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Identifying limiting nutrient(s) for better bread wheat and tef productivity in acidic soils of north-west Amhara, Ethiopia

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Abstract

Food crop productivity is still low because of the decline of soil fertility in Ethiopia, particularly in north-western Amhara. Fine-tuning the source and rate of nutrients is required to solve soil fertility problems along landscape positions. Therefore, this study was initiated to investigate the need to apply selected nutrients to tef and wheat in acidic soils. This nutrient omission study was conducted in 74 farmers' fields of Gozamen and Machakel districts. The omitted nutrients were sulfur (S), zinc (Zn), and boron (B). Potassium (K) was added, consisting of N, P, K, S, Zn, and B (All+K). Nitrogen plus phosphorus (NP) and no fertilizer treatments were used as positive and negative controls, respectively. Furthermore, 50% and 150% of the All+K treatments were also included. The finding revealed that the application of different nutrient types at variable rates had a significant role in the grain and biomass yield of both test crops in the acidic soils. No tef yield and the lowest yield of bread wheat were obtained from the no fertilizer application treatment. The application of All+K had no significant yield advantage compared to NP fertilizer alone. This implies that N and P are the most yield-limiting nutrients to produce tef and bread wheat, whereas KSZnB nutrients are not yield limiting. Therefore, refining the rates of N and P in acidic soils is needed for the economical use of fertilizers. Finally, applying blended fertilizers without empirical evidence is not recommended for smallholder farmers in the study area.

1 | INTRODUCTION

Achieving food security is the main challenge for the agricultural sector in Ethiopia (Yigezu Wendimu, 2021). It is possible to address the food security and sustainability challenges that lie ahead, but it will demand significant shifts in how nutrients and water are managed (Mueller et al., 2012). Crop productivity has not been improved due to the decline in soil fertility (Amare et al., 2018; Hirpa et al., 2012; Kebede & Ketema, 2017). Adding synthetic fertilizer is one of the major option to enhance crop productivity. Annual fertilizer use rose by about 30% from 1994 to 2005 and by 63% from 2005 to 2010 in Ethiopia (Birhan et al., 2017; Tefera et al., 2012). Recently, the use of synthetic fertilizers for crop production has increased

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Abbreviations: Av.P, available phosphorus; CEC, cation exchange capacity; SOC, soil organic carbon; TN, total nitrogen.

drastically, even though the expected crop yield has not been achieved (Dorosh & Rashid, 2013).

During the last decades, many studies have indicated that crop production constraints are mainly deficiencies of macronutrients nitrogen (N) and phosphorus (P) and, to some extent, potassium (K) and sulfur (S) (Aleminew & Legas, 2015; Argaw & Tsigie, 2015; Ayalew et al., 2011; Tamene et al., 2017). The addition of sulfur is also recommended to boost crop productivity in lowland parts of the country (Habtegebrial, 2013; Habtegebrial & Singh, 2009). Contrary to these reports, other studies show that the deficiency of K is not a major problem for most agricultural soils in Ethiopia (Amare et al., 2018, 2019). However, limitations of secondary nutrients and deficiencies of micronutrients have also been reported in the agricultural lands of Ethiopia (Ethiopian Soil Information System (EthioSIS), 2016).

The responses to fertilizer application varied across geographical locations (Amare et al., 2018; Tamene et al., 2017) and environments. Fertilizer applications should consider landscape positions on soils with undulating topographic features (Amede et al., 2020). The response of crops to fertilizers is ranged from low to high for any nutrient combination along the landscape (Amede et al., 2022). These are associated with nutrient depletion and water availability along the slope gradient in the landscape. Moreover, the responses of nutrients can vary due to management factors and biophysical attributes. As a result, fertilizer use efficiencies and economic profitability have differed in the landscape positions (Desta et al., 2023). Thus, optimizing the use of nutrients through the right fertilizer source, rate placement, and time of application during the crop growing season is critical to solving soil fertility problems (Ahmad et al., 2018; Barłóg et al., 2022) and the economical use of fertilizers.

Fertilizer rates are better recommended based on the available nutrients in the soil and the crops' requirements for those nutrients (Scherer, 2001). The demand for the plant should be addressed through the supply of the required plant nutrients in adequate amounts. However, this has not been done in previous soil management efforts to halt soil fertility declines in Ethiopia. This is due to a lack of fertilizer rate and the right fertilizer combination along the landscape (Amede et al., 2022). On the other hand, there is a yield gap for wheat (*Triticum vulgare*) and tef (*Eragrostic tef*) in Ethiopia due to inadequate fertilizer use (Birhan et al., 2017; Mann & Warner, 2015; Tadesse et al., 2000; Zeleke et al., 2010). The yield gaps of these crops suggest that there is potential for increasing production through lime application, selection of acid-tolerant crop varieties, use of fertilizers, and identification of the right nutrient types for each location, landscape positions, and crop type, particularly in acidic areas.

In designing fertilizer recommendations along the landscape positions, an understanding of the effects of each nutrient or fertilizer type of crop is required. Moreover, increasing crop production with the use of synthetic fertilizer must be profitable for smallholder farmers to promote sustainably (Tamene et al., 2017). Inefficient use of chemical fertilizer might cost the farmer and pollute the environment (Vanlauwe et al., 2011). This problem is severe in hillslope landscapes due to the removal of nutrients by erosion. In addition, the high variability between and within farms calls for nutrient type and rate recommendations that will reduce waste and reap maximum benefits from fertilizer use. Therefore, fine-tuning fertilizer recommendations is required by selecting the right nutrient types along landscape positions in acidic soils. Hence, the objective of this study was to evaluate the rates of different nutrients along the landscape and identify the major yield-limiting nutrients for wheat and tef production in acidic-prone areas of north-west Amhara, Ethiopia.

Core Ideas

- Right nutrient management maximizes crop yield.
- Identifying yield-limiting nutrients in acidic soils is crucial.
- Understanding micronutrients' role boosts tef and wheat productivity.
- Major nutrients for tef and wheat production are identified in acidic soils.
- Assessing yield-limiting nutrients is vital, with or without lime amendment.

2 | MATERIALS AND METHODS

2.1 | Descriptions of the study areas

On-farm plant nutrient omission experiments were conducted in acid-prone areas of the Northern Highlands of Ethiopia (Gozamen and Machakel districts), within the geographical coordinates of 10°00′–10°40′ N latitudes and 37°20′–37°50′ E longitudes (Figure 1). The elevation of the Gozamen districts is found between 1200 and 3510 m, while Machakel district is found between 1200 and 3200 m above sea level.

In both districts, the average annual rainfall ranges between 1300 and 1900 mm (Ethiopia Metreological Agency [EMA], 2020), with the highest amount of rainfall received in July and August. The maximum and minimum annual average temperatures are 27°C and 8°C, respectively. Wheat (*Triticum vulgare*), tef (*Eragrostic tef*), maize (*Zea mays*), barley (*Hordeum vulgare*), white lupine (*Lupines albus*), and food oats are the dominant cereal crops that are grown in both districts. Nitisols, followed by vertisols, are the most dominant agricultural soils in the study districts.

