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# Yield-limiting nutrients for wheat (*Triticum aestivum* L.) production in Farta to Lay Gayint districts of the Amhara Region in Northwest Ethiopia

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Wheat (*Triticum aestivum* L.) is the third most important crop in Ethiopia yet its productivity in the country remains significantly below experimental yields and water-limited yield potential due to soil fertility variability and the absence of site-specific fertilizer recommendations. To identify yield-limiting nutrients and support the development of a precision fertilizer recommendation tool, a nutrient omission study was conducted in the 2021 main cropping season across eight sites in the South Gondar Zone of Northwestern Ethiopia. The study evaluated eight treatments: (1) NF (NPKSZnB), (2) -B, (3) -Zn, (4) -S, (5) -K, (6) -P, (7) -N, and (8) F0, with nutrients applied at 138 kg N, 46 kg P<sub>2</sub>O<sub>5</sub>, 60 kg K<sub>2</sub>O, 10.5 kg S, 5 kg Zn, and 1 kg B ha<sup>-1</sup>. Results indicated that N omission significantly reduced wheat yield and yield-related traits across all sites, while P limitation was significant in 50% of the locations. The average yield response to N application was 2071.9 kg ha<sup>-1</sup> (ranging from 847.2 to 2873.6 kg ha<sup>-1</sup>), followed by P, with a mean response of 499.1 kg ha<sup>-1</sup> (16.6–850.8 kg ha<sup>-1</sup>). Soil indigenous nutrient supply (SINS) assessments revealed that N was only 45.0% sufficient, whereas P sufficiency was higher (87.0%). Potassium (K), sulfur (S), zinc (Zn), and boron (B) were found to be non-limiting, with soil supplies exceeding 90%. Yield gaps due to N and P omission averaged 53.9% and 11.9%, respectively, while omissions of K, S, Zn, and B had negligible effects. Agronomic efficiency was highest for P (22.2 kg kg<sup>-1</sup>), followed by N (13.1 kg kg<sup>-1</sup>) and K (5.2 kg kg<sup>-1</sup>). These findings demonstrate that N is the primary yield-limiting nutrient in the study area, with P being secondary in half of the evaluated farms. To enhance wheat productivity and minimize yield gaps, site-specific fertilizer recommendations emphasizing optimized N and P application are critical. The study was conducted for one season, and hence multi-year experiments to address season variation on the effect of the nutrient omission treatments is recommended.

## KEYWORDS

site-specific, yield gap, yield-limiting nutrient, yield response, wheat

# 1 Introduction

With an annual production of 5.78 million metric tons (Mt) cultivated across 1.9 million hectares, Ethiopia stands as Africa's second-largest wheat (*Triticum aestivum* L.) producer after Egypt (FAOSTAT, 2020; CSA, 2022). As the nation's third most economically significant cereal crop following teff (*Eragrostis tef*) and maize (*Zea mays* L.), wheat production engages approximately 4.9 million smallholder farmers, predominantly under rain-fed conditions, accounting for 12.2% of the country's total harvested cropland (CSA, 2022). Recent agricultural intensification efforts, particularly government-sponsored irrigation schemes, have expanded cultivation to 2.6 million hectares with concomitant production increases to 8.2 Mt (Effa et al., 2023). Nevertheless, persistent yield limitations are evident, as current average productivity (3.05 t ha<sup>-1</sup>) represents just 61% of experimental yields (5.0 t ha<sup>-1</sup>) and a mere 36.3% of the estimated water-limited yield potential (8.4 t ha<sup>-1</sup>), underscoring substantial untapped production capacity within existing agroecological systems (Abdulkadir et al., 2016; [www.yieldgap.org](http://www.yieldgap.org)).

The persistent yield gap in Ethiopian wheat production systems necessitates a comprehensive understanding of its underlying drivers to inform targeted policy interventions and strategic investments. Current evidence identifies technological constraints as the primary limiting factors, particularly: (1) inadequate access to and inefficient use of mineral fertilizers, (2) limited availability of improved seed varieties, and (3) suboptimal pest and disease management practices (Yirga et al., 2002; Silva et al., 2021). These challenges are exacerbated by the predominant rain-fed production systems characterized by low-input use (Anteneh and Asrat, 2020), with national fertilizer application rates averaging just 40 kg ha<sup>-1</sup> - among the lowest in Africa and substantially below recommended levels of 64 kg N and 20 kg P ha<sup>-1</sup> (IFDC, 2015). Current fertilizer recommendation systems demonstrate significant limitations, being both spatially fragmented (Gorfu et al., 1991) and temporally inconsistent. These 'blanket' recommendations fail to account for substantial spatial and temporal variability in soil fertility (Stoorvogel et al., 1993; Tadesse et al., 2019; Sileshi et al., 2022) and differential access to nutrient resources among farms (Sanchez, 2002). Consequently, fertilizer application often results in either suboptimal or excessive use, leading to inconsistent yield responses (Erkossa et al., 2022; Abera et al., 2023). To address these limitations, the development of precision-based, site-specific fertilizer recommendations through advanced decision support tools (DSTs) is imperative. Nutrient omission trials (NOTs) serve as a critical methodological approach in this context, generating essential empirical data on soil nutrient dynamics. The present

study was specifically designed to contribute to national efforts in precision agriculture by: (1) identifying key yield-limiting nutrients, (2) quantifying existing yield gaps, and (3) determining indigenous soil nutrient supply capacities. These objectives collectively aim to establish a robust foundation for the development of an optimized DST that can enhance wheat productivity through tailored nutrient management strategies.

