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Response of maize to different nutrient sources under different landscape positions in cereal mixed farming systems of tropical agroecosystems

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Abstract

Nutrient omission trials were conducted on farmers' fields in 2020 and 2022. The experiment included nine treatments: three treatments with nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B) as individual, blended, and compound fertilizer; four treatments with the omission of K, S, Zn, or B; NP-only; and control without any nutrient. Treatments were arranged in a randomized complete block design with three replications under foot slope (FS), mid-slope (MS), and hillslope (HS) positions. Results showed that soil properties and maize yield significantly varied among landscape positions, with substantial soil fertility and yield increasing trends from HS to FS position. The highest grain yield (6.18 t ha^{-1}) was recorded at the FS position, with the respective yield increments of 14% and 16% compared to the MS and HS positions. Applying all nutrients in blended form resulted in the highest grain yield (6.52 t ha^{-1}), but it was not significantly different

Abbreviations: BCR, benefit-cost ratio; CEC, cation exchange capacity; FS, foot slope; HS, hillslope; MNB, marginal net benefit; MRR, marginal rate of return; MS, mid-slope; NB, net benefit; TC, total carbon; TN, total nitrogen.

from yields of compound and individual fertilizer forms. Applying all nutrients in blended form increased grain yield by 7.4% and 264.2% compared to the NP-only and the control, respectively, indicating the non-significant effects of K, S, Zn, and B on yield. Overall, N and P are the most yield-limiting nutrients for maize production, and site-specific NP fertilizer recommendations targeting landscape position are required to enhance nutrient use efficiency and sustainably intensify maize yield. Developing site-specific fertilizer recommendations advisory will enhance nutrient use efficiency, increase and sustain yield, and benefit farmers while improving soil and environmental quality.

Plain Language Summary

This paper reports research targeting different nutrient sources on maize yield and soil properties under different landscape positions. Our understanding of the management of plant nutrients under different landscape positions in tropical farming systems is still limited, where soil fertility depletion and nutrient mining are key constraints to increased and sustainable crop yield because of low soil organic matter content, low nutrient and water retention capacity, and nutrient losses. Optimizing fertilizer use efficiency at a landscape level is an efficient approach for reducing soil erosion and nutrient losses, reducing environmental pollution, and improving food and nutrition security while sustaining crop yield. Several fertilizer trials were piecemeal and mostly on suitable landscapes. Hence, this research may contribute information to research and development, and enhance our scientific understanding of landscape features and their impact on soil properties and crop yield.

1 | INTRODUCTION

Agriculture remains central to the livelihoods of people in Ethiopia. Soil fertility depletion and nutrient mining are critical challenges for Ethiopian agriculture and sustainable crop production (Agegnehu & Amede, 2017; Zelleke et al., 2010). Widespread soil degradation and soil fertility depletion are the major biophysical root causes of sub-Saharan Africa's declining per capita food production and natural resource conservation (Sanchez et al., 1997). Despite increased fertilizer supply and usage, low crop response to applied fertilizers remains a major concern, which may be associated with factors beyond fertilizer application (ICRISAT, 2017; Sileshi et al., 2022). These include low soil organic matter (OM) content; nutrient deficiencies/imbalances; inappropriate rate, time, or application methods of fertilizers; soil moisture deficits; use of low-yielding varieties; and other agronomic practices. The effectiveness of matching fertilizer types to soil fertility problems depends on the ability to identify limiting factors, characterize sites, and develop appropriate recommendations. To determine nutrient management zones, the collection and interpretation of spatial data, such as yield, elevation, soil nutrient maps, farmers' classification criteria, and so on, are required.

Low soil fertility and nutrient imbalances are among the main constraints to increased and sustainable crop productivity and production in Sub-Saharan Africa. Nevertheless, the response of major cereals to fertilizer applications is often far below the potential yields. Low nutrient use efficiency, insufficient fertilizer recommendations, and disregarding nutrients other than nitrogen (N), phosphorus (P), and potassium (K) may limit crop production (Nziguheba et al., 2009). Severe OM depletion driven by competing uses for crop residues and manure as livestock feed and fuel in Ethiopia has exacerbated the mining of nutrients and the overall soil fertility decline. Yield benefits were more evident when fertilizer application was accompanied by integrated soil fertility management practices, such as crop rotation, green manuring, or crop residue management (Amede et al., 2021; Vanlauwe et al., 2010). For example, the combined application of organic and inorganic fertilizers increased wheat yield by 50%–100%, while crop rotation with legumes increased cereal grain yields by up to 200% (Agegnehu & Amede, 2017).

