harvest index. Greater photo assimilate production and its subsequent partitioning into grain yield may be responsible for the increase in harvest index with higher rates of NPSB fertilizer. In accordance with our current result, Tagesse and Adinew(Tagesse Abera & Adinew, 2020) reported the highest value of harvest index (43.96%) with the application of 200 kg NPS ha^{-1}.

Table 4. The integrated effects of lime and NPSB fertilizer on yield attributes and harvest index of wheat under acidic soil condition

Treatments	Total tillers (No)	Effective tillers (No)	Plant height (cm)	Spike length (cm)	Seeds spike^{-1} (No)	Seed weight (mg)	Harvest index (%)
			Lime				
Without lime	4.2^{b}	3.6^{b}	65.1^{b}	6.9^{b}	41.1^{b}	58.1^{b}	35.3^{b}
With lime	5.7^{a}	5.5^{a}	74.4^{a}	8.0^{a}	47.9^{a}	62.9^{a}	36.5^{a}
LSD	0.24	0.26	3.79	0.29	3.54	0.61	0.01
			NPSB rates (kg ha^{-1})				
0	3.2^{d}	2.8^{c}	53.3^{c}	5.2^{c}	33.7^{c}	53.9^{c}	28.7^{c}
50	4.3^{c}	3.7^{b}	67.5^{b}	6.8^{b}	41.7^{b}	58.9^{b}	32.9^{b}
100	5.5^{b}	5.2^{a}	71.4^{b}	8.2^{a}	47.4^{a}	62.8^{a}	39.0^{a}
150	5.9^{a}	5.5^{a}	77.8^{a}	8.5^{a}	49.8^{a}	63.3^{a}	38.1^{a}
200	5.9^{a}	5.6^{a}	78.8^{a}	8.5^{a}	49.8^{a}	63.5^{a}	40.8^{a}
CV	**6.46**	**7.64**	**7.08**	**5.13**	**10.38**	**1.31**	**20.69**
LSD	**0.38**	**0.42**	**5.99**	**0.46**	**5.6**	**0.96**	**0.9**

The combined effects of lime and NPSB fertilizer on yield of wheat

The analysis of variance showed a significant (p<0.001) difference in grain and biomass yields due to the interaction between lime and NPSB fertilizer rates (Table 5).Combining lime with NPSB fertilizers increased wheat grain and biomass yields. Combined applications of lime and NPSB fertilizer at a rate of 150 kg ha^{-1} resulted in the highest grain (5.38 t ha^{-1}) and biomass (14.72 t ha^{-1}) yields of wheat. Likewise, combining lime with 200 kg ha^{-1}NPSB and 100 kg ha^{-1}NPSB also yielded comparable grain (5.36 and 5.35 t ha^{-1}, respectively) and biomass (14.57 and 14.44 t ha^{-1}, respectively) yields (Table 5). Furthermore, statistically equivalent grain yields were attained with the application of 200 kg ha^{-1}NPSB (4.11 t ha^{-1}) and 150 kg ha^{-1}NPSB (3.78 t ha^{-1}) without lime. However, the biomass yields at these rates without lime were significantly lower compared to the same rates with lime, underscoring the positive impact of lime in ameliorating soil acidity and consequently enhancing yield. Reducing the NPSB rates to 50 and 100 kg ha^{-1}, with or without lime, resulted in significantly lower grain and biomass yields compared to higher NPSB fertilizer rates (Table 5). The lowest grain yields were observed with the treatments receiving no inputs, whether without lime (0.99 t ha^{-1}) or with lime (1.31 t ha^{-1}), which were statistically indistinguishable from each other. Similarly, the lowest biomass yields were also observed in the treatments without inputs, whether without lime (3.91 t ha^{-1}) or with lime (4.12 t ha^{-1}; Table 5). Overall, the results highlighted that the application of lime with any level of NPSB led to higher grain and biomass yields compared to the same rates without lime (Table 5). For instance, the application of lime with 150 kg ha^{-1}NPSB resulted in 42% and 54% increases in grain and biomass yields, respectively, compared to the same rate without lime. This underscores the beneficial effects of lime in enhancing nutrient availability, improving soil health, and boosting wheat yield (Table 5).