# 2 Materials and methods

## 2.1 Study area description

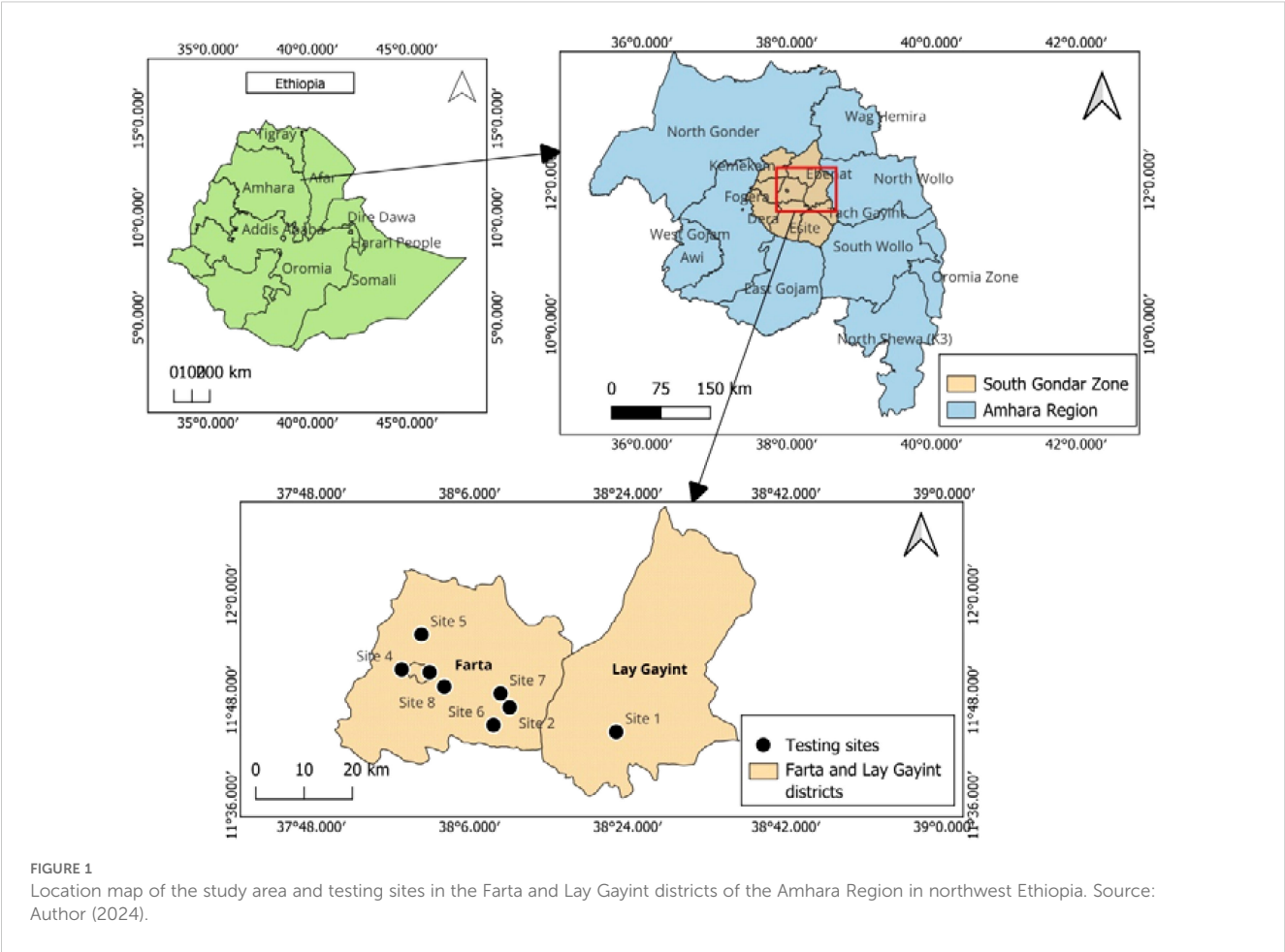
The research was conducted during the 2021 main cropping season (June-September) across eight farmers' fields distributed in seven kebeles (the smallest administrative units in Ethiopia) within Farta and Lay Gayint districts of South Gondar Zone, Amhara Region, northwestern Ethiopia (Figure 1, Table 1). The study area encompasses a topographically diverse landscape comprising highland plateaus (>3,000 m asl), deep valleys, and rolling hills with elevations ranging from approximately 2,300 to 3,200 meters above sea level (Tefera et al., 2019).

Climatically, the region is classified as "Woyna Dega" (mid-altitude; 1,500-2,300 m asl) to "Dega" (high-altitude; 2,300-3,200 m asl) agroecological zones (Taye, 2017). Meteorological data obtained from the Ethiopian Meteorological Agency (Northwestern Region, Bahir Dar) indicate a mean annual precipitation range of 1,300-1,900 mm, with mean monthly temperatures varying between 9.4°C (minimum) and 23.1°C (maximum) (Figure 2). The soils in the study area are predominantly Leptosols, Luvisols and Cambisols (Abayneh, 2017, unpublished data; Beyene et al., 2023; Sisay et al., 2023, preprint). These soil types present distinct agronomic constraints and management requirements that influence local cropping patterns. The predominant cropping system features a cereal-legume rotation dominated by bread wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), teff (*Eragrostis tef* L.), and maize (*Zea mays* L.), intercropped with or rotated with faba beans (*Vicia faba* L.) and field peas (*Pisum sativum* L.) (Alemayehu et al., 2019). This diversified cropping system operates within an integrated crop-livestock production framework, where smallholder farmers strategically combine agricultural and animal husbandry activities to optimize resource use efficiency, manage risk, and sustain household food security (Tadesse and Solomon, 2018).

## 2.2 Experimental set up

The study employed a randomized complete block design (RCBD) with three replications to evaluate the full nutrient treatment (NPKSZnB) against various nutrient omission treatments (Table 2). The selection of nutrient types was based on a soil fertility map specific to the study area (EthioSIS, 2014). The nutrient rates were adapted from existing research recommendations for wheat in the study area and from regions with similar agro-ecological conditions. Individual experimental

**Abbreviations:** ANOVA, Analysis of Variance; AE, Agronomic use efficiency; AEN, Agronomic use efficiency of nitrogen; AEP, Agronomic use efficiency of phosphorus; AEK, Agronomic use efficiency of potassium; CSA, Central Statistics Agency of Ethiopia; DST, Decision Support Tool; DMRT, Duncan's Multiple Range Test; FAO, Food and Agricultural Organization; NOTs, Nutrient Omission Trials; SAS, Statistical Analysis Software; SINS, Soil Indigenous Nutrient Supply.



plots consisted of a gross area of 12 m<sup>2</sup> (4 m × 3 m) with a net harvestable area of 10.8 m<sup>2</sup> (3.6 m × 3.0 m), separated by 1 m buffer zones between plots and blocks. The widely cultivated bread wheat (*Triticum aestivum* L.) cultivar ‘Tay’ was selected for the study based on its regional adaptation and farmer preference. Seeds were drill-sown at a rate of 150 kg ha<sup>-1</sup> with 20 cm inter-row spacing. Nutrient applications followed standardized protocols: phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B) were applied in full as basal dressings at planting, while nitrogen (N) was split-

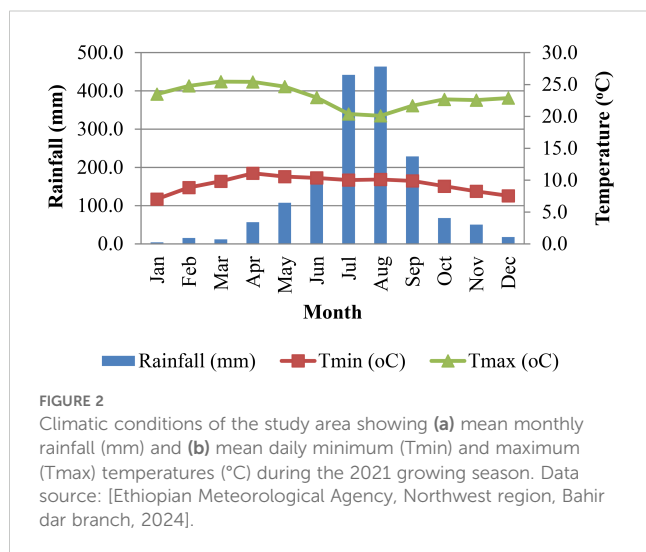
applied (50% at planting and 50% side-dressed at 40 days after sowing).