A total of 74 trial sites were used for both test crops. Half (37) of these sites were used for tef, the remaining sites were

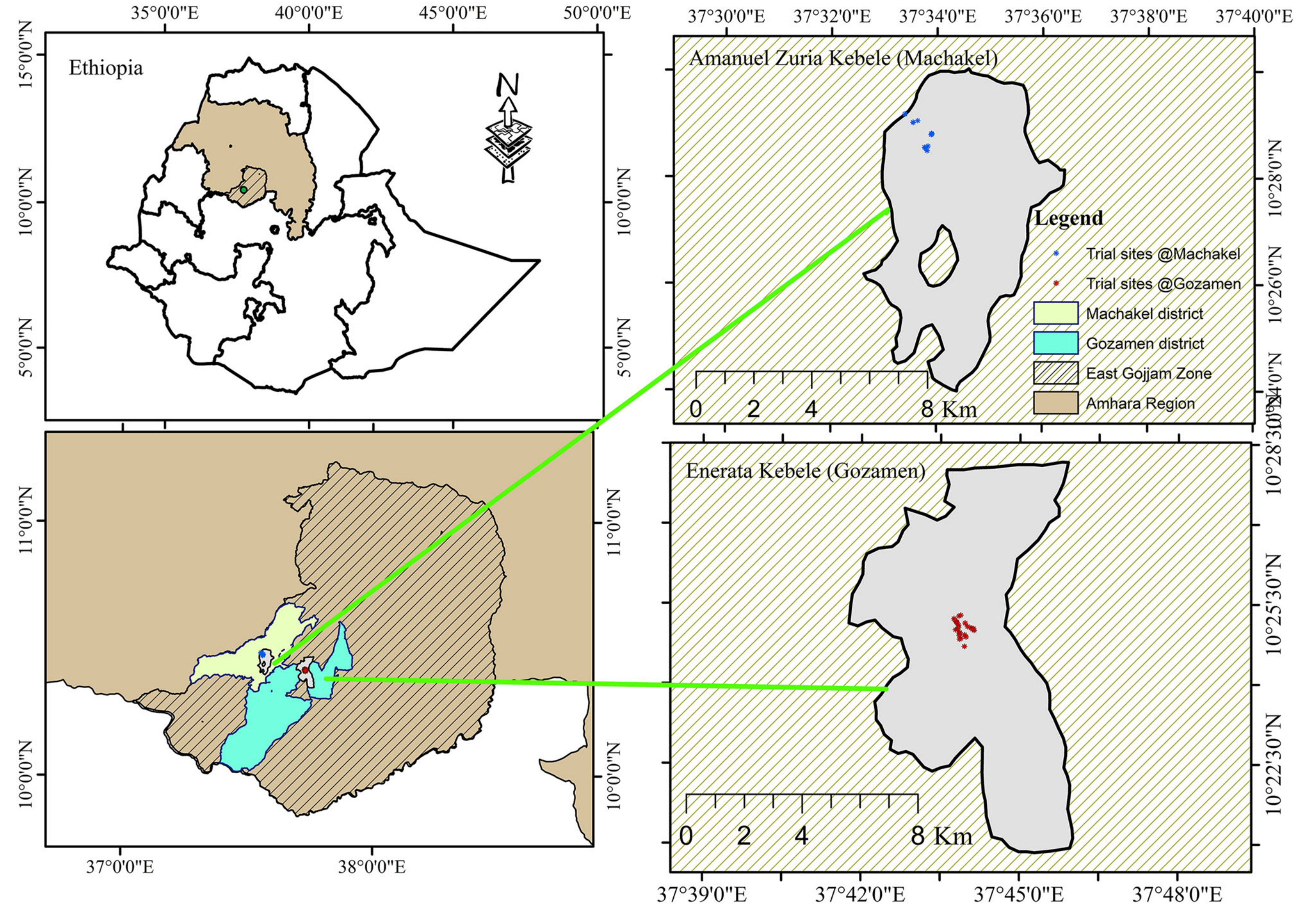

FIGURE 1 Location map trial sites in Gozamen and Mackale districts.

TABLE 1 Details of the number of sites in study districts.

Districts	Landscape positions	Test crops	Soil acidity management		Total number of sites (*N*)
			Lime amended	Not lime amended	
Gozamen		2	22	22	44
	Hill	Tef and wheat	6	6	12
	Mid	Tef and wheat	12	12	24
	Foot	Tef and wheat	4	4	8
Machakel		2	16	14	30
	Hill	Tef and wheat	6	4	10
	Mid	Tef and wheat	6	6	12
	Foot	Tef and wheat	4	4	8
Total (*N*)		2	38	36	74

used for bread wheat nutrient omission experiments. Out of 74 sites, 44 trial sites have been found in Gozamen and 30 in Machakel districts that represent the acid soils of north-west Amhara, Ethiopia (Table 1). About 38 sites were previously amended by lime, whereas the remaining 36 sites were not amended by lime before the experimentation year.

This experiment was superimposed on previously lime-amended farmer fields in both districts. Previously, lime-amended sites were managed with a lime application by farmers with the help of development agents. The lime, which is fine calcium carbonate ($CaCO_3$), was applied based on the blanket recommendation (100 kg ha^{-1}). Thus, lime-amended and not amended farmers' fields were purposefully selected and implemented side by side in the same farmers' fields at all landscape positions for both test crops.

TABLE 2 Description of treatments in the nutrient omission trials conducted in acidic soils of study areas.

	Nutrient types and rates (kg ha^{-1})											
	Bread wheat						Tef					
Treatments	N	P_2O_5	S	K_2O	Zn	B	N	P_2O_5	S	K_2O	Zn	B
Control	–	–	–	–		–	–	–	–	–	–	–
All	120	76	7	–	1	0.3	80	57	7	–	1	0.3
All-S	120	76	–	–	1	0.3	80	57	–	–	1	0.3
All-Zn	120	76	7	–	–	0.3	80	57	7	–		0.3
All-B	120	76	7	–	1	–	80	57	7	–	1	–
All+K	120	76	7	30	1	0.3	80	57	7	30	1	0.3
NP	120	76	–	–	–	–	80	57	–	–	–	–
50% All+K	60	38	3.5	15	0.5	0.15	40	28.5	3.5	15	0.5	0.15
150% All+K	180	114	10.5	45	1.5	0.45	120	85.5	10.5	45	1.5	0.45

Note: All represent NPSZnB nutrients.

2.2 | Trial design

The core set of treatments was harmonized with nutrient omission design. Treatments were arranged in a completely randomized block design with two or three replications in three landscape positions (foot, mid, and hill) (Table 2). This experiment comprised with nine treatments, including NPSZnB (All), by omitting S (All-S), Zn (All-Zn), and boron (B) (All-B) nutrients, whereas K was added (All+K). Non-fertilized (negative control) and recommended NP (positive control) treatments were included. Moreover, two treatments with rates of 50% and 150% of All+K nutrients were added. These treatments were used to evaluate fertilizer rate responses in different landscape positions. Because nutrient responses are varied along the slope gradient in the landscape, the soil fertility status might be lower at the hillslope landscape position.

2.3 | Fertilizer sources, test crop, and experimental management

Urea, triple superphosphate, potassium chloride, and borax are used as sources of fertilizer for nitrogen, phosphorus, potassium, and boron, respectively, whereas zinc sulfate was used as a source for both S and zinc (Zn). The test crops used for this study were bread wheat (*Ogalcho variety*) and tef (*Kuncho*) at a seed rate of 150 and 10 kg ha^{-1}, respectively.

All trials were implemented on farmers' fields, and crop management practices were done following research recommendations. After preparing the trial sites, test crops were planted by the drill method at 20-cm spacing from July 21 to July 31, 2020. All fertilizers were applied by band application at planting except urea, which was divided for split. The second split dose of nitrogen was applied 1 month after emergence. Weed management was started just after 2 weeks of seed emergence in the trials. Each site had been weeded twice. All experimental sites were harvested after data measurements. Then, the threshing was done after drying the harvested test crop. All crop management practices were done manually by labor.

2.4 | Data collection

2.4.1 | Soil sampling

A composite soil sample was collected at 0–20 cm of depth from each trial site. The composite samples were collected from 11 sites with lime-amended farmers and 12 non-lime-amended sites in Gozamen. Moreover, samples were also collected from eight sites with lime-amended and six sites with non-amended farmers in Machakel district. Composite soil samples were collected from 37 common experimental sites in all landscape positions and lime amendments where tef and bread wheat nutrient omission trials were implemented. Thus, a total of 74 sites were separately used for each tef and wheat omission trial.