In Ethiopia, research and development institutions are making great efforts to test and develop site-specific balanced fertilizer recommendations for increased yield and quality of crops. Fertilizer trials were conducted using balanced blended fertilizers containing multiple nutrients, including nitrogen

(N), phosphorus (P), and sulfur (S) with or without potassium (K), zinc (Zn), and boron (B). The basis for formulating these fertilizers was an analysis of data collected under the Ethiopian Soils Information System (EthioSIS) project, which identified S, Zn, and B as deficient nutrients in Ethiopian soils (EthioSIS, 2015). Fertilizer trials were conducted for the last half a century on research stations and a few selected testing sites, with limited effort to extrapolate the results to a wider range of environments. This could be one of the reasons for crop yield variation in the different areas, as soil properties are variable and change rapidly (Assefa et al., 2020; Desta et al., 2022). For instance, the fertilizer research conducted by the Institute of Agricultural Research (IAR) and the Ministry of Agriculture in collaboration with FAO in the 1980s and early 1990s across representative agroecological zones and soil types recommended 30–138 kg N ha^{-1} and 0–50 kg P ha^{-1} for major cereal crops (Erkossa et al., 2022). However, only 30%–40% of the smallholder farmers have used fertilizers at rates less than the recommended rate, that is, 37–40 kg ha^{-1} on average (Spielman et al., 2013). Consequently, the yields of cereals have been only 10% despite a fivefold increase in fertilizer usage in the country.

Provided the diverse rainfall regimes, farming systems, and topographic conditions, coupled with the low dose of fertilizer application and the high level of nutrient mining, achieving food and nutrition security in Ethiopia could be challenging. In Ethiopia, approximately 80% of agricultural lands exhibit undulating topography, with slopes reaching up to 60% (Belete, 2016), presenting significant challenges in the development of fertilizer and crop management recommendations. The response of cereal crop yields varied significantly across different landscape positions (Agegnehu et al., 2023). For instance, wheat yields showed a remarkable increase of 50%–300% at the foot slope (FS) position compared to the hillslope (HS) position, with the extent of improvement depending on location and input level (Agegnehu et al., 2023). Significant variations were observed in crop fertilizer response with topo-sequence (Desta et al., 2023; Gedamu et al., 2023) due to a significant decrease in soil organic carbon (SOC) and clay content and soil water content (Agegnehu et al., 2023; Amede et al., 2020). There is limited information on how landscape positions could be used for refining fertilizer recommendations. In this study, maize was used as a test crop to understand the factors affecting the crop response to different nutrient sources under different landscape positions. Generally, research information about the effects of landscape position variation on crop yield response to different fertilizer sources is inadequate in the Ethiopian context. So, a fertilizer trial was conducted under field conditions to test the hypothesis that applying different nutrient sources would improve soil properties and the yield of maize under different landscape positions and agroecological zones.

Core Ideas

- The study characterized soil properties and identified key yield-limiting nutrients targeting landscape positions.
- Maize yield among landscape positions was in decreasing order of foot-slope > mid-slope > hillslope.
- The highest maize grain yield (6.18 t ha^{-1}) was recorded at the foot slope position, with a yield increment of 16%.
- Omitting K, S, Zn, and B did not show statistically significant yield variations over the recommended NP rate.
- Soil testing showed N and P were the most commonly deficient and yield-limiting nutrients.

Understanding how crops respond to nutrients varies markedly across different landscape positions and environmental conditions, influenced by factors like soil type, water availability, and agronomic practices. The absence of practical, appropriate, and site-specific fertilizer recommendations has been a limitation in achieving increased yield and quality of crops. Hence, developing and transferring soil fertility management practices that improve nutrient use efficiency following the 4Rs of Nutrient Stewardship, right source, right time, right rate, and right place, is of paramount significance for healthier and more productive farming systems. This is achieved by strengthening inorganic fertilizer-based systems and promoting integrated soil health and fertility management practices for optimal economic returns, focusing on smallholder cropping systems. Therefore, the major objectives of this study were to (1) investigate the effect of landscape variability on maize yield response to different nutrient sources; (2) evaluate the main and interaction effect of nutrient sources, landscape position, and growing potential on maize yield and soil properties; and (3) identify variations in soil nutrient status and yield-limiting nutrients (N, P, K, S, Zn, and B) for maize production.

2 | MATERIALS AND METHODS

2.1 | Characteristics of trial sites

Nutrient omission field trials were conducted in three representative maize-growing districts in the Amhara and Oromia Regional States of Ethiopia (Figure 1; Table 1). The districts selected were Alefa and Takussa from the Amhara region and Sokoru from the Oromia region. A total of 15 trial sites were selected in the three districts (Figure 1).