All experimental plots received uniform agronomic management throughout the growing season to ensure consistency in cultivation practices and minimize confounding variables. Standardized protocols were implemented for land preparation, planting, weed control, and other crop management interventions. The following fertilizers were utilized as nutrient sources in the study: urea (CO(NH<sub>2</sub>)<sub>2</sub>) for N, triple superphosphate

TABLE 1 Geographic location of experimental sites in Farta and Lay Gayint districts, showing GPS coordinates (latitude, longitude), and elevation.

Testing site	District	Kebele	Longitude (E)	Latitude (N)	Altitude (m a.s.l)*
Site 1	Lay Gayint	Gob gob	38.37831	11.73969	3046
Site 2	Farta	Ata	38.17633	11.78597	2855
Site 3	Farta	Selamko	38.02450	11.85248	2592
Site 4	Farta	Tsegur	37.97153	11.85775	2632
Site 5	Farta	Kolay	38.00894	11.92469	2444
Site 6	Farta	Awuzet	38.14556	11.75256	3046
Site 7	Farta	Ata	38.15897	11.81231	2797
Site 8	Farta	Kanat	38.05231	11.82528	2597

\*m a.s.l, Meters above sea level.



( $\text{Ca}(\text{H}_2\text{PO}_4)_2$ ) for P, potassium chloride (KCl) for K, calcium sulfate ( $\text{CaSO}_4$ ) for S, zinc sulfate ( $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ ) for Zn, and borax ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) for B.

## 2.3 Soil sampling and analysis

Prior to planting, representative composite soil samples were obtained from each experimental field by combining five spatially distributed subsamples collected from a 0–20 cm depth using a standardized soil auger. Following collection, samples were air-dried, ground mechanically, and sieved through a 2-mm mesh to ensure particle size uniformity. Soil analyses were conducted at Bahir Dar Design and Supervision Works Authority laboratory, following standard soil testing methods to determine selected soil chemical properties including: soil pH (1:2.5 soil: water suspension), total nitrogen (micro-Kjeldahl digestion), available phosphorus (Olsen extraction), exchangeable potassium (ammonium acetate extraction), available boron (hot water extraction), and DTPA-extractable zinc.

**TABLE 2** Nutrient application treatments and rates ( $\text{kg ha}^{-1}$ ) used in the wheat fertilization study, including: (i) Full fertilization ( $\text{N}_F$ ), (ii) individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and (iii) zero-fertilization control ( $\text{F}_0$ ).

No.	Treatment	N	$\text{P}_2\text{O}_5$	$\text{K}_2\text{O}$	S	Zn	B
1	NPKSZnB ( $\text{N}_F$ )	138	46	60	10.5	5	1
2	NPKSZn (-B)	138	46	60	10.5	5	–
3	NPKSB (-Zn)	138	46	60	10.5	–	1
4	NPKZnB (-S)	138	46	60	–	5	1
5	NPSZnB (-K)	138	46	–	10.5	5	1
6	NKSZnB (-P)	138	–	60	10.5	5	1
7	PKSZnB (-N)	–	46	60	10.5	5	1
8	Zero fertilizer ( $\text{F}_0$ )	–	–	–	–	–	–

## 2.4 Data collection

All plant measurements were conducted using standardized protocols on the net plot area of  $10.8 \text{ m}^2$  ( $3.6 \text{ m} \times 3.0 \text{ m}$ ), excluding border rows from both ends of each plot to eliminate edge effects. The following parameters were systematically recorded:

Plant height: was measured from soil surface to spike tip (excluding awns) for 10 randomly selected plants per plot using a graduated meter stick.

Spike length: was determined from spike base to tip (excluding awns) for 10 randomly sampled spikes per plot.

Seeds per spike: was calculated as the mean value from manual seed counts of 10 randomly selected spikes.

Aboveground biomass: Total sun-dried biomass from the harvest area was weighed using a suspension balance.

Grain yield: was measured using a precision balance ( $0.1 \text{ g}$  accuracy) after threshing and adjusted to 12.5% moisture content.

Thousand seed weight: was determined by weighing 1000 randomly selected, disease-free seeds using an analytical balance, with moisture content similarly adjusted to 12.5%.

## 2.5 Statistical analysis and data interpretation

The experimental data were analyzed using one-way ANOVA in SAS version 9.2 (SAS/STAT Software, 2008) at a significance level of  $\alpha = 0.05$ , with nutrient omission treatments as fixed effects. Assumptions of normality were verified using different normality test methods including Shapiro-Wilk test. Where ANOVA indicated significant differences ( $p < 0.05$ ), treatment means were separated using Duncan's Multiple Range Test (DMRT). Data are presented as treatment means  $\pm$  standard error (SE) of three replicates ( $n = 3$ ). Graphical outputs were generated in Microsoft Excel (version 2016).

### 2.5.1 Yield response

Yield response (YR) to a nutrient serves as a direct and practical indicator of inherent soil fertility. It quantifies the difference between the attainable yield (the yield obtained from non-nutrient limited yield i.e. the yield from full nutrient supplied treatment) and the yield from the nutrient omission plots. This metric reflects the extent to which crop productivity is constrained by the deficiency of a specific nutrient, while also providing insight into the indigenous soil nutrient supply (Dobermann et al., 2003; Xu et al., 2014).

The yield response for each nutrient was computed using Equation 1:

$$\text{YR} = \text{Y}_{\text{NF}} - \text{Y}_{\text{no}} \quad (1)$$

where YR stands for yield response to a nutrient in  $\text{kg ha}^{-1}$ ,  $\text{Y}_{\text{NF}}$  is the attainable yield, the grain yield ( $\text{kg ha}^{-1}$ ) from the full nutrient (NPKSZnB) supplied treatment and  $\text{Y}_{\text{no}}$  is the grain yield ( $\text{kg ha}^{-1}$ ) from the nutrient omitted treatment.