2.5 | Biological data

Measurements of total aboveground biomass and grain yield were done for each test crop. Harvesting was done from the middle rows of a 3.2 m by 3 m area (9.6 m^2 net plot area), leaving the outside rows as a buffer to avoid border effects. Then, total biomass was determined from plants harvested from the net plot area after sun drying to a constant weight and converted to kg per hectare for statistical analysis. Grain yield was also collected after threshing the total biomass harvested from the net plot area and converted into kg ha^{-1}. The grain yield was adjusted to 12.5% moisture content.

2.6 | Soil analysis

All collected soil samples were air-dried and crushed to pass a 2-mm sieve. Analysis was performed on surface samples (0–20 cm) including pH (H_2O), soil organic carbon (SOC), cation exchange capacity (CEC), and exchangeable aluminum (Ex.Al^{3+}) following standard soil laboratory procedures in the Adet Agricultural Research Center's soil laboratory, whereas total nitrogen (TN), available phosphorus (Av.P), sulfur (S), zinc (Zn), and boron (B) were sent and analyzed in the laboratory of the International Fertilizer Development Center in the United States. Soil pH(H_2O) was determined in soil–water suspensions at 1:2.5 ratios (McLean, 1982). Av.P was also measured following the Mehlich 3 method (Mehlich, 1984), while TN was done using the Kjeldahl method (Bremner & Mulvaney, 1982). The wet oxidation method was used to determine SOC (Walkley & Black, 1934). CEC was also determined by ammonium acetate extraction procedures (Houba et al., 1986). Ex.Al^{3+} was determined by the titration method (McLean, 1965). The oxidation method was used to determine the S status of the soil (Bardsley & Lancaster, 1965). Zinc was determined by the diethylene triamine-pentaacetic acid (DTPA) extraction method (Lindsay & Norvell, 1978). Boron was determined by procedures adopted from Berger and Truog (1939).

2.7 | Data analysis

For all the sites, yield and biomass data were arranged in Excel and subjected to analysis of variance using R programming software. Mixed model analysis was performed for unbalanced yield datasets collected from each landscape and all sites. A test of significance for the treatment–site interaction of the combined analysis was done as outlined by Cochran and Cox (1992) for situations with heterogeneous variance among sites. The mean separation was carried out by Duns multiple range test at a 5% level of significance.

The model for this analysis was given as: $y_{ikjl} = \mu + \mathrm{Nut}_i + \mathrm{LS}_j + \mathrm{LA}_k + (\mathrm{Nut} \times \mathrm{LS} \times \mathrm{LA})_{ijk} + B_l + E_{ijkl}$, where y_{ijk} is the yield, μ is the overall mean, Nut_i is the effect of nutrient types and rates, LS_j is the effect of landscape positions, LA_k is the effect of previous lime amendment, $(\mathrm{Nut} \times \mathrm{LS} \times \mathrm{LA})_{ijk}$ is the interaction effects of each factors, B_l is the effect of the block, and E_{ijkl} is the error term associated with the *ijkl*th level of each factor.

3 | RESULTS

3.1 | Description of soil properties

In the Machakel district, the soil pH (H_2O) of the experimental sites without lime amendment ranged from 5.4 to 5.8 (Table 3), whereas experimental sites that were previously lime amended were found to be between 5.3 and 6.0. The soil pH (H_2O) of the experimental sites (without lime amendment) was found between 4.8 (foot) and 6.4 (hill) in the Gozamen district (Table 3), whereas experimental sites that were previously lime-amended were found between 5.0 and 6.0. An exchangeable acidity value of 2.1 and 1.6 (meq 100 g^{-1} soil) was recorded at the hill and mid-experimental sites, particularly in the Gozamen district.

The highest SOC content of 2.7% and 2.3% was recorded at hillslopes with lime-amended and non-amended sites, respectively (Table 3), while the lowest SOC of 1.1% was obtained from foot landscapes with lime-amended soils. The mean value of Av.P ranged between 0.3 and 10.7 mg kg^{-1}. The maximum (18.7 mg kg^{-1}) and the lowest (1.7 mg kg^{-1}) S content were found in soils at mid-slope in Gozamen and at hillslope in Machekel districts, respectively. The Zn content of soil was ranged from 0.07 to 3.6 mg kg$^{-1,}$ whereas B was ranged between 0.05 and 0.80 mg kg^{-1}. The highest CEC (38 Cmol kg^{-1}) value was observed from the mid-slope, while the lowest CEC (22.3 Cmol kg^{-1}) was recorded from the hillslope in the soils of the study areas.

3.2 | Tef grain and biomass yield response to nutrients

For all the sites and landscape positions, the application of All+K treatment did not show a significant tef yield increment ($p > 0.05$) as compared to N and P nutrients in Gozamen and Machakel districts except at the hillslope of Machakel district (Tables 4 and 5). Generally, tef grain yield was ranged between 447.9 and 1260.4 kg ha^{-1} (Table 4). The highest and non-significant yield was obtained from the All+K treatment across all landscape positions. Higher grain yield was observed when both N and P nutrients were applied, except for the hillslope regions in Machakel district.

Based on the analysis of variance, there were no significant differences ($p > 0.05$) in the tef grain and biomass yield due to various nutrients and rates across different landscapes and liming conditions, except for the mid-landscape position in the Gozamen district, except at the foot slope for biomass yield (Tables 6 and 7).

Although there was no significant difference in tef yield across the trial sites, relatively low yield variability was

TABLE 3 The range values of soil characteristics at experimental sites before planting time in the study area.

			Soil parameters								
Districts	**Liming condition**	**Landscape positions**	**Soil pH (H_2O)**	**Ex. Al (cmol kg^{-1})**	**TN (%)**	**S (mg kg^{-1})**	**Av.P (mg kg^{-1})**	**Zn (mg kg^{-1})**	**B (mg kg^{-1})**	**SOC (%)**	**CEC ($cmol_c$ kg^{-1})**
Gozamen	Without lime amendment	Foot	5.1–5.5 [5.1]	0.4–3.4 [2.2]	0.15–0.19 [0.17]	9.0–22.4 [16.9]	0.8–3.7 [2.1]	0.07–1.16 [0.71]	0.05–0.44 [0.26]	1.5–1.7 [1.6]	25.0–29.0 [27.3]
		Mid	5.1–5.2 [5.1]	0.2–2.4 [0.8]	0.19–0.24 [0.21]	18.7–28.4 [23.6]	1.7–3.2 [2.5]	0.93–1.31 [1.14]	0.28–0.47 [0.38]	1.4–2.1 [1.8]	27.0–38.0 [31.7]
		Hill	5.3–5.5 [5.4]	0.2–0.8 [2.0]	0.15–0.21 [0.18]	4.9–16.7 [10.6]	1.4–10.5 [4.3]	0.48–2.50 [1.23]	0.05–0.40 [0.15]	1.0–1.9 [1.6]	28.9–35.0 [32.0]
	Previously lime amended	Foot	5.4–5.7 [5.5]	0.2–1.38 [0.9]	0.13–0.20 [0.16]	9.2–19.5 [16.3]	1.9–4.0 [2.9]	0.61–0.82 [0.71]	0.41–0.68 [0.53]	1.5–1.9 [1.6]	28.9–37.6 [35.3]
		Mid	5.2–6.2 [5.5]	0.1–2.6 [1.1]	0.16–0.21 [0.18]	8.5–20.1 [15.2]	2.0–10.7 [4.5]	1.32–3.51 [1.83]	0.41–0.68 [0.53]	1.1–1.8 [1.5]	28.8–31.7 [30.3]
		Hill	5.3–5.9 [5.6]	0.1–3.5 [1.8]	0.12–0.14 [0.13]	3.8–26.2 [15.0]	1.9–3.7 [2.8]	0.95–3.60 [2.27]	0.40–0.80 [0.60]	1.2–1.3 [1.2]	25.0–35.5 [33.0]
Machakel	Without lime amendment	Foot	5.3–5.4 [5.4]	0.2–0.8 [0.5]	0.13–1.7 [0.15]	7.4–9.6 [8.5]	0.9–1.6 [1.3]	0.07 [0.07]	0.05–0.15 [0.10]	1.2–1.3 [1.2]	30.0–32.0 [30.8]
		Mid	5.0–5.4 [5.2]	0.4–1.5 [1.0]	0.16–0.22 [0.19]	3.2–15.6 [10.9]	0.5–2.0 [1.0]	0.07–1.10 [0.42]	0.05–0.25 [0.13]	1.3–1.5 [1.4]	34.2–34.7 [34.5]
		Hill	5.0–5.3 [5.2]	0.7–1.2 [0.9]	0.24–0.32 [0.27]	11.1–17.8 [14.8]	1.3–1.5 [1.4]	0.16–0.30 [0.2]	0.05–0.20 [0.10]	1.2–1.3 [1.3]	22.7–29.8 [26.3]
	Previously lime amended	Foot	5.1–5.7 [5.4]	0.6–1.3 [0.9]	0.17–0.21 [0.19]	5.5–13.1 [9.3]	1.9–5.6 [3.8)	1.29–2.99 [2.14]	0.37–0.44 [0.41]	1.1–1.3 [1.2]	29.3–31.2 [30.3]
		Mid	4.8–5.2 [5.1]	0.1–1.6 [0.7]	0.19–0.24 [0.21]	2.2–5.5 [4.2]	0.7–2.4 [1.4]	1.69–2.99 [2.27]	0.33–0.37 [0.33]	2.7–8.7 [2.2]	26.3–27.9 [27.0]
		Hill	5.1–5.2 [5.1]	0.3–2.1 [1.2]	0.17–0.24 [0.20]	1.7–3.4 [2.6]	0.3–0.9 [0.5]	0.69–2.83 [1.52]	0.23–0.41 [0.29]	1.4–1.7 [1.5]	22.3–31.1 [27.5]