The comparable wheat yield obtained with higher NPSB rates at 150 and 200 kg ha^{-1} without lime may be attributed to the surplus availability P and N for plant nutrition, surpassing soil fixation capacities. The rapid dissolution of N and P from the NPSB fertilizer in the soil yields readily absorbable phosphate and ammonium for plants. Consequently, the application of higher NPSB rates at 150 and 200 kg ha^{-1} enhances soil P levels, facilitating nutrient uptake and root growth, thereby ultimately enhancing grain and biomass yields. In agreement to our findings, (Ejigu, Selassie, Elias, & Molla, 2023) reported that applying 150 kg ha^{-1}NPSB without lime and 200 kg ha^{-1}NPSB without lime equivalently enhanced grain yield compared to applying 200 kg ha^{-1}NPSB with lime, 150 kg ha^{-1}NPSB with lime, and 100 kg ha^{-1}NPSB with lime. The inclusion of N, P, and S in blends at higher rates appears to have improved the yield without significant deviation from the results observed in limed treatments. Similar results were also found when comparing the mean grain yield of wheat across different NPS rates. The maximum grain yield of wheat (7.28 tha^{-1}) was recorded from a balanced application, whereas the control treatment yielded lower grain yield (2.24 tha^{-1}) (Jemal, Ahmad, & Hassen, 2022). The significant increase in grain and total biomass observed with combined applications of lime with 100, 150, or 200 kg ha^{-1}NPBS, compared to the 50kg ha^{-1}NPSB and control treatment, may be attributed to the significant increase in yield components such as the number of effective tillers, spike length, number of seeds per spike, and grain weight. Our findings, indicating increased wheat yield with the combined application of lime and NPSB fertilizers, align closely with the previous studies reported in the literature. Specifically, our results are consistent with those of (Ejigu, Selassie, Elias, et al., 2023), who demonstrated that adding 2 t ha^{-1} lime to acidic soil treatments resulted in a 24.2 t when compared to the control. Our findings are also consistent with those of (Ejigu, Selassie, Elias, et al., 2023),who reported that increasing lime application rates significantly enhanced wheat growth and yield characteristics compared to unlimed plots. Additionally, (T. Tesfaye, Laekemariam, & Habte, 2021)also observed similar trends, reporting that as the rates of NPS and KCl application rose from 0 to 50 kg ha^{-1} and 0 to 150 kg ha^{-1}, the total above-ground biomass yield of wheat demonstrated an increase of 49% and 279%, respectively.

Table 5. The integrated effects of lime and NPSB fertilizer on grain and above-ground biomass yields of wheat under acidic soil condition

Treatments	Grain yield (t ha^{-1})	Biomass yield (t ha^{-1})
No input with no lime	0.99^{c}	3.91^{d}
No input with lime	1.31^{c}	4.12^{d}
50 kg NPSB ha^{-1} with no lime	1.39^{c}	5.22^{cd}
50 kg NPSB ha^{-1} with lime	2.52^{bc}	6.32^{c}
100 kg NPSB ha^{-1} with no lime	3.58^{b}	8.77^{b}
100 kg NPSB ha^{-1} with lime	5.35^{a}	14.44^{a}
150 kg NPSB ha^{-1} with no lime	3.78^{ab}	9.53^{b}
150 kg NPSB ha^{-1} with lime	5.38^{a}	14.72^{a}
200 kg NPSB ha^{-1} with no lime	4.11^{ab}	9.19^{b}
200 kg NPSB ha^{-1} with lime	5.36^{a}	14.57^{a}
CV (%)	12.78	11.03
LSD (0.05)	1.59	1.67

Note*: Means within a column followed by the same letter are not significantly different at 5% probability level*

Effects of lime and NPSB fertilizer on economic benefits of wheat production

The results of the partial budget analyses for the combined use of lime with various rates of NPSB fertilizers are presented in Tables 6.The combined applications of lime with 100 kg ha^{-1} NPSB fertilizer yielded the highest net benefit of 75,494.50 ETB ha^{-1}, accompanied by an impressive marginal rate of return (MRR) of 7838%, as demonstrated in Table 6. This suggests that farmers could potentially earn 7,838.00 ETB ha^{-1} for each unit of investment on lime and NPSB fertilizer. Similarly, employing lime integrated with 150 kg ha^{-1} NPSB or 200 kg ha^{-1} NPSB also resulted in substantial net benefits of 75,397.00 and 74,437.00 ETB ha^{-1}, respectively. However, despite these higher returns, the marginal benefit of these treatments was outweighed by their marginal costs, rendering them less feasible options for farmers.