## 2.5.2 Agronomic use efficiency of N, P and K

Agronomic use efficiency of N (AEN), P (AEP), and K (AEK) were calculated to quantify the yield increase per unit of applied nutrient, following the methodology established by Craswell and Godwin (1984) and Mengel and Kirkby (1996). These efficiency indices were determined using the following equations (Equations 2–4):

$$AEN \text{ (kg/kg)} = \frac{YNF - YNo}{N} \quad (2)$$

$$AEP \text{ (kg/kg)} = \frac{YNF - YPo}{P} \quad (3)$$

$$AEK \text{ (kg/kg)} = \frac{YNF - YKo}{K} \quad (4)$$

Where  $Y_{No}$ ,  $Y_{Po}$ , and  $Y_{Ko}$  are the yield obtained from the N-omitted, P-omitted and K-omitted treatments, respectively and N, P, K are the amount of N, P, and K applied in  $\text{kg ha}^{-1}$  in the full nutrient-supplied treatment.

## 2.5.3 Yield gap

The yield gap, expressed as a percentage, was calculated to assess the production losses attributable to the omission of individual nutrients. The following formula (Equation 5) was used to calculate the yield gaps due to the omission of each nutrient:

$$\text{Yield gap (\%)} = \frac{YNF - Yno}{YNF} \times 100 \quad (5)$$

## 2.5.4 The indigenous soil nutrient supply

The indigenous soil nutrient supply serves as a critical indicator of inherent soil fertility and provides a scientific basis for developing fertilizer recommendations. This parameter reflects the soil's natural capacity to provide essential nutrients for crop growth. Following established methodologies (Xu et al., 2014), we quantified the indigenous nutrient supply through relative yield calculations, where higher values indicate greater native soil fertility.

The relative yield, representing the soil's indigenous nutrient-supplying capacity, was calculated as follows (Equation 6):

$$\text{Relative yield (\%)} = \left( \frac{Yno}{YNF} \right) \times 100 \quad (6)$$

# 3 Results

## 3.1 Initial soil properties of the testing sites

The soil analysis results (Table 3) indicated a moderately to slightly acidic pH range (5.3–6.4) across the sampling sites (Jones, 2003). Total nitrogen (N) content (0.15–0.18%) was within the medium range, while plant-available phosphorus (P) exhibited substantial spatial variability (6.4–36.8  $\text{mg kg}^{-1}$ ), ranging from low to high (Hazelton and Murphy, 2007). Exchangeable potassium (K) levels (0.58–2.56  $\text{cmolC}_{(+)}$   $\text{kg}^{-1}$ ) were classified as high (FAO, 2006), whereas micronutrient analysis revealed available boron (B) concentrations spanning insufficient to adequate and extractable zinc (Zn) levels within the medium-to-high range (Jones, 2003). Additionally, available sulfur (S) content (4.2–5.5  $\text{mg kg}^{-1}$ ) was categorized as medium (Landon, 1991).

## 3.2 Growth and yield attributes

The -N and  $F_0$  treatments significantly reduced plant height, spike length, and seed number per spike across most sites (Tables 4–6), though thousand seed weight remained unaffected (Table 7). While -P and -K treatments only impacted plant height at 25% (Sites 5 and 8) and 12.5% (Site 8) of sites, respectively, the most severe growth reductions occurred under  $F_0$  (73.0 cm) and -N (81.1 cm) treatments. In contrast, the -Zn treatment produced the tallest plants (103.1 cm), comparable to  $N_F$ . Spike morphology followed similar trends:  $F_0$  and -N treatments yielded the shortest spikes (7.1–7.5 cm) and fewest seeds (35–42.4), whereas  $N_F$  produced the longest spikes (9.2 cm) and -K (statistically similar to  $N_F$ ) the highest seed number (52.9). Notably,  $N_F$  outperformed -N by 18.7% in spike length and 15.2% in seed number. No significant effects of -P, -K, -S, -Zn, or -B were observed for spike traits across sites.

TABLE 3 Mean soil chemical properties (0–20 cm depth) across eight experimental sites in Farta and Lay Gayint districts in 2022 cropping season.

Site	pH (H <sub>2</sub> O)	Available P (mg kg <sup>-1</sup> )	Available S (SO <sub>4</sub> <sup>2-</sup> ) (mg kg <sup>-1</sup> )	Available B (mg kg <sup>-1</sup> )	Total N (%)	Extractable Zn (mg kg <sup>-1</sup> )	Exchangeable K (Cmol <sub>c</sub> kg <sup>-1</sup> )
Site 1	5.8	11.2	4.9	0.76	0.18	1.31	0.92
Site 2	6.4	18.8	4.2	1.04	0.17	1.63	2.56
Site 3	6.2	36.8	5.5	1.35	0.16	0.67	1.03
Site 4	5.3	8.4	4.2	0.95	0.15	0.35	0.58
Site 5	5.7	6.4	4.2	1.14	0.18	0.58	1.24
Site 6	5.8	16.4	4.9	0.67	0.16	0.80	0.64
Site 7	6.0	20.0	4.2	1.27	0.17	1.15	0.93
Site 8	Nd	Nd	Nd	Nd	Nd	Nd	Nd

Nd, Not determined.

TABLE 4 Treatment effects on wheat plant height (cm) across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	112.6a	108.8ab	99.9a	94.9a	108.4a	100.1a	104.9a	78.3a
-B	111.3a	108.8ab	99.5a	94.7a	106.2a	98.1a	106.0a	78.9a
-Zn	113.7a	115.9a	97.1a	101.8a	111.1a	100.6a	107.5a	77.4a
-S	105.2a	121.4a	98.9a	92.0a	108.3a	99.0a	102.5ab	78.9a
-K	110.2a	106.7ab	97.5a	94.7a	107.9a	94.5a	104.1a	68.6b
-P	108.4a	104.1ab	95.7a	89.7a	99.7b	91.8a	99.3abc	68.2b
-N	75.9b	97.3b	84.9b	74.7b	84.0c	77.0b	89.5bc	65.4b
F <sub>0</sub>	72.7b	79.4c	76.3b	66.3b	78.8d	67.0b	87.1c	56.6c
Mean	101.3	105.7	93.7	88.6	100.5	92.9	100.1	71.5
CV (%)	7.7	8.0	6.2	7.7	2.9	4.8	7.2	4.9
SEM	7.85	8.5	5.8	6.8	2.9	4.5	7.6	3.5
P value	<.0001	0.020	0.002	<.0003	<.0001	<.0001	0.04	<.0001

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).

\*Treatments within a column followed by the same letter are not significantly different at  $p \geq 0.05$ . SEM, Standard error of the mean.