Note: Numbers in brackets indicate the mean of each soil parameter.

Abbreviations: Av.P, available phosphorus; B, boron; CEC, cation exchange capacity; Ex. Al^{3+}, exchangeable aluminum; SOC, soil organic carbon; S, sulfur; TN, total nitrogen; Zn, zinc.

TABLE 4 Tef grain and biomass yield without lime-amended farm sites of three landscapes in Machakel district.

	Landscape					
	Foot [2]		Mid [3]		Hill [2]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
All	692.7	3020.8	508.3bc	4437.5bc^{4}	781.3c	3052.1b^{c}
All-S	666.7	2656.3	556.3bc	4608.3bc	760.4c	2555.6cd
All-Zn	447.9	2265.6	636.3b	3875.0bc	847.2bc	2979.2bc
All-B	661.5	2838.5	595.8b	3316.7c	687.5c	2336.8de
All+K	666.7	3046.9	704.2ab	4941.7ab	989.6b	3402.8b
NP	682.3	2500.0	641.7b	5175.0ab	736.1c	2725.7cd
50% All+K	401.0	1250.0	327.1c	3643.8bc	642.4c	1961.8e
150% All+K	937.5	4302.1	895.8a	6330.4a	1260.4a	4836.8a
CV (%)	15.1	16.9	29.3	26.2	13.1	10.5
p (0.05)	ns	ns	**	***	***	***

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviation: CV, coefficient of variation.

** Highly significant at 1%. *** Significant at 0.1%.

TABLE 5 Tef grain and biomass yield at previously lime-amended farm sites of three landscape positions in Machakel district.

	Landscape					
	Foot [2]		Mid [3]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
All	942.7	3614.6	377.1c	1404.2c	491.7bc	1633.3bc
All-S	1005.2	2958.3	514.6bc	1722.9bc	670.8ab	2247.9b
All-Zn	802.1	2765.6	427.1c	1697.9bc	504.2bc	1702.1bc
All-B	776.0	2947.9	495.8bc	1627.1bc	466.7bc	1575.0bc
All+K	963.5	3218.8	664.6ab	2227.1b	633.3ab	2079.2b
NP	859.4	2880.2	489.6bc	1795.8bc	485.4bc	1727.1bc
50% All+K	505.2	1520.8	308.3c	1102.1c	306.3c	1045.8c
150% All+K	1119.8	5479.2	852.1a	3162.5a	818.8a	3243.8a
CV (%)	12.9	17.1	28.7	27.7	31	27.4
p (0.05)	ns	ns	***	***	**	***

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

, * Significant at 1% and 0.1%, respectively.

observed when K, S, Zn, and B nutrients were omitted (Figure 2). By omitting the K and S nutrients, the yield was relatively increased by 9%–11% (58–98 kg ha^{-1}) and 12%–23% (106–145 kg ha^{-1}), whereas by omitting the Zn nutrient, the yield decreased by 0.4%–2% (4–28 kg ha^{-1}). With the omission of B nutrient, the yield declined by 2% (15 kg ha^{-1}) in Machakel district, whereas the yield increased by 7% (60 kg ha^{-1}) in Gozamen district. When the rate of All+K was reduced by 50% the yield was significantly reduced by 18%–22% (152–222 kg ha^{-1}).

3.3 | Response of bread wheat to applied fertilizer

The result yield showed that there was a significant difference ($p < 0.001$) among nutrient types and rates as compared to the control (no fertilizer) in the Machakel district, except for biomass yield at hill landscape positions (Tables 8 and 9). Higher rates of All+K nutrients received treatment gave maximum yield but no significant difference ($p > 0.05$) as compared to NP nutrients. Bread wheat grain yield ranged

TABLE 6 Tef grain and biomass yield without lime-amended farm sites of three landscapes in the Gozamen district.

	Landscape					
	Foot [2]		Mid [5]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
All	764.3	2791.7bc	926.3	3386.9	871.9	3482.6
All-S	699.2	2932.3b	1043.9	3809.5	993.1	4388.9
All-Zn	584.6	2237.0bc	831.1	2614.6	902.8	3347.2
All-B	563.8	2554.7bc	1035.7	3651.8	984.4	3510.4
All+K	658.9	3099.0b	1157.7	3474.0	923.6	3833.3
NP	713.5	2744.8bc	1037.2	3522.3	944.4	3506.9
50% All+K	505.2	1700.5c	873.3	2841.1	819.4	3454.9
150% All+K	1056.0	5471.4a	1026.8	4075.9	861.9	3295.1
CV (%)	34.2	25.0	33.0	29.1	15.2	21.9
p (0.05)	ns	***	ns	ns	ns	ns

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

*** Significant at 0.1%.

TABLE 7 Tef grain and biomass yield at previously lime-amended farm sites of three landscape positions in the Gozamen district.

	Landscape					
	Foot [2]		Mid [6]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
All	868.5	4420.6	910.3bc	3094.3bc	739.6	3289.9
All-S	914.1	4078.1	935.8abc	3256.9bc	965.3	4130.2
All-Zn	1001.3	4404.9	859.4bc	3024.3bc	849.0	3529.5
All-B	885.4	4242.2	957.8ab	3686.9bc	788.2	3187.5
All+K	1128.9	4386.7	828.1bc	2931.1bc	925.3	3673.6
NP	791.7	4658.9	979.2ab	3464.1bc	854.2	3262.2
50% All+K	688.8	2819.4	703.7c	2478.6c	675.3	2342.0
150% All+K	1096.4	4153.6	1151.6a	4861.7a	849.0	3588.5
CV (%)	27.8	30.02	25.1	31.3	21.8	31.1
p (0.05)	ns	ns	*	**	ns	ns

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

* Significant at 5%. ** Highly significant at 1%.

between 145.8 and 2678.6 kg ha^{-1} in the Machakel district (Table 8), whereas it ranged from 300.7 to 3942.5 kg ha^{-1} in the Gozamen district (Table 10).