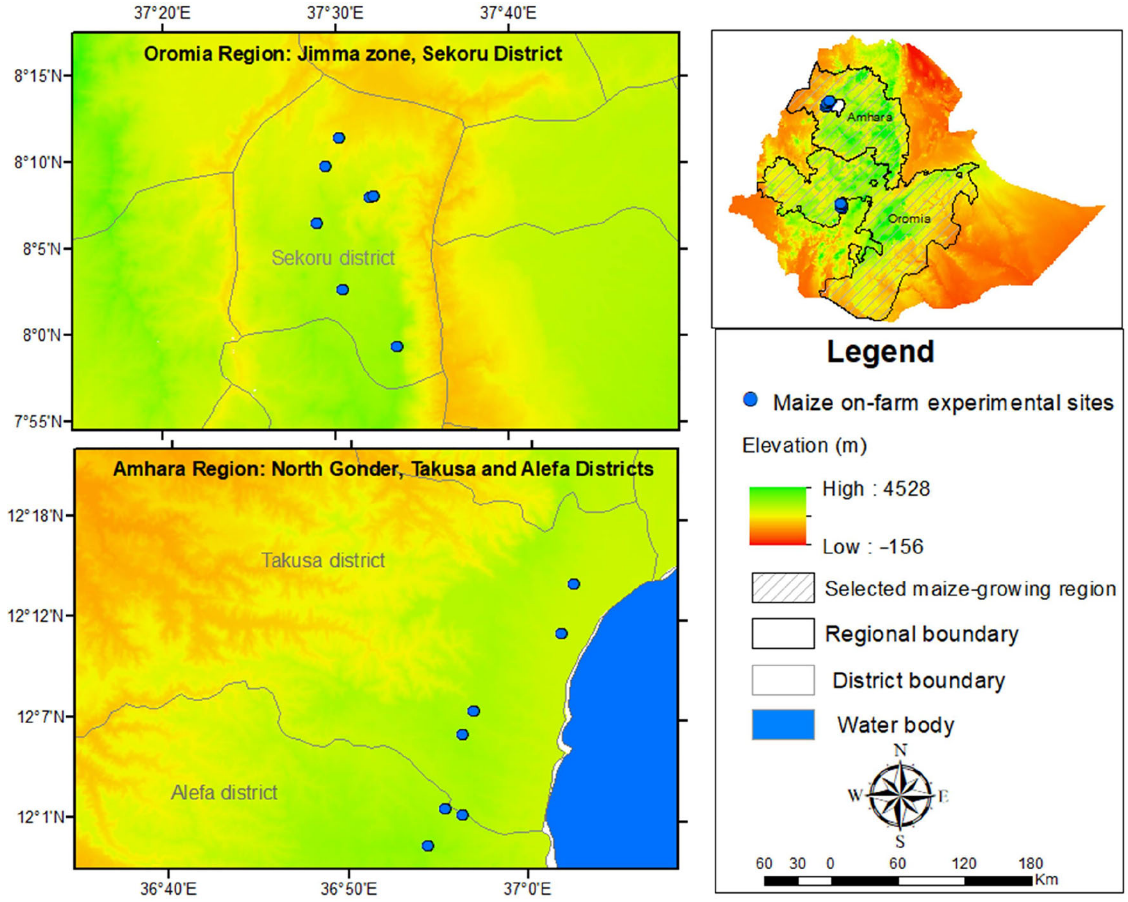


FIGURE 1 Distribution of maize nutrient omission experimental sites across the Amhara and Oromia regions for the 2022/23 cropping season.

TABLE 1 General characteristics of maize experimental sites in the Amhara and Oromia regions.

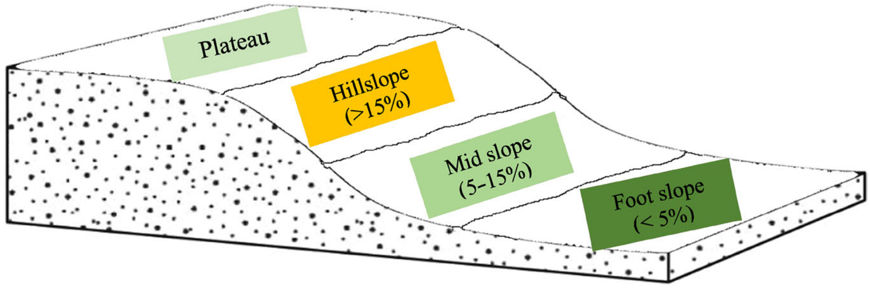
Location (district)	Rainfall (mm)[a]	Minimum temperature (˚C)[a]	Maximum temperature (˚C)[a]	Soil type	Agroecological zone
Amhara region					
Alefa	1375–1425 (1394)	9–11 (10)	25–27 (26)	Eutric Regosols	Tepid moist mid-highlands
Takussa	1252–1365 (1307)	10–13 (12)	26–29 (27.7)	Eutric Regosols and Orthic Solonchaks	Tepid moist mid-highlands
Oromia region					
Sokoru	1424–1796 (1636)	11.3–17.7 (12.6)	24–29 (25.8)	Eutric Cambisols, Dystric Nitisols and Dystric Fluvisols	Tepid sub-humid mid-highlands and warm sub-humid lowlands

[a]Range (average value).

The landscape positions, namely HS, mid-slope (MS), and FS, were considered to identify the trial sites in each district. Landscape positions were categorized based on slope classes for homogenous cropping management zones as indicated in Figure 2. This study followed the classification made by Amede et al. (2020), in which landscape positions with slope ranges from 15% to 30%, 5% to 15%, and <5% were categorized as HS, MS, and FS, respectively. Two to four farmers per landscape position were selected, and the trials were replicated two to three times at each site based on the availability of sufficient places.