### 3.3 Grain yield and dry biomass

All testing sites showed significant ( $p < 0.05$ ) treatment effects on grain yield and dry biomass (Tables 8, 9). The -N and F<sub>0</sub> treatments consistently and significantly reduced both parameters across all sites, with -N causing average yield and biomass losses of 56.5% and 56.9%, respectively, relative to N<sub>F</sub>. While the -P treatment significantly affected yield and biomass in 50% of sites (mean reduction: 13.6%), -K effects were limited to a single site. No significant impacts ( $p > 0.05$ ) were observed for -S, -Zn, or -B treatments in any location.

### 3.4 Yield response

The -N and F<sub>0</sub> treatments demonstrated the most substantial and consistent yield reductions across all experimental sites (Table 10, Figure 3). Nitrogen omission (-N) resulted in yield responses ranging from 847 to 2,874 kg ha<sup>-1</sup> (mean = 2,072 kg ha<sup>-1</sup>). Phosphorus omission (-P) effects were more variable, with yield responses ranging from 17 to 851 kg ha<sup>-1</sup> (mean = 499 kg ha<sup>-1</sup>). Potassium omission showed particularly wide variation, yielding responses between -524 and 557 kg ha<sup>-1</sup> (mean = 261.7 kg ha<sup>-1</sup>). Negative mean yield responses to -S, -Zn, and -B treatments at most sites

TABLE 5 Treatment effects on wheat spike length (cm) across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	9.4a	9.3	10.2a	7.9	9.6a	9.3a	10.1bc	8.1a
-B	10.0a	8.9	9.5ab	7.9	9.5a	8.5a	11.5a	7.6ab
-Zn	9.1a	9.1	9.4ab	8.7	9.5a	9.1a	11.1ab	7.3bc
-S	9.7a	9.1	9.8ab	7.5	9.6a	9.1a	11.7a	7.7ab
-K	9.2a	9.1	9.3ab	8.3	9.3a	8.9a	10.6abc	7.5ab
-P	9.1a	9.3	9.3ab	7.7	9.1ab	9.2a	11.5ab	7.7ab
-N	5.5b	8.3	8.2bc	7.5	8.1bc	6.1b	9.7c	6.7cd
F <sub>0</sub>	5.4b	7.9	7.5c	6.6	7.4c	5.8b	9.7c	6.1d
Mean	8.4	8.9	9.1	7.8	9.0	8.4	10.7	7.3
CV (%)	6.5	9.3	9.7	8.4	6.4	5.1	6.9	5.5
SEM	0.55	0.82	0.88	0.65	0.57	0.43	0.74	0.40
P value	<.0001	0.0391	0.038	0.06	0.002	<.0001	0.02	0.001

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).

\*Treatments within a column followed by the same letter are not significantly different at  $p \geq 0.05$ . SEM, Standard error of the mean.

TABLE 6 Treatment effects on wheat seed number per spike across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	46.8b	57.5	62.4a	52.8a	60.1a	44.2a	49.1	43.7ab
-B	45.0bc	43.7	62.1a	50.4a	62.4a	43.8a	46.0	40.6ab
-Zn	57.1a	45.9	50.0b	43.2ab	63.3a	49.3a	48.7	45.5a
-S	57.5a	41.5	53.7ab	48.9a	58.8a	50.7a	43.8	34.1cd
-K	60.1a	53.7	54.5ab	54.1a	63.1a	48.3a	51.9	37.9bc
-P	53.2ab	49.0	55.4ab	45.5a	61.0a	46.3a	43.8	31.7cde
-N	50.8ab	54.6	48.1b	43.5ab	45.5b	26.8b	39.8	30.1de
F <sub>0</sub>	36.5c	44.3	33.9c	33.3b	41.1b	29.4b	34.2	27.2e
Mean	52.0	48.0	52.5	46.5	56.9	45.2	45.4	36.3
CV (%)	9.1	10.5	11.0	13.8	12.8	13.1	10.9	9.5
SEM	4.73	5.03	5.80	6.4	7.3	5.9	5.0	3.4
P value	0.020	0.063	0.001	0.028	0.011	0.03	0.06	0.0001

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).

\*Treatments within a column followed by the same letter are not significantly different at  $p \geq 0.05$ . SEM, Standard error of the mean.

indicated these nutrients were present at sufficient or potentially supra-optimal levels, where additional fertilization could potentially induce phytotoxicity and yield depression.

efficiency (0.6–12.7 kg kg<sup>-1</sup>, mean: 5.2 kg kg<sup>-1</sup>). The overall trend (AEP > AEN > AEK) suggests that P fertilization generated the highest yield response per unit applied, followed by N and then K, highlighting differential nutrient utilization efficiencies in the studied wheat systems.

### 3.5 Agronomic use efficiency

The agronomic use efficiency (AE; kg grain yield per kg applied nutrient) of N (AEN), P (AEP), and K (AEK) varied significantly across testing sites (Table 11). AEN ranged from 6.1 to 20.8 kg kg<sup>-1</sup> (mean: 13.1 kg kg<sup>-1</sup>), while AEP exhibited a broader range (0.8–42.5 kg kg<sup>-1</sup>, mean: 22.2 kg kg<sup>-1</sup>) and AEK showed lower but consistent

### 3.6 The soil indigenous nutrient supply

Analysis of relative yield data revealed significant variation in indigenous nutrient supply across the study sites. The soil indigenous N supply ranged from 29.6% to 56.5% (mean: 45.0%), demonstrating substantial N deficiency, while P supply showed higher values (72.6%

TABLE 7 Treatment effects on wheat thousand seed weight (g) across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	36.9	40.6	37.1	47.5	39.3	22.7	31.2
-B	40.5	40.2	34.1	48.3	39.4	20.9	30.6
-Zn	38.0	40.1	36.2	48.4	40.3	23.7	30.5
-S	37.6	41.2	36.8	46.7	39.6	25.0	31.5
-K	38.1	36.6	34.9	49.3	37.8	21.1	29.0
-P	37.1	39.4	35.2	48.4	37.7	21.4	30.5
-N	35.2	44.4	36.6	48.5	37.4	22.8	29.8
F <sub>0</sub>	37.6	37.0	34.7	48.6	37.8	20.3	31.4
Mean	37.5	39.9	35.7	48.2	38.6	22.2	30.5
CV (%)	6.2	13.2	8.3	3.3	3.0	11.9	8.4
SEM	2.31	5.3	2.95	1.59	1.14	2.64	2.56
P value	0.322	0.718	0.861	0.636	0.077	0.42	0.931

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).