The findings of our experiment showed that there was a significant difference ($p < 0.01$) in grain and biomass yield between the omitted nutrients, All+K, All, and NP, and the control treatment in the Gozamen district (Tables 10 and 11).

Bread wheat yield was varied from site to site due to the omission of macronutrient (K and S) treatments and micronutrients (Zn and B) in study areas (Figure 3). The highest grain yield difference from 1807 to 1939 kg ha^{-1} (negative 85%–89%) was obtained from no input treatment. The omission of K, S, and B nutrients did not significantly increase wheat yield from 5% to 15% (115–345 kg ha^{-1}), whereas the omission of Zn nutrient was increased by 3% (68 kg ha^{-1}) in the Gozamen district and decreased by −2% (35 kg ha^{-1}) in the Machakel district.

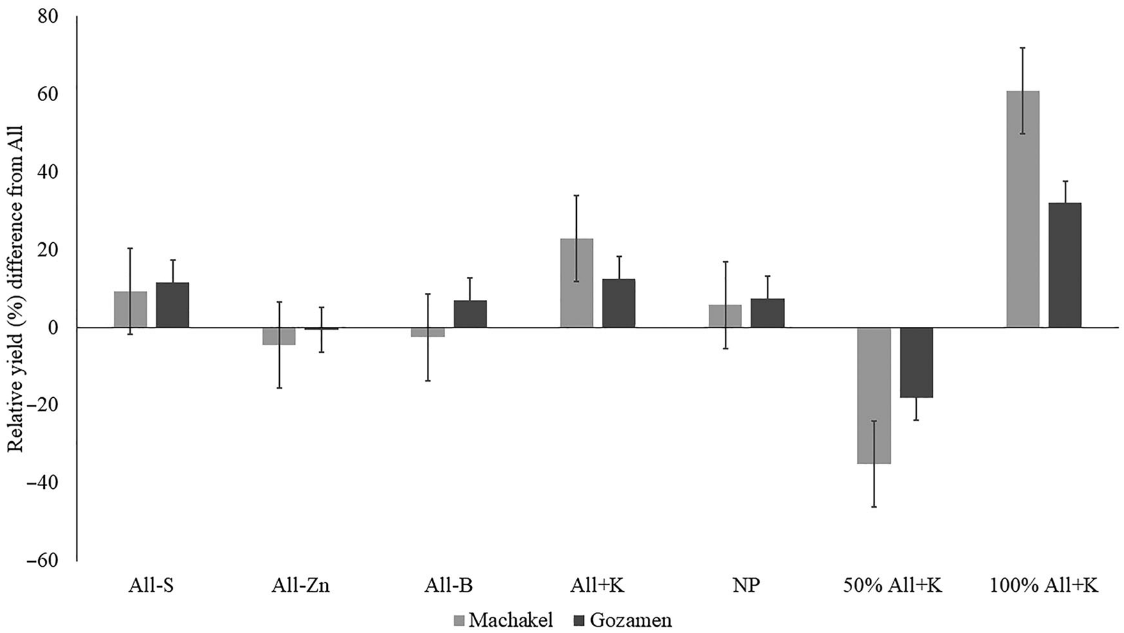

FIGURE 2 Tef yield difference from omitted nutrients relative to NPSZnB (All) applied treatments in Machakel and Gozamen districts. All-B, NPSZn; All+K, NPKSZnB; All-S, NPZnB; All-Zn; NPSB.

TABLE 8 Bread wheat grain and biomass yield from without lime-amended farm sites of three landscapes in the Machakel district.

	Landscape					
	Foot [2]		**Mid [3]**		**Hill [3]**	
Nutrient type	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Control	145.8	484.4	255.8d	1554.2d	261.0d	819.4
All	2106.7	4739.6	1863.5b	4437.5bc	1268.6bc	3641.7
All-S	2025.6	4614.6	2075.8b	4608.3bc	1484.4bc	4023.4
All-Zn	2187.5	4885.4	1782.3b	3875.0bc	1313.5bc	3630.2
All-B	2123.4	4687.5	2139.9b	3316.7c	1301.6bc	3893.0
All+K	2110.4	5057.3	1941.2b	4941.7ab	1692.9b	4592.2
NP	2069.4	4531.3	1868.7b	5175.0ab	1369.9bc	4083.3
50% All+K	1180.8	2541.7	1327.0c	3643.8bc	996.9c	3653.6
150% All+K	2678.9	6500.0	2641.6a	6330.4a	2261.9a	3942.7
CV (%)	13.2	17.3	15.7	26.2	24.3	35.1
p (0.05)	*	*	***	***	***	ns

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

*, *** Significant at 5% and 0.1%, respectively.

3.4 | Tef and bread wheat yield response to the nutrient type and rate across three landscape positions and lime amendment

The highest mean tef grain yields of 958 kg ha^{-1} were recorded with All nutrient's application at mid-slope landscape (Figure 4), while the lowest yield of 594 kg ha^{-1} was observed with All+K treatment at mid-slope landscape (Figure 4).

The combined analysis revealed that the mean tef yield highly significantly differed among nutrient types ($p < 0.001$), whereas a non-significant ($p > 0.05$) variation of tef yield was found from the interaction effect of nutrient types, lime amendment, and landscape positions (Table 12). The

TABLE 9 Bread wheat grain and biomass yield at previously lime-amended farm sites of three landscape positions in Machakel district.

	Landscape					
	Foot [2]		Mid [3]		Hill [3]	
Nutrient types	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Control	72.9	218.8	343.4d	819.4	333.7b	819.4
NPSZnB	1278.0	3036.5	2317.3b	3641.7	1864.4a	3641.7
NPZnB	1488.2	3395.8	2459.9ab	4023.4	2025.1a	4023.4
NPSB	1520.3	3474.0	2319.6b	3630.2	1828.4a	3630.2
NPSZn	1596.9	1958.3	2456.1ab	3893.0	1810.0a	3893.0
NPKSZnB	1750.7	3963.5	2495.5ab	4592.2	2030.3a	4592.2
NP	1636.6	3682.3	2394.8b	4083.3	1964.4a	4083.3
50% NPKSZnB	1073.2	2484.4	1696.3c	3653.6	1377.9a	3653.6
150% NPKSZnB	2653.6	6000.0	2955.5a	3942.7	1942.1a	3942.7
CV (%)	14.1	16.7	17.1	35.1	26.9	35.1
p (0.05)	*	*	***	ns	***	ns

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

*, *** Significant at 5% and 0.1%, respectively.

TABLE 10 Bread wheat grain and biomass yield without lime-amended farm sites of three landscapes in Gozamen district.

	Landscape					
	Foot [2]		Mid [6]		Hill [3]	
Nutrient type	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Control	220.9c	861.1c	265.0e	551.2c	329.2c	819.4
All	1814.2ab	4825.5ab	2510.8cd	5886.2a	1338.0b	3641.7
All-S	1937.3ab	4656.3ab	3441.2ab	6773.1a	1787.9ab	4023.4
All-Zn	1464.9b	4875.0ab	2825.5bc	5720.2a	2033.1ab	3630.2
All-B	1821.0ab	5112.0ab	3468.4ab	6601.3a	1991.9ab	3893.0
All+K	2325.0ab	5838.5a	3020.8abc	6561.0a	2223.7a	4592.2
NP	2238.3ab	5697.9a	2914.8bc	6639.9a	1740.0ab	4083.3
50% All+K	1630.1ab	3697.9b	2025.4d	4113.1b	1807.6ab	3653.6
150% All+K	2535.6a	6455.7a	3618.4a	7103.4a	2067.7ab	3942.7
CV (%)	34.1	23.7	21.2	20.2	28.4	35.1
p (0.05)	**	***	***	***	**	ns

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

, * Significant at 1% and 0.1%, respectively.

grain yield of tef significantly varied with lime amendment ($p < 0.01$) and landscape positions ($p < 0.05$) in the Machakel district (Table 12).