The trial sites were also selected considering the rainfall status, which is an indicator of crop production potential at different agroecological zones in Ethiopia. Variations in rainfall, minimum and maximum air temperatures, soil types, and agroecological zones were observed in all on-farm trial sites

FIGURE 2 Schematic presentation of the three landscape positions and the plateau at the top.



in the selected districts (Table 1). Crop production potential is directly related to rainfall status, where adequate and timely rainfall is crucial for successful yields, particularly in rain-fed agriculture. Variability in rainfall patterns, including timing, amount, and distribution, significantly impacts crop growth and yield. According to the agroecological classification, the trial sites are found under high-potential areas in terms of rainfall amount and distribution, which are above the national average, during the crop growing season. For instance, Sokoru, Alefa, and Takusa receive the average annual rainfall of 1636, 1394, and 1307, respectively. About 85% of the rainfall is received in the main rainy season (June to September), which coincides with the main crop season, and the rest from January to May. The average range of annual maximum and minimum air temperatures of the maize-growing trial locations was from 24 to 29°C and 9.5 to 15.7°C, respectively. Tepid moist mid-highlands (M3) and tepid sub-humid mid-highlands (SH3) are the predominant agroecologies, while Nitisols, Cambisols, Regosols, and Fluvisols are the dominant soil types in the study areas.

Maize (*Zea mays* L.) was used as a test crop. It is the widely grown and leading cereal in terms of area and production. Maize is a multi-purpose crop, which is primarily used as feed globally and as a food crop, especially in sub-Saharan Africa and Latin America (Erenstein et al., 2022). Maize is also one of the five major cereal crops, including teff, wheat, barley, and sorghum, in terms of area coverage, production, and household consumption in Ethiopia (CSA, 2021). It is mainly cultivated as a monocrop, rotated, or intercropped with beans. The crop covers an area of about 2.56 million ha, the second-largest production area next to teff in Ethiopia (CSA, 2021). However, despite the high potential for increasing the production of maize in the country, its productivity is still low, with an average yield of 4.2 t ha^{-1} (CSA, 2021), which is less than the world average yield of 5.8 t ha^{-1} (FAOStat, 2021). This could mainly be attributed to poor soil fertility, inadequate nutrient supply, and crop management practices (Zelleke et al., 2010).

2.2 | Treatments and experimental design

Nutrient omission field trials were conducted using balanced blended fertilizers containing macro- and micronutrients, including nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B). The formulations of different fertilizer types were based on an analysis of data collected under the EthioSIS project, which identified N, P, S, Zn, and B as deficient nutrients in Ethiopian soils. The experiments in each location were established at HS, MS, and FS landscape positions. Three treatments with NPKSZnB nutrients in the form of individual, blended, and compound sources of fertilizers and four treatments with the omission of one of the four nutrients (K, S, Zn, and B) were evaluated. The other two treatments with only N and P and the control without any nutrients were also included as positive and negative controls, respectively, comprising a total of nine treatments (Table 2).

TABLE 2 Nutrient types with rates (kg ha^{-1}) under the high rainfall regime.

Nutrient type	N	P_2O_5	K_2O	S	B	Zn
All (NPKSZnB-blended)	120	76	60	14.8	0.5	1.5
All (NPKSZnB-compound)	120	76	60	14.8	0.5	1.5
All (NPKSZnB-individual)	120	76	60	14.8	0.5	1.5
All-K (blended)	120	76	0	14.8	0.5	1.5
All-S (blended)	120	76	60	0	0.5	1.5
All-Zn (blended)	120	76	60	14.8	0.5	0
All-B (blended)	120	76	60	14.8	0	1.5
NP	120	76	0	0	0	0
Control	0	0	0	0	0	0

Note: All: Application of all nutrients (N, P, K, S, Zn, B) in different forms.

The sources of nutrients were N from diammonium phosphate (DAP) (18–46–0 N–P_2O_5–K_2O) or NPS (19–38–0-7) and urea (46–0–0), P from DAP or NPS (N-P_2O_5-K_2O-S), K from potassium chloride (KCl) (0–0–60), S from NPS, Zn from zinc sulfate monohydrate (33% Zn), and B from Solubor (20.8% B). The fertilizers were blended in a small cement mixer per treatment, and the blends were divided into quantities appropriate for individual plots, following the guidelines of the International Fertilizer Development Center (IFDC). Zinc and B were coated onto granules of NPKS to ensure their even distribution. Fertilizers were blended in a small cement mixer per treatment, and blends were divided into quantities appropriate for individual plots.