TABLE 8 Treatment effects on wheat grain yield (kg ha<sup>-1</sup>) across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	4739.5a	4371.8a	4537.9a	3975.4ab	4582.7a	2867.7a	2290.5a	1942.7ab
-B	5146.9a	4495.8a	4979.7a	3945.3ab	4046.6ab	2911.7a	1924.5ab	2224.5a
-Zn	4476.0a	4733.1a	4074.2a	4260.7a	4252.4ab	2883.9a	2227.9a	2190.4a
-S	4874.1a	4284.7a	4470.9a	4197.3a	4224.0ab	3401.4a	1879.9ab	2176.5a
-K	4706.9a	3736.7b	4173.3a	3602.5bc	4027.1ab	3391.4a	2011.2a	1565.9bc
-P	4722.9a	3521.0b	4192.9a	3407.7c	3597.7b	2672.6a	1790.2ab	1410.6c
-N	2004.6b	2082.3c	2108.2b	1177.4d	1709.1c	1275.9b	1279.7bc	1095.5cd
F <sub>0</sub>	1405.3b	1898.1c	1737.5b	1050.9d	1581.9c	846.2b	954.6c	844.1d
Mean	4035.0	3756.8	3784.3	3295.7	3502.7	2598.3	1838.7	1681.3
CV (%)	10.8	5.5	17.8	6.7	10.1	12.4	18.0	15.7
SEM	437.4	208.71	672.2	220.6	353.3	321.4	331.8	263.3
P value	<.0001	<.0001	<.0002	<.0001	<.0001	0.0003	0.02	0.0001

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).  
\*Treatments within a column followed by the same letter are not significantly different at p≥0.05. SEM, Standard error of the mean.

to 99.6%, mean: 87.0%) (Figure 4). These results clearly indicate that N was the most limiting nutrient for wheat production in the study area. In contrast, indigenous supplies of K, S, Zn, and B consistently exceeded 90%, confirming their adequate availability to support optimal wheat growth and yield under prevailing soil conditions.

### 3.7 Yield gaps

The yield gap analysis revealed substantial differences in productivity losses across nutrient omission treatments (Figure 5). The most severe yield reduction (63.0% mean loss) occurred in the F<sub>0</sub> treatment, followed closely by N omission (-N) at 53.9%. Phosphorus

omission (-P) resulted in a moderate 11.9% yield loss, while -K, -S, -Zn, and -B showed negligible impacts on productivity. These findings demonstrate that N represents the primary yield-limiting factor for wheat cultivation in the study area, with P emerging as the secondary constraint. The minimal yield gaps observed for other nutrients confirm their adequate soil availability for optimal crop performance.

## 4 Discussion

### 4.1 Soil characteristics of the testing sites

The study sites exhibited medium to slightly acidic pH ranges (5.3-6.4), consistent with previous findings for Luvisols in the study

TABLE 9 Treatment effects on wheat aboveground dry biomass (kg ha<sup>-1</sup>) across eight experimental sites during 2022 growing season.

Treatment*	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
NPKSZnB (N <sub>F</sub> )	19792a	20938ab	11667a	8681abc	10035a	9688a	7222a	5069a
-B	20972a	21563a	13090a	9201ab	9375ab	9167a	7083a	5555a
-Zn	19375a	20625ab	11285a	9948a	9132ab	8854a	7777a	5208a
-S	19375a	20000ab	10833a	9028ab	9410ab	10382a	6929a	5486a
-K	19167a	15938bc	10660a	7882bc	9306ab	10313a	7500a	4027b
-P	19653a	14688c	11007a	7431c	7569b	10469a	6041b	3611b
-N	9167b	9392d	4549b	2674d	3646c	3750b	4687c	2291c
F <sub>0</sub>	7917b	9583d	4826b	2240d	3715c	3958b	3020d	1944c
Mean	17048.6	16590.3	9739.6	7230.1	7773.4	8443.6	6503.6	4149.3
CV (%)	10.9	12.4	17.0	9.8	12.8	14.0	6.5	13.2
SEM	1857.5	2063.1	1656.8	711.6	993.2	1182.7	425.7	548.1
P value	<.0001	0.005	<.0001	<.0001	<.0001	0.003	<.001	0.0001

Treatments include: full fertilization (N<sub>F</sub>), individual nutrient omissions (-N, -P, -K, -S, -Zn, -B), and unfertilized control (F<sub>0</sub>).  
\*Treatments within a column followed by the same letter are not significantly different at p≥0.05. SEM, Standard error of the mean.

TABLE 10 Wheat grain yield response (kg ha<sup>-1</sup>) to nutrient omission treatments across eight experimental sites during 2022 growing season.

Treatment	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Mean
-B	-407.4	-124.0	-441.8	30.1	536.1	-44.0	366.0	-281.8	-45.9
-Zn	263.5	-361.3	463.7	-285.3	330.3	-16.2	62.6	-247.7	26.2
-S	-134.6	87.1	67.0	-221.9	358.7	-533.7	410.6	-233.8	-25.1
-K	32.6	635.1	364.6	372.9	555.6	-523.7	279.3	376.8	261.7
-P	16.6	850.8	345.0	567.7	985.0	195.1	500.3	532.1	499.1
-N	2734.9	2289.5	2429.7	2798.0	2873.6	1591.8	1010.8	847.2	2071.9
F <sub>0</sub>	3334.2	2473.7	2800.4	2924.5	3000.8	2021.5	1335.9	1098.6	2373.7

area (G/Selassie, 2002; Beyene et al., 2023). Various study reports also revealed soil acidity problems in the study areas (Abayneh, Draft report, unpublished, 2017 draft; Fekadu et al., 2017), attributable primarily to basic cation leaching from intensive rainfall, erosion on cultivated slopes, and inadequate conservation practices (Abebe, 1998). Soil N content showed medium levels, likely reflecting organic matter depletion from crop residue removal, intensive tillage, and limited organic inputs. The available P levels exhibited significant spatial variability across testing sites (range: 6.4–36.8 mg kg<sup>-1</sup>), underscoring the need for site-specific P management strategies. Our observed mean available P level (11.2 mg kg<sup>-1</sup>) in Lay Gayint district was comparable to values reported by Fekadu et al. (2017) for similar soils (6–10 mg kg<sup>-1</sup>). A notable discrepancy emerged in K status, with our study showing high exchangeable K levels contrasting with previous reports of K deficiency in the region (Abayneh, 2017; Fekadu et al., 2017). Zinc concentrations were consistent with regional benchmarks (Abayneh, 2017), while B availability showed marked differences, with the present study results indicating sufficient levels compared to earlier findings of widespread deficiency (Abayneh, 2017).