Likewise, the result for bread wheat indicated that a highly significant ($p < 0.001$) yield difference was observed among nutrient types and rates at landscape positions with lime amendment (Table 13). Maximum and significant biological grain and biomass yields were obtained from 150% of All+K applied nutrients in both districts.

The maximum grain yield (1026 and 942 kg ha^{-1}) and biomass (4246 and 3703 kg ha^{-1}) were observed from 150% of All+K treatment (Table 14). In Gozamen district, a non-significant grain yield variability was found between N and P, All+K, and 150% of All+K. A higher and significant

TABLE 11 Bread wheat grain and biomass yield at previously lime-amended farm sites of three landscape positions in Gozamen district.

	Landscape					
	Foot [2]		**Mid [6]**		**Hill [3]**	
Nutrient types	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Control	300.7b	916.7b	419.5d	1218.8d	566.6b	1222.2b
All	2112.9a	5099.0a	3126.6b	7283.6b	2536.7a	5644.1a
All-S	2437.2a	6059.9a	3081.3b	7030.7b	2965.2a	6982.6a
All-Zn	2364.8a	5904.9a	2924.8b	6877.3b	2295.9a	5191.0a
All-B	2418.4a	5346.4a	2945.4b	6588.0b	2704.5a	5704.9a
All+K	2066.8a	6615.9a	3270.2b	7071.8b	2570.3a	5362.8a
NP	2697.1a	5113.3a	3226.7b	7134.3b	2703.5a	6053.8a
50% All+K	1772.7a	4147.2a	2409.3c	4871.5c	2352.8a	5215.3a
150% All+K	2615.1a	6163.8a	3942.5a	8383.1a	2535.7a	5474.0a
CV (%)	26.3	28.8	17.1	15.9	18.0	19.2
p (0.05)	***	***	***	***	***	***

Note: All treatment contains NPSZnB nutrients. Numbers in brackets indicate the number of observations in each landscape. Lowercase letters show the significant difference between treatments.

Abbreviation: CV, coefficient of variation.

*** Significant at 0.1%.

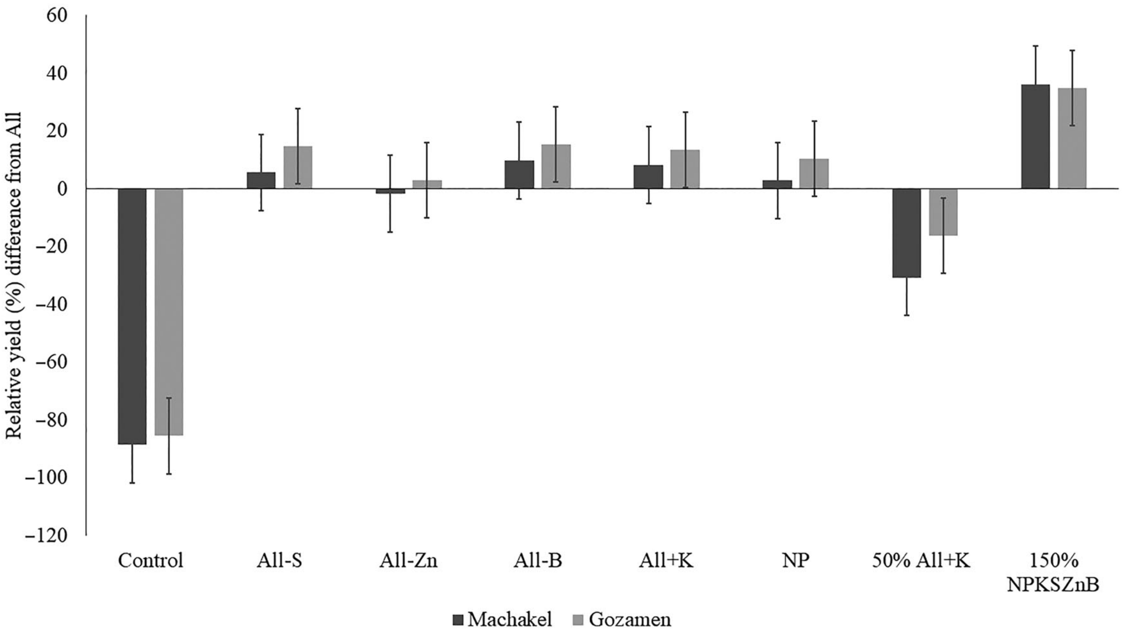

FIGURE 3 Effect of omissions of S, Zn, B and addition of K nutrients compared to NPSZnB (All) on bread wheat yield (%).

(758 kg ha^{-1}) grain yield was observed at the foot slope in the Machake district, whereas maximum and significant (950 kg ha^{-1}) grain yield was at the mid-slope in the Gozamen district.

The result indicated that lime amendment plus nutrient type and rate had a relatively higher yield of tef and bread wheat across all landscape positions in Machakel and Gozamen districts. Yield variability was observed across landscape positions within farmers' fields, with a range of 588–901 kg ha^{-1} (Table 15). A higher yield (2789 kg ha^{-1}) of bread wheat was obtained from the mid-landscape position. The maximum (2569 kg ha^{-1}) bread wheat yield was observed from lime-amended sites.

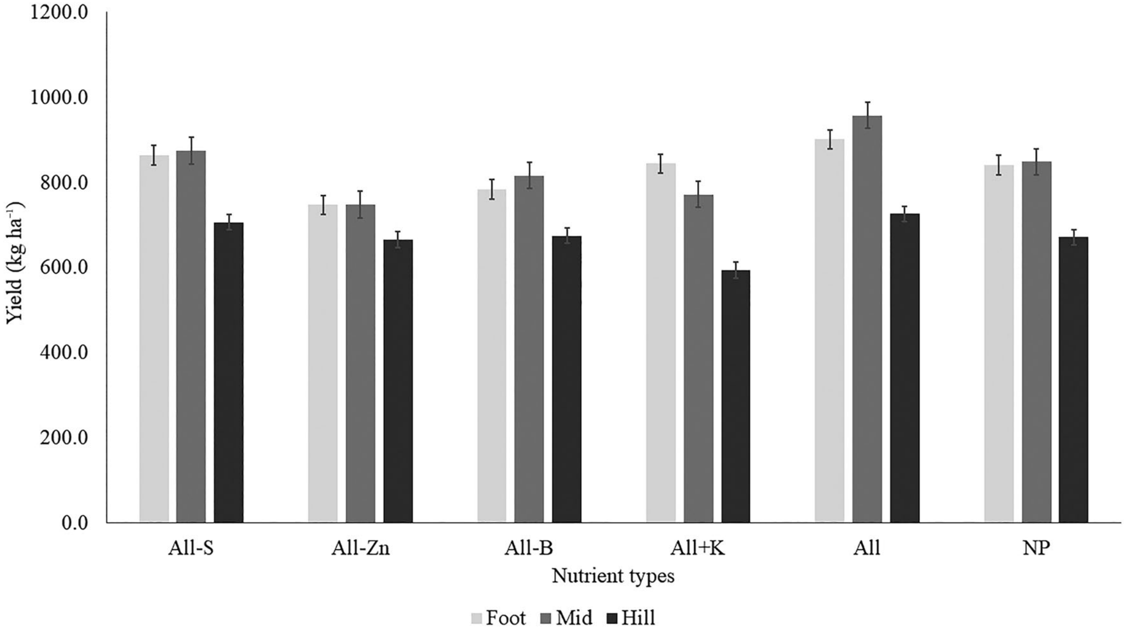

FIGURE 4 Tef yield response to applied nutrients across landscapes in the study area, NPZnB (All-S), NPSB (All-Zn), and NPSZn (All-B) nutrients represents omission of S, Zn, and B, whereas NPKSZnB (All+K) represents addition of K nutrient.