Land preparation was done using an animal-drawn local ox plow according to the crop's requirements. The field operations were done using manual labor. The experiment was arranged in a randomized complete block design and replicated thrice at each landscape position. A plot size of 3 m by 4.5 m (13.5 m^2) was used for each treatment, and the distances between blocks and experimental plots were 1 and 0.75 m, respectively. The space between the experimental plots and the borders on all four sides was 1 m. The treatments containing all nutrients—nitrogen (N), phosphorus (P), potassium (K), sulfur (S), zinc (Zn), and boron (B)—were applied in blended, compound, and individual forms. The nitrogen content in DAP or NPS was balanced by applying urea as splits, with half at planting and half at the knee-high stage. Phosphorus was applied in bands as DAP or NPS at planting. Potassium and sulfur were applied as KCl and NPS, respectively, at planting. Zinc and boron were applied as Zn sulfate monohydrate and Solubor, respectively. Improved varieties of maize seeds were sown in rows with a spacing of 0.75 m between rows and 0.25 m between plants, with a total population of about 53,333 plants ha^{-1}. Other agronomic practices were applied uniformly for all plots during the crop growth period as per the recommendations made for the maize crop. Insecticide (Agrolambas) was used to control the maize stalk borer.

2.3 | Data collection

Agronomic data collected included total aboveground biomass, grain yield, straw yield, and harvest index of maize. Grain moisture content is crucial for yield, quality, transportation, and storage of maize (Gao et al., 2024). The moisture content of maize grain at maturity is one of the key indicators for harvesting. The presence of a black tip on maize kernels is often used as an index of physiological maturity. Hence, harvesting follows after physiological maturity, when the grain moisture content is around 30%. The whole plot was manually harvested at maturity to measure the total biomass and grain yields of maize. The harvested biomass was air-dried to constant moisture content, threshed manually, and the seeds were cleaned and weighed. The grain moisture content was measured and adjusted to a standard moisture content of 12.5%. The total biomass, grain, and straw yields of maize recorded on a plot basis were converted to t ha^{-1} for statistical analysis.

Soil samples were collected randomly before planting at two depths of 0–20 and 20–60 cm using hand-held augers in the 2020/2021 cropping season from each experimental site, considering three distinctly identified landscape (HS, MS, and FS) positions, following the random soil sampling procedure. Ten soil samples were collected from each trial plot and bulked to make one composite sample. The samples were air-dried and milled to pass through a 2-mm sieve and sent to the laboratory of the IFDC in the United States for the analysis of soil pH, total carbon (TC), total nitrogen (TN), sulfur, available phosphorus, zinc, and boron. The pH of the soil was measured using the pH-water method by making a soil-to-water suspension of a 1:2.0 ratio and was measured using a pH meter. The total soil nitrogen and carbon were determined by the combustion method (Horwitz, 2000), an analytical method to quantitatively determine the abundance of TC and TN in the soil using an instrument that utilizes a combustion system with an induction furnace coupled with a thermal conductivity detector system and an infrared (IR) detector system. Soil P, S, Zn, B, and aluminum (Al) were determined using the Mehlich 3 soil test extraction method (Mehlich, 1984).

2.4 | Statistical analysis

Before performing statistical analysis, the data across environments were combined into a dataset. The data were cleaned and arranged for statistical analysis. The data were analyzed using a mixed model of the SAS statistical package (SAS/STAT version 9.4).

$$Y = \mu + \mathrm{Rep} + \mathrm{LS} + \mathrm{Nut} + \mathrm{LS} \times \mathrm{Nut} + \mathrm{Loc} + \mathrm{AEZ} + \varepsilon$$

where Y is the measured value, μ is the grand mean, Rep is the replication in each farmer's field, LS is the landscape position, Nut is a nutrient type and source, AEZ is the agro-ecological zone, Loc is the district where the experiment was conducted, and ε is the error term. Location and AEZ were considered random components in the model.

A mixed model was used to analyze the data as mixed model analysis combines both fixed and random effects, allowing for a comprehensive understanding of the factors influencing the dependent variables. In many designed experiments, the random effects are not of interest to researchers in most cases, but in an adequate analysis, it is necessary to understand the variation that they contribute. This can be done using a mixed effects model that contains both fixed and random effects, which is not handled by the usual analysis of variance. Before choosing a specific model, the fit of the models was assessed using Akaike's information criterion (AIC) and Bayesian information criterion (BIC). The model was ultimately selected as it had lower AIC and BIC values compared to the other models. This is because a lower AIC and BIC indicate a better fit for the model. As a general guideline, a difference in BIC of 2–6 suggests weak evidence in favor of the more complex model, while differences greater than 10 provide strong evidence favoring the more complex model (Fabozzi et al., 2014). Therefore, the chosen model was deemed satisfactory. To assess the significance of the variations in yields with fixed effects, the intraclass correlation coefficient (ICC) was calculated by comparing the covariance estimate of the random intercept to the covariance estimate of the residual intercept. The ICC provides insight into how much the location values the total variation in the outcome. The significance of the variations in yield with fixed effects was considered when $p \leq 0.05$. Means for the main effects of landscape positions and fertilizer treatments were compared using the least significant difference test at $p < 0.05$.