## 4.2 Yield response of wheat to N, P, K, S, Zn and B

The observed yield responses strongly correlated with soil indigenous nutrient supply, demonstrating an inverse relationship between response magnitude and native soil nutrient availability. Maximum yield response (mean 2071.9 kg kg<sup>-1</sup>) was recorded from N omission (-N), confirming severe N deficiency across the testing sites. The recorded yield response to N application might be resulted from significant N loss through leaching under the study area's high rainfall regime (>1200 mm) and depletion of organic matter through repeated tillage. These findings align with Limin et al. (2013), who reported comparable N response ranges (800–2400 kg ha<sup>-1</sup>, mean: 1700 kg ha<sup>-1</sup>). The yield enhancement from N fertilization reflects its fundamental physiological roles in wheat growth, including: stimulating vegetative growth and tiller development, enhancing photosynthetic capacity, and facilitating protein and carbohydrate synthesis (Havlin et al., 1999). This response pattern underscores the importance of N as the primary

limiting nutrient for wheat production in the study area. Phosphorus omission (-P) showed significant but variable yield responses (16.6–850.8 kg ha<sup>-1</sup>, mean: 499.1 kg ha<sup>-1</sup>) at 50% of sites, consistent with regional studies (Dargie et al., 2022; Bazie et al., 2024). Notably, K, S, Zn, and B omissions showed minimal yield impacts, corroborating findings from multiple Ethiopian studies (Getinet et al., 2024; Abdulkadir et al., 2016). The consistent pattern across studies establishes N and P as primary limiting factors for wheat production in Ethiopian highlands, while other nutrients remain non-limiting under current management systems.

## 4.3 Soil indigenous nutrient supply

The soil indigenous nutrient supply (SINS), defined as the total nutrient uptake in an omission plot (Janssen et al., 1990), was estimated using relative yield percentages. Higher relative yields reflect greater SINS and soil fertility, while lower values indicate reduced SINS and poorer fertility. As a key indicator of soil fertility, SINS enables site-specific fertilizer recommendations (Dobermann et al., 2002, 2003; Cui et al., 2008). In this study, indigenous N supply ranged from 29.6 to 56.5% (mean = 45.0%), suggesting poor soil N status. In contrast, indigenous P supply (72.6–99.6%; mean = 87.0%) indicated favorable P availability, aligning with findings by Limin et al. (2013), who reported mean relative yields of 85% (P) and 90% (K) in similar soils.

## 4.4 Agronomic use efficiency of wheat

The agronomic N use efficiency (AEN) in this study (6.1–20.8 kg kg<sup>-1</sup>; mean = 13.1 kg kg<sup>-1</sup>) was below the global average (18 kg kg<sup>-1</sup>; Ladha et al., 2005), indicating opportunities for improved N management. Similar findings were reported by Dargie et al. (2022) (1.3–15.2 kg kg<sup>-1</sup>) across diverse soils and by Duan et al. (2014) (1.1–19.0 kg kg<sup>-1</sup>) in rice-wheat systems. AEN variability reflects management practices and soil N supply, with studies demonstrating potential increases (e.g., 10.5–28.7 kg kg<sup>-1</sup>; Belete et al., 2018) through optimized N splitting. While Limin et al. (2013) reported lower AEN (mean = 9.4 kg kg<sup>-1</sup>) in North China, Dobermann (2007) noted that cereals in developing countries typically achieve 10–30 kg kg<sup>-1</sup>, with well-managed systems

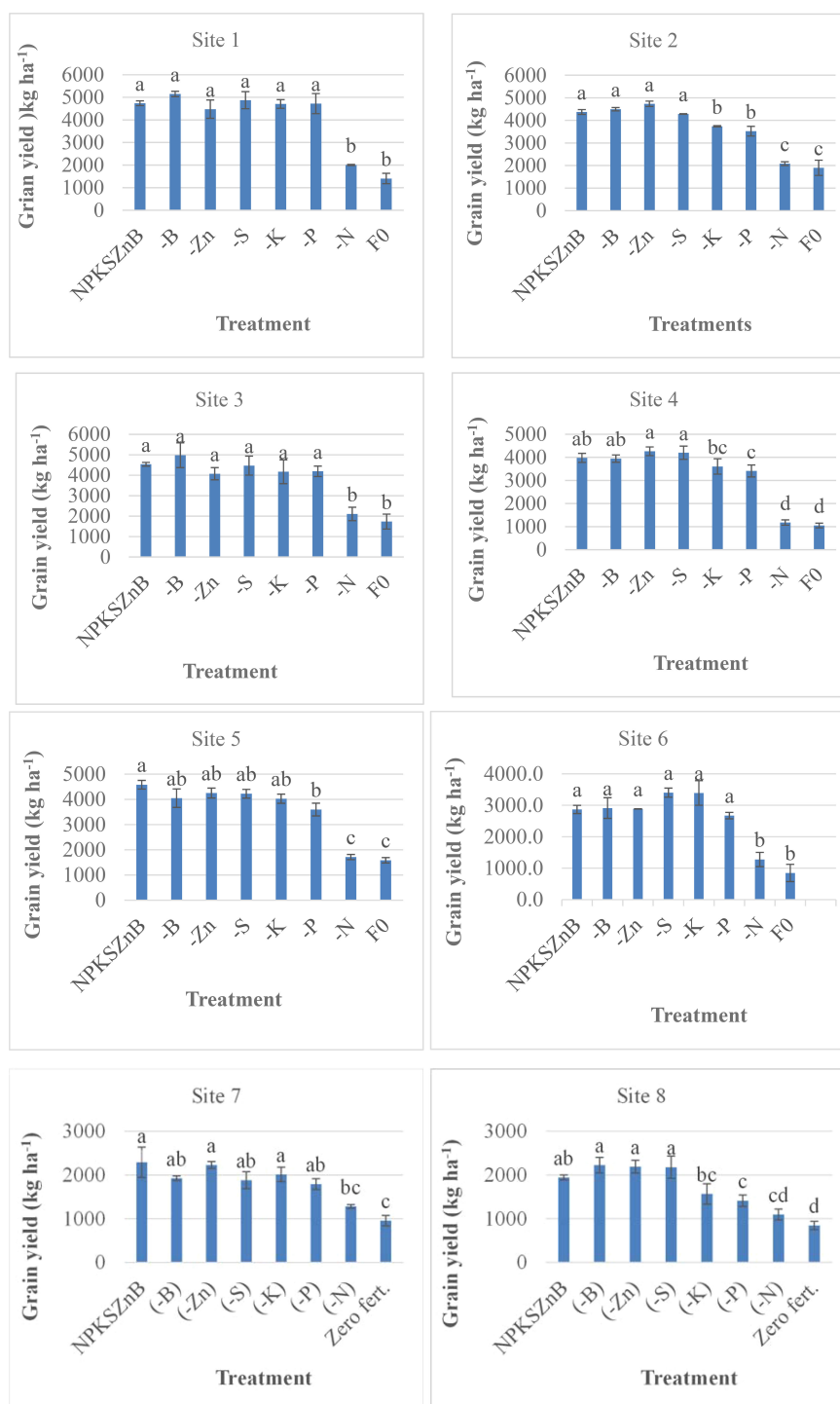


FIGURE 3

Wheat grain yield response to nutrient omission treatments across eight experimental sites in Farta and Lay Gayint districts during the 2021 growing season. Bars represent treatment means  $\pm$  standard error ( $n = 3$  replicates per site). Letters above bars indicate significant differences (Duncan's Multiple Range Test,  $p < 0.05$ ) within each site.