In contrast, the application of 100 kg ha^{-1} NPSB without lime still generated a considerable net benefit of 57,462.00 ETB ha^{-1}, with appreciable MRR of 6043%. Likewise, employing 50 kg ha^{-1} NPSB with or without lime yielded net benefits of 27,292.00 and 20,299.50 ETB ha^{-1}, respectively, with corresponding MRRs of 3294% and 1022%. Furthermore, the application of 200 kg ha^{-1} NPSB and 150 kg ha^{-1} NPSB without lime also resulted in net benefits of 65,374.50 and ETB ha^{-1}, respectively, accompanied by MRRs of 826% and 461%, respectively (Table 6).

Our findings demonstrate the economic viability of combining lime with NPSB fertilizers, especially at a rate of 100 kgha^{-1} for wheat production barley in the acidic soils of Harbagona. This application package yielded the highest net benefit and a significant MRR. While higher doses of NPSB in conjunction with lime exhibited significant net gains, they were constrained by escalating marginal costs. Applying NPSB without lime still resulted in considerable net benefits, highlighting the importance of appropriate fertilization approach. These findings emphasize the need to consider both economic and agronomic factors in fertilizer management decisions in agriculture.

Table 6. Economic evaluation for testing the feasibility of combined application of lime and NPSB fertilizer for enhancing wheat production in the acidic soils of Harbagona

Treatments	Adjusted grain yield (t ha^{-1})	Adjusted straw yield (t ha^{-1})	Total variable cost (ETB ha^{-1})	Net benefits (ETB ha^{-1})	Marginal rate of return (%)
100 kg ha^{-1} NPSB with lime	4.82	13.00	15,068.00	75,494.50	7838
150 kg ha^{-1} NPSB with lime	4.84	13.25	15,683.00	75,397.00	-
200 kg ha^{-1} NPSB with lime	4.82	13.11	16,298.00	74,437.00	-
200 kg ha^{-1} NPSB without lime	3.70	8.27	3,798.00	65,374.50	826
150 kg ha^{-1} NPSB without lime	3.40	8.58	3,183.00	60,297.00	461
100 kg ha^{-1} NPSB without lime	3.22	7.89	2,568.00	57,462.00	6043
50 kg ha^{-1} NPSB with lime	2.27	5.69	14,453.00	27,292.00	3294
50 kg ha^{-1} NPSB with no lime	1.25	4.70	1,953.00	20,299.50	1022
0 NPSB with no lime	0.89	3.52	1,338.00	14,014.50	-
0 kg ha^{-1} NPSB with lime	1.18	3.71	13,838.00	7,034.50	-

Conclusion

Our findings from this study underscore the significant positive impact of integrating lime with NPSB fertilizers on enhancing grain and biomass yields, soil health, and economic returns for farmers. Our results underscore the pivotal role of lime in ameliorating soil acidity, thereby improving nutrient availability and fostering optimal conditions for crop growth. The synergistic effect of lime with varying levels of NPSB fertilizer demonstrated remarkable improvements in grain and biomass yields, with the highest yields achieved at a combined application rate of 150 kg ha^{-1} NPSB fertilizer and lime. Notably, the beneficial effects of lime were evident across all levels of NPSB application, emphasizing its role in ameliorating soil acidity and enhancing nutrient availability. This synergy was further highlighted by the notable improvements in soil pH, reduced exchangeable acidity, and enhanced cation exchange capacity and nutrient availability, particularly phosphorus, calcium, and magnesium by the combined treatment. Economic analysis revealed substantial net benefits and impressive marginal rates of return, particularly with the application of 100 kg ha^{-1} NPSB fertilizer integrated with lime, indicating its viability and profitability for farmers. Furthermore, the application of lime contributed to the improvement of various yield attributes of wheat including tiller count, plant height, spike length, seeds per spike, seed weight, and harvest index, emphasizing its role in optimizing crop development and quality. These findings underscore the importance of nutrient management and soil amelioration strategies in maximizing wheat productivity. Overall, our study highlights the importance of combined application of lime and NPSB fertilizer, in addressing soil acidity issues, enhancing nutrient availability, and ultimately maximizing wheat yield and farmer profitability. These findings offer valuable insights for sustainable agricultural practices aimed at ensuring food security and livelihood improvement in farming communities.

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Availability of data and materials

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

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