The Tukey–Cramer method was employed to adjust the p values for comparing least-squares means. Statistical inference was based on least squares estimates and their 95% confidence intervals (CIs). The use of the 95% CI served as a cautious test for the hypothesis and provided a measure of uncertainty for sample statistics (Du Prel et al., 2009). If the 95% CI of the means for two or more levels of a fixed effect did not overlap, it would indicate that they were significantly different from one another. In addition, percent yield differences of maize were computed to determine the efficiency of fertilizer forms and the relative importance of nutrients for maize production along landscape positions in two ways: First, maize yield from different forms of fertilizers (blended, individual, and compound) and control treatments were compared relative to the yield from NP. Second, yield from treatments with omitted nutrients (All (B)-K, All (B)-S, All (B)-Zn, All (B)-B), including NP only and the control treatments, was compared relative to the yield from All (B).

Moreover, partial budget analysis was performed to investigate the economic feasibility of the different fertilizer treatments (CIMMYT, 1988). The average yield was adjusted downward by 10% to reflect the difference between the experimental yield and the expected yield of farmers from the same treatment. Because experimental yields from on-farm experiments under representative conditions are often higher than the yields that farmers could expect using the same treatments (CIMMYT, 1988). The average market prices of maize grain and fertilizers were used for economic analysis.

3 | RESULTS

3.1 | Soil chemical properties as influenced by different landscape positions

Soil analytical results indicated that selected pre-planting soil chemical properties significantly (<0.01) differed between landscape positions and soil sampling depth. Soil pH, TC, TN, available P, sulfur (S), zinc (Zn), and boron (B) were increased down the slope. The soil pH was strongly to moderately acidic (5.1–5.85) at the experimental sites in the Sokoru district of the Jimma zone (Table 3). The TC content is low (ranging between 0.83% and 1.56%) and the TN is low to medium (0.11%–0.17%), where the highest values were recorded at the FS and the lowest at the HS position for all parameters of soil chemical properties. The critical level of soil organic carbon (OC) is 2% (Carter & Stewart, 1996), and TN is 0.15% (Horneck et al., 2011), below which a potentially serious decline in soil quality will occur and affect agricultural productivity. In contrast, the nutrient concentrations of the same parameters of soil chemical properties substantially decreased with the increase in sampling depth.

Available soil P content was drastically low (0.02–0.14 mg kg^{-1}) across the trial sites due to acidity and inherently poor soil fertility. Soil sulfur concentration ranged between 0.40 and 2.1 mg kg^{-1} under different landscape positions. Thus, based on the sufficiency range of S (Horneck et al., 2011), the soil S concentrations were very low to meet the requirements of the crop (Table 3). Although micronutrients are required in small quantities, the absence of any of these crucial elements can have critical effects on the growth and yields of crops. Soil zinc and boron concentrations were low in the trial sites (Table 3), where a zinc soil test above 1.5 mg kg^{-1} using the diethylenetriaminepentaacetic acid (DTPA) extraction method is sufficient for most crops, while soil B test values below 0.50 mg kg^{-1} are low (Horneck et al., 2011). Soil Zn concentrations ranged between 0.14 and 1.26 mg kg^{-1} under different landscape positions and 0.54 and 1.07 mg kg^{-1} between the two soil sampling depths, where the highest values were recorded at the FS and surface soil depth (0–20 cm) and the lowest at the HS position and the lower soil depth (20–60 cm) (Table 3).

3.2 | Crop yield response to nutrient sources under different landscape positions

The results indicated significant variations ($p < 0.001$) in aboveground total biomass, straw, and grain yields of maize among different landscape positions, nutrient types, and sources (Table 4). However, the interaction between landscape position and the nutrient source was not statistically significant ($p > 0.05$) for the aboveground total biomass, grain, and straw yields of maize. Similarly, the main and interaction effects of landscape position, fertilizer type, and nutrient source were not significant for the harvest index of maize (Table 4). The statistical analysis over landscape positions and nutrient sources revealed that the highest total aboveground biomass (13.36 t ha^{-1}) was recorded from trial sites located at the FS position, with total biomass increments of 26.2% and 31.4% compared to the MS (10.59 t ha^{-1}) and HS (10.17 t ha^{-1}) positions, respectively (Table 5). Similarly, the highest maize grain yield of 6.18 t ha^{-1} was recorded from the trial sites set at the FS position, with grain yield advantages of 14% and 16% compared to the sites at the mid (5.42 t ha^{-1}) and HS (5.33 t ha^{-1}) positions (Table 5). Comparisons between landscape positions also indicated that significant ($p < 0.001$) variations were observed in maize total biomass and grain yield for FS versus HS and FS versus MS position, but not for MS versus HS position (data not shown).