TABLE 12 Mean square value of different factors to tef in acidic soils of East Gojjam zone districts.

	Gozamen		Machakel	
Factors	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Nutrient types	0.09$^{\text{ns}}$	0.003**	1.6^{-11}***	2.2^{-16}***
Landscape	0.03*	0.7$^{\text{ns}}$	0.0001***	5.5^{-10}***
Amendment	0.9$^{\text{ns}}$	0.2$^{\text{ns}}$	0.003**	9.2^{-5}***
Nutrient types × landscape	1.0$^{\text{ns}}$	0.9$^{\text{ns}}$	1.0$^{\text{ns}}$	0.4$^{\text{ns}}$
Nutrient types × amendment	1.0$^{\text{ns}}$	0.9$^{\text{ns}}$	1.0$^{\text{ns}}$	0.9$^{\text{ns}}$
Landscape × amendment	0.02*	0.007**	1.9^{-5}***	2.2^{-5}***
Nutrient types × landscape × amendment	1.0$^{\text{ns}}$	1.0$^{\text{ns}}$	1.0$^{\text{ns}}$	0.9$^{\text{ns}}$

*, **, *** Significant at 5%, 1%, and 0.1%, respectively. ns, non-significant.

TABLE 13 Mean square value of bread wheat yield and biomass response across landscapes and lime amendment in acidic soils of study districts.

	Gozmen		Machakel	
Factors	**Grain yield**	**Biomass**	**Grain yield**	**Biomass**
Nutrient types	2.2^{-16}***	2.2^{-16}***	2.2^{-16}***	2.2^{-16}***
Landscape	3.3^{-14}***	4.3^{-13}***	3.4^{-8}***	1.4^{-6}***
Amendment	0.002**	4.5^{-6}***	0.0003***	0.0005***
Nutrient types × landscape	0.7$^{\text{ns}}$	0.8$^{\text{ns}}$	0.9$^{\text{ns}}$	1.0$^{\text{ns}}$
Nutrient types × amendment	0.7$^{\text{ns}}$	0.04*	0.9$^{\text{ns}}$	0.8$^{\text{ns}}$
Landscape × amendment	0.047*	1.0$^{\text{ns}}$	0.0002***	0.0001***
Nutrient types × landscape × amendment	0.9$^{\text{ns}}$	0.85$^{\text{ns}}$	0.9$^{\text{ns}}$	0.8$^{\text{ns}}$

Abbreviations: Amendment, lime management; CV, coefficient of variation; ns, non-significant.
*, **, *** Significant at 5%, 1%, and 0.1%, respectively.

TABLE 14 Combined tef and biomass yield response to nutrient types and rate across landscapes and lime amendment in acidic soils of East Gojjam zone districts.

Factors	Gozamen Grain yield	Gozamen Biomass	Machakel Grain yield	Machakel Biomass
Nutrient types				
All	868.1ab	3357.5bc	568.2c	1252.4d
All-S	935.2a	3652.6ab	651.5bc	2129.3bc
All-Zn	838.4ab	3090.6bc	585.4c	2178.0bc
All-B	896.6ab	3535.0ab	578.6c	2120.1bc
All+K	941.8a	3438.7b	738.2b	2058.2c
NP	916.3ab	3606.4ab	608.0bc	2557.8b
50% All+K	736.0b	2636.2c	384.0d	2170.0bc
150% All+K	1026.1a	4245.8a	942.2a	3703.1a
Landscape				
Foot	807.5b	3543.5	758.1a	2954.1a
Mid	949.5a	3488.5	562.2c	1967.0c
Hill	869.3ab	3385.6	656.3b	2309.7b
Amendment				
Lime	901.3	3553.5	588.3b	2091.0b
No lime	888.7	3326.0	684.4a	2487.2a
CV (%)	38.3	40.4	34.4	29.2

Note: All treatment contains NPSZnB nutrients. Lowercase letters show the significant difference between treatments.

Abbreviations: CV, coefficient of variation; ns, non-significant.

, * Significant at 1% and 0.1%, respectively.

TABLE 15 Overall bread wheat yield and biomass response to nutrient types and rate across landscapes and lime amendment in acidic soils of East Gojjam zone districts.

Factors	Gozmen Grain yield	Gozmen Biomass	Machakel Grain yield	Machakel Biomass
Nutrient types				
Control	351.8d	941.9c	267.5d	1067.5f
All	2399.5bc	5740.4a	1805.8b	4351.6cd
All-S	2753.7ab	6148.2a	1968.9b	4492.9cd
All-Zn	2465.8bc	5650.0a	1818.1b	4193.6cd
All-B	2704.1ab	5807.1a	1915.8b	3806.9de
All+K	2733.9ab	6059.3a	2021.7b	5274.3b
NP	2758.9ab	6316.2a	1891.7b	4706.2bc
50% All+K	2167.5c	4548.1b	1318.2c	3294.4e
150% All+K	2999.5a	6457.0a	2486.3a	6387.0a
Landscape				
Foot	1958.6b	4922.0b	1663.3b	3713.4b
Mid	2789.2a	6028.2b	1963.0a	4733.3a
Hill	2010.4b	4336.3c	1535.4b	3868.1b
Amendment				
Lime	2568.7a	5808.3a	1844.6a	4475.8a
No lime	2220.0b	4883.4b	1626.5b	3933.0b
CV (%)	32.9	27.7	28.8	30.6

Note: All treatment contains NPSZnB nutrients. Treatment: nutrient type and rate, amendment: lime management. Lowercase letters show the significant difference between treatments.

Abbreviation: CV, coefficient of variation; ns, non-significant.

, * Significant at 5% and 1%, respectively.

4 | DISCUSSION

4.1 | Soil properties of study sites

The soil pH (H_2O) of experimental sites has been shown to be strongly to moderately acidic in the study areas (Tadesse et al., 1991). Some sites on the hill and mid have higher exchangeable acidity, particularly in the Gozamen district. These observed values are above a critical level of exchangeable acidity. Thus, crop productivity is negatively affected by soil acidity in the study area (Demil et al., 2020). The causes of the soil acidity are the removal of crop residue and soil erosion due to higher rainfall. Low soil pH inhibits nutrient availability and soil health. Similarly, the lowest SOC from foot landscapes with lime-amended soils is a result of a complete harvest of crops and continuous tillage. This result is in agreement with many previous studies that reported that cropland had low SOC due to frequent tillage and removal of residue (Nega & Heluf, 2009; Tamene et al., 2017). The Av.P is ranked very low to low in the soils of the study area (Don & Richard, 2001). The low available soil P is associated with the fixation of P on acidic soils, crop residual removal, and nutrient depletion due to erosion (Aleminew & Alemayehu, 2020). The S content ranged from very low to very high across the study area (Don & Richard, 2001). This result shows that S is highly varied due to the landscape position that affects the soil fertility status of the area. About 46% of the experimental site nitisols showed Zn deficiency, where the figures revealed a lower critical level of 1.0 mg kg^{-1} as indicated by Lindsay and Norvell (1978). Another study by Abera and Kebede (2013) reported that Zn deficiency is observed in most of the vertisols of the Central Highlands of Ethiopia. Boron is mostly deficient in nitisols (Baissa et al., 2003).