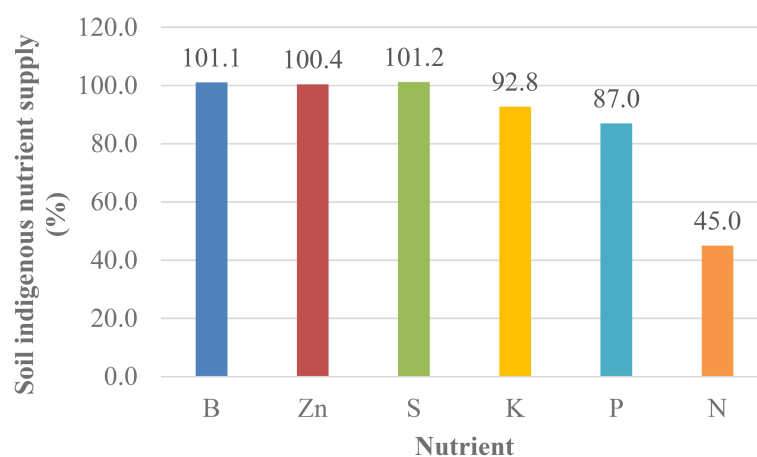
exceeding 25 kg kg<sup>-1</sup> under low N inputs. For P, our AEP range (0.8–42.5 kg kg<sup>-1</sup>) aligned with Dargie et al. (2022) (1.2–49 kg kg<sup>-1</sup>). AEK values (0.6–12.7 kg kg<sup>-1</sup>) were consistent with Limin et al. (2013) (mean = 6.5 kg kg<sup>-1</sup>) but lower than reports from Vertisols (18.0 kg kg<sup>-1</sup>; Birhane et al., 2017).

## 5 Conclusions

This study demonstrates that nitrogen (N) availability is the primary constraint to wheat productivity, as evidenced by significant yield reductions (mean response: 2,071.9 kg ha<sup>-1</sup>; yield

**TABLE 11** Agronomic efficiency (kg grain kg<sup>-1</sup> nutrient applied) of N (AEN), P (AEP), and K (AEK) for wheat across eight experimental sites in Farta and Lay Gayint districts during 2022 growing season.

AE (kg kg <sup>-1</sup> )	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Mean
AEN	19.8	16.6	17.6	20.3	20.8	11.5	7.3	6.1	13.1
AEP	0.8	42.5	17.2	28.4	49.2	9.7	25.0	26.6	22.2
AEK	0.6	12.7	7.3	7.5	11.1	–	5.6	7.5	5.2

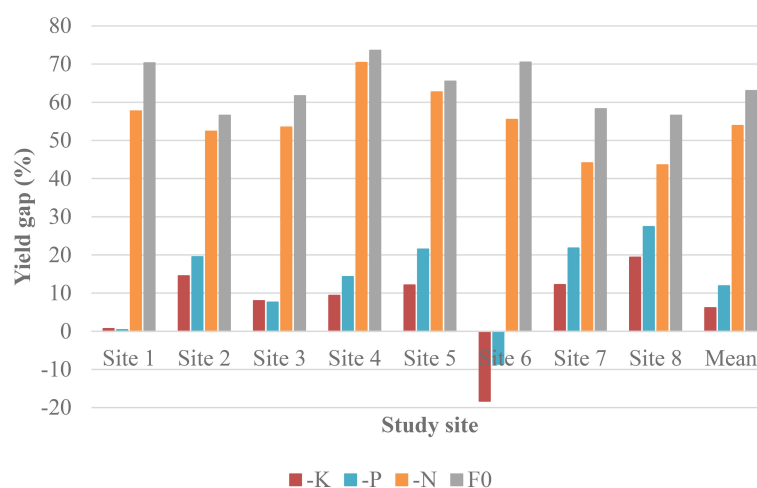


**FIGURE 4**

Soil Indigenous Nutrient Supplying (SINS) capacity for wheat production across eight experimental sites in Farta and Lay Gayint district in the 2021 growing season. Values represent mean relative grain yield in omission plots for (a) N, (b) P, (c) K, (d) Zn, and (e) B.

gap: 53.9%) and critically low indigenous soil supply (mean: 45.0%) across all test sites, coupled with suboptimal agronomic efficiency (mean AEN: 13.1 kg kg<sup>-1</sup>). Phosphorus (P) emerged as a secondary limiting factor, showing variable but substantial yield responses (mean: 499.1 kg ha<sup>-1</sup>; yield gap: 11.9%) in 50% of sites, despite relatively adequate soil indigenous supply (mean: 87.0%). In contrast, potassium (K), sulfur (S), zinc (Zn), and boron (B)

proved non-limiting, with soil indigenous supplies exceeding 90% and negligible yield gaps, indicating these nutrients currently require no supplemental fertilization. These findings establish a clear nutrient management priority: targeted N optimization and site-specific P applications are essential to enhance wheat production in the study area. While this single-season study identified key yield-limiting nutrients (N, P) in the study area,



**FIGURE 5**

Wheat yield gaps attributed to nutrient omissions treatments across eight experimental sites in the 2021 growing season: (a) N omission (-N), (b) P omission (-P), (c) K omission (-K), and (d) zero-fertilization control (F0). Values represent mean yield differences (%) relative to the full fertilization (NF) (NPKSZnB).

interannual climatic variability may influence nutrient response dynamics. We recommend multi-year trials to validate the temporal stability of soil indigenous nutrient supply (SINS) values, quantify weather-mediated nutrient use efficiency variations, particularly for P which showed site-specific responses, and develop climate-adaptive fertilizer recommendations.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

AA: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. DG: Data curation, Methodology, Supervision, Conceptualization, Formal analysis. GA: Data curation, Methodology, Investigation, Resources, Supervision, Writing – review & editing. WW: Conceptualization, Data curation, Investigation, Methodology, Writing – review & editing. TG: Data curation, Methodology, Supervision, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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