TABLE 3 Soil physicochemical properties of Sokoru district based on landscape position and soil sampling depth.

	pH (1:2 H_2O)	TC (%)	TN (%)	Av. P (mg kg^{-1})	S (mg kg^{-1})	Zn (mg kg^{-1})	B (mg kg^{-1})
Landscape							
Foot slope	5.85a	1.56a	0.17a	0.14a	2.15a	1.26a	0.13a
Mid-Slope	5.58b	1.48a	0.16a	0.07b	0.61b	1.01a	0.06b
Hillslope	5.14c	0.83b	0.11b	0.05b	0.40b	0.14b	0.04b
LSD (0.05)	0.18	0.35	0.03	0.03	0.95	0.63	0.04
Soil depth (cm)							
0–20	5.64a	1.49a	0.16a	0.11	1.49a	1.07a	0.08
20–60	5.40b	1.09b	0.13b	0.07	0.62b	0.54b	0.07
LSD (0.05)	0.12	0.23	0.02	0.02	0.75	0.48	0.02

Note: Within each column, means followed with different letters are significantly different at $p < 0.05$.
Abbreviation: LSD, least significant difference.

TABLE 4 The significance level of fixed effects on biomass, grain and straw yields (t ha^{-1}), and harvest index (%) of maize.

	F value				$p > F$			
Fixed effects	**Biomass yield**	**Grain yield**	**Straw yield**	**Harvest index**	**Biomass yield**	**Grain yield**	**Straw yield**	**Harvest index**
Rep	2.88	3.47	1.68	0.31	0.0571	0.0321	0.1874	0.7357
LP	37.86	65.64	15.44	0.92	<0.0001	<0.0001	<0.0001	0.4009
NS	17.05	29.31	7.29	1.67	<0.0001	<0.0001	<0.0001	0.1042
LP × NS	0.48	0.61	0.64	1.19	0.9560	0.8748	0.8476	0.2739

Abbreviations: LP, landscape position; NS, nutrient source; Rep, replication.

TABLE 5 The main effect of landscape position, fertilizer source, and rate on biomass, straw, and grain yield of maize (t ha^{-1}).

Treatments	Total biomass	Grain yield	Straw yield
Landscape position			
Foot slope	13.36a	6.18a	7.18a
Mid-slope	10.59b	5.42b	5.17b
Hill slope	10.17b	5.33b	4.84b
$LSD_{0.05}$	1.85	0.70	1.24
Nutrient type and source			
All (blended)	12.93a	6.52a	6.40a
All (compound)	12.57a	5.98a	6.59a
All (individual)	11.05a	5.52a	5.53a
All-B (blended)	12.08a	6.30a	5.78a
All-K (blended)	12.00a	5.99a	6.01a
All-S (blended)	12.92a	6.24a	6.69a
All-Zn (blended)	12.44a	6.37a	6.07a
NP	12.57a	6.07a	6.50a
Control	3.78b	1.79b	1.99b
$LSD_{0.05}$	3.45	1.47	2.59

Note: All: NPKSZnB nutrients. Within each column, means followed with different letters are significantly different at $p < 0.05$.
Abbreviation: LSD, least significant difference.

The results also revealed that the highest (12.93 t ha^{-1}) and lowest (3.78 t ha^{-1}) total aboveground biomass yields were recorded from the application of all nutrients in the blended form and the unfertilized control treatment, respectively. The increments in the total biomass ranged from 2.9 (7.27 t ha^{-1}) with individual application of all nutrients to 3.4 times (9.15 t ha^{-1}) with application of all nutrients in the blended form, compared to the unfertilized control treatment (Table 5). Likewise, the highest (12.93 t ha^{-1}) and lowest (1.79 t ha^{-1}) grain yields of maize were obtained from all nutrients applied in the blended form and unfertilized control treatment. The increments in grain yields relative to the unfertilized control treatment ranged from 3.1 (3.73 t ha^{-1}) with the application of all nutrients individually to 3.6 times (4.73 t ha^{-1}) with the application of all nutrients in the blended form. In contrast, applying all nutrients in blended form increased grain yield by 8.6% and 21.3%, compared to the yields recorded from the NP treatment and all nutrients applied in individual form, respectively (Table 5). The highest (7.90 t ha^{-1}) and lowest (5.66 t ha^{-1}) straw yields (total biomass minus grain yield) of maize were recorded at the foot and HS positions (Table 5). Applying all nutrients without sulfur in blended form gave the highest straw yield of 6.69 t ha^{-1}, which is closely followed by the yield of 6.59 t ha^{-1} with the addition of all nutrients in the compound form. The lowest straw yield of 1.99 t ha^{-1} was obtained from the unfertilized control plot. All nutrients in blended and compound forms and all-S (blended) and NP treatments yielded similar straw yields with statistically nonsignificant differences between them. Straw yield increments of 2.8–3.3 times were recorded due to the application of

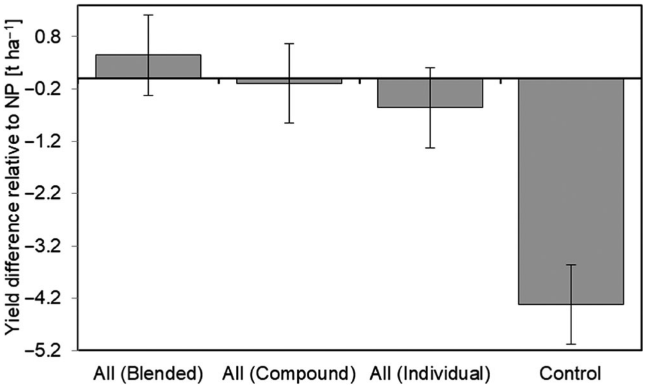


FIGURE 3 Variations in maize grain yield (t ha^{-1}) in response to applications of different forms of fertilizers relative to the application of NP nutrients.

different nutrient forms compared to the control treatment, with the highest from all nutrients in the compound form and the lowest from all nutrients applied individually (Table 5).