4.2 | Tef yield response to applied nutrient types

The non-significant tef grain and biomass yield difference showed that the application of all nutrient types (K, S, Zn, and B) did not have a significant contribution to yield as compared to N and P nutrients. However, the result disagreed with Gessesew et al. (2022) and Chala et al. (2022), who described that applying higher rates of N, P, S, Zn, and B nutrients enhances crop yield. Only increasing the rate of All+K by 150% gave a higher biological yield than NP nutrients. Nevertheless, we are not sure whether the higher yield at 150% of All+K treatment comes from the increase of N and P nutrients or other added nutrients (K, S, Zn, and B). However, the result disagreed with Gessesew et al. (2022) and Chala et al. (2022) who described that applying higher rates of N, P, S, Zn, and B nutrients enhances crop yield.Tef grain yields varied from site to site in each district. The biomass yield showed a similar trend to the applied nutrient types and rates. The productivity of tef is very low, and even if it is not possible to harvest yield from those plots without fertilizer in the acidic soils of highland areas. The possible explanation could be connected to the depletion of N soil reserves in agricultural soils (Mesfin et al., 2020).This tells us that it is difficult to produce tef under the current farming system without nutrient application. Combined application of both N and P nutrients increased tef yield across all sites. Pre-planting soil analysis also revealed that the inherent soil supply is deficient in N and P nutrients. This limitation in plant growth and productivity can be attributed to the availability of nitrogen and/or phosphorus (Guignard et al., 2017). The study conducted by Kolawole et al. (2018) similarly revealed that without N and P, nutrients led to the most significant reduction in yield. Thus, N and P nutrients are yield limiting nutrients for tef. The application of these fertilizers with other soil amendment practices is mandatory to improve productivity (Guignard et al., 2017).

The omitted treatments did not show a significant yield difference in both previously lime-amended and not-amended trial sites. The omission of sulfur (All-S) led to a reduction in yield compared to the applications of N, P, K, S, Zn, and B nutrients in mid and hill-landscape positions in previously lime-amended sites, but this reduction was not significantly varied in each district. This result is consistent with earlier research showing that adding K, S, Zn, and B did not substantially boost crop yield in the major tef-growing regions of Ethiopia (Amare et al., 2018, 2019). It had a similar trend in the K-omitted treatment that shows no significant decline in yield in the foot and mid-landscape. Contrary to our findings, applying K nutrient improves the grain and biomass yield of tef on vertisols in Central Highland of Ethiopia (Demiss et al., 2020). Similarly, the trends of crop response results matched the inherent soil supply capacity, that is, soil can supply relatively enough of those nutrients to produce tef in the study area.

As mentioned in different studies, the addition of B had a beneficial impact on tef growth. The research conducted by Asefa et al. (2014) suggests that using fertilizer enriched with boron could increase tef grain yield. Correspondingly, the additional application of Zn with blended NPSZn improved tef grain yield on Vertic Cambisols (Haileselassie et al., 2018). Even though the omission of B also declined the tef grain yield in mid-landscape, both without lime application and lime-amended sites in the Gozamen district. It did not significantly differ from NP nutrients. From this result, we can infer that K, S, Zn, and B are not yield-limiting for tef in the study area. This finding is supported by Alemayehu et al. (2022), who stated that the yield of tef is not maximized due to the application of K, S, Zn, and B nutrients.

4.3 | Response of bread wheat to applied fertilizer

A highly significant yield of bread wheat was obtained due to the application of nutrients compared to no input at all (control). Higher rates and All+K received treatments gave the maximum yield but not significantly varied as compared to N and P nutrients. Grain and biomass yield variability were observed among the experimental sites. Generally, a higher and more significant yield was recorded when 150% of the All+K treatment is applied. However, the relatively equal biological yield of bread wheat was obtained from the N and P nutrients applied. So, the application of N and P nutrients alone had a yield advantage for smallholder farmers in highland areas. This finding is confirmed by Kolawole et al. (2018), who stated that N and P are critical nutrients for cereal crop production. This finding also agreed with Rawal et al. (2018), who reported that N and P are found to be the most limiting nutrients for wheat production. The main reason for soil N deficiency is directly linked to low N use efficiency of cereals, which accounts for about 33% globally (Peter et al., 2019). Similarly, low P reserves in the soil and P fixation in problematic soils are major drivers of P insufficiency in most agricultural soils (Nziguheba et al., 2015). The yield response of crops is connected with soil test results, mainly for N and P, which are very low in soils of the study sites.

The non-significant variability of yield was noticed among trial sites due to the omission of macronutrients (K and S) and micronutrients (Zn and B) treatments in study areas. This shows that without K, S, Zn, or B nutrients, the yields of bread wheat may not decline. This result is supported by Nziguheba et al. (2009), who indicate that K and B omissions do not reduce cereal crop yield. This finding is harmonized with Amare et al. (2018, 2019), which indicates that the addition of K does not increase crop yield significantly in most bread wheat-growing areas of Ethiopia. In the Machakel district, the omission of Zn exhibited a negative effect on yield in hill landscapes. This finding, however, contradicts that of Kihara et al. (2022), who stated that micronutrients are required to increase wheat output. The results of crop response and pre-planting soil samples directly exhibited a similar trend, in which most of the trial sites are not deficient in micronutrients.

Yield variability was observed across landscape positions and experimental sites. A higher yield of bread wheat was obtained from the mid-landscape position. This finding was contrary to Amede et al. (2020), who stated higher yields are observed in foot landscapes due to relatively improved soil fertility on the lower slopes. The rate of nutrient application shall be varied across landscape positions. Because when the slope is increased, there is a decrease in crop yield (Amede et al., 2020). It might be related to the decline of soil fertility along the slope gradient.

The application of lime brings a yield advantage in some trial sites. This might be associated with the lime application having a positive contribution to improving soil health and enhancing grain yield. However, the lower blanket rate of lime did not significantly increase yields. The availability of soil nutrients is fixed by Al^{3+} and H^{+}. Our finding agreed with Demil et al. (2020) who showed that liming with the recommended rate of NP fertilizer significantly increased wheat yield in acidic soils of Machakel district. The lime amendment had also reclaimed the soil pH, which increased the nutrient availability to the grown crops.

5 | CONCLUSION AND RECOMMENDATIONS

The application of different nutrient types and rates had a significant effect on the grain and biomass yield of tef and bread wheat in the study areas. Blanket previous lime amendment had not significantly affected the yield of test crops. Tef yield could not be obtained without nutrient application in the study area. The application of six nutrient types (N, P, K, S, Zn, and B) did not offer any significant yield advantage compared to both N and P nutrients. This indicates that N and P are the most yield-limiting nutrients compared to other nutrients in acidic soils along the landscape of the Machakel and Gozamen districts. On the other hand, the application of K, S, Zn, and B nutrients was not reduced yield of bread wheat and tef. Therefore, it is suggested to refine the rates of N and P nutrients in acidic soils along the landscape for the sustainable use of inorganic fertilizers. Future studies should focus on ways to fine-tune crop response to micronutrient elements' limitations for grain yield and nutritional quality analysis to meet the demand for nutritious food.

AUTHOR CONTRIBUTIONS

Zerfu Bazie: Data curation; formal analysis; methodology; software; supervision; visualization; writing—original draft; writing—review and editing. **Tadele Amare**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing. **Erkihun Alemu**: Data curation; methodology; supervision; validation; visualization. **Getachew Agegnew**: Data curation; methodology. **Gizaw Desta**: Data curation; methodology. **Abere Tenagne**: Data curation; methodology; supervision. **Bitewlgn Kerebh**: Data curation; methodology; supervision. **Atakltie Abebe**: Data curation; methodology; supervision; validation. **Abrham Awoke**: Data curation; methodology; supervision. **Zmie Ambaw**: Data curation; methodology; supervision. **Tesfaye Feyisa**: Conceptualization; methodology; project administration; supervision. **Zelalem Adise**: Data curation. **Sefinew Wale**: Data curation; methodology; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The corresponding author can provide the data that were utilized to support the study's conclusions upon request.

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