Despite numerical variations, statistically significant differences were not observed in the total biomass, straw, and grain yields of maize among applications of all nutrients in the blended, compound, and individual forms (Figure 3) and nutrient sources (Table 5). The application of the recommended N and P only slightly decreased the grain and biomass yields of maize by 7.4% (0.45 t ha^{-1}) and 2.8% (0.36 t ha^{-1}), respectively, compared to the application of all nutrients in the blended form (Figure 4). Similarly, the omission of K, S, B, or Zn from all nutrients also had grain yield penalties of −8.8% (−0.53 t ha^{-1}), −4.5% (−0.28 t ha^{-1}), −3.5% (−0.22 t ha^{-1}), or −2.4% (−0.15 t ha^{-1}) relative to the application of all nutrients in the blended form. Among the nutrients, the magnitude of grain yield penalty due to omission of K looked relatively the highest, indicating its potential importance in maize production. However, maize grain yield penalties were not significant (Figure 4).

As farmers attempt to evaluate the economic benefits of the shift in practice, it is necessary to conduct a partial budget analysis to identify rewarding fertilizer treatments. For a treatment to be considered a worthwhile option for farmers, the marginal rate of return (MRR) should be at least between 50% and 100% (CIMMYT, 1988). Thus, for this study to make farmer recommendations from marginal analysis, a 100% return on the investment is a reasonable minimum acceptable rate of return. As a result, the highest net benefit (NB) of \$2735.65 ha^{-1} was recorded from the applications of all nutrients in the blended form, followed by NBs of \$2671.15 and \$2642.67 ha^{-1} from All-Zn and All-B treatments, respectively (Table 6). The unfertilized control treatment received the lowest NB of \$785.10 ha^{-1}. Likewise, the highest marginal net benefit (MNB) of \$1950.55 ha^{-1} was recorded from all nutrients applied in the blended form, followed by the zinc-omitted treatment (\$1886.05 ha^{-1}). The K-omitted (\$1735.56 ha^{-1}) and boron-omitted (\$1857.57 ha^{-1}) treatments provided positive MNBs almost comparable to the value of the recommended NP treatment (Table 6). The lowest MNB of \$1512.00 ha^{-1} was recorded from the application of all nutrients in the individual form relative to the recommended NP rate (Table 6). Similar to the MNBs, the highest benefit-cost ratio (BCR) of 25.38 was recorded from the K-omitted treatment, followed by the BCRs of 23.34 from the addition of all nutrients sulfur-omitted, 23.06 from all nutrients in the blended form, and 22.93 from the boron-omitted treatment. The lowest BCR of 19.53 was obtained from the application of all nutrients in the individual form (Table 6).

4 | DISCUSSION

4.1 | Soil properties as influenced by landscape position

The spatial arrangement of landforms significantly affects soil properties along different landscape positions, influencing factors such as soil texture, nutrient content, and water-holding capacity, and consequently impacts crop yield across varying landscape strata. Upper slopes often have thinner soils with lower OM, nutrients, and water-holding capacity, leading to lower fertility and increased erosion risk, while MSs may have better soil properties than HSs, but are still susceptible to erosion and nutrient loss. In contrast, soils at lower slope positions tend to accumulate more OM and nutrients (Bufebo et al., 2021; Sun et al., 2021), resulting in higher fertility and water availability for crop growth and yield (Haile et al., 2024).

Soil quality is critical in improving water productivity, nutrient use efficiency, and crop yield (Z. Li et al., 2020). Soil pH, C, TN, available phosphorus (P), sulfur (S), zinc (Zn), and boron (B) showed significant variation due to land gradient differences and soil sampling depth. It was found that the FS position, followed by the MS position, had higher mean soil nutrient concentrations than the HS position, which is in line with the growth and yield of maize (Table 3). Previous studies also reported that higher mean values of SOC, TN, available P, cation exchange capacity (CEC), exchangeable cations, and available micronutrients were recorded at the lower landscape positions and forest land, while lower mean values of these nutrients were obtained from the upper landscape positions and intensively cultivated lands (Amare et al., 2013; Bufebo et al., 2021; Negasa et al., 2017). The gradient of land also directly affects soil-forming processes through erosion and deposition, and thus variations were observed in soil texture, N, P, and potassium (K) content along the topo-sequence (Eshett et al., 1989; Posner & Crawford, 1992; Yamauchi, 1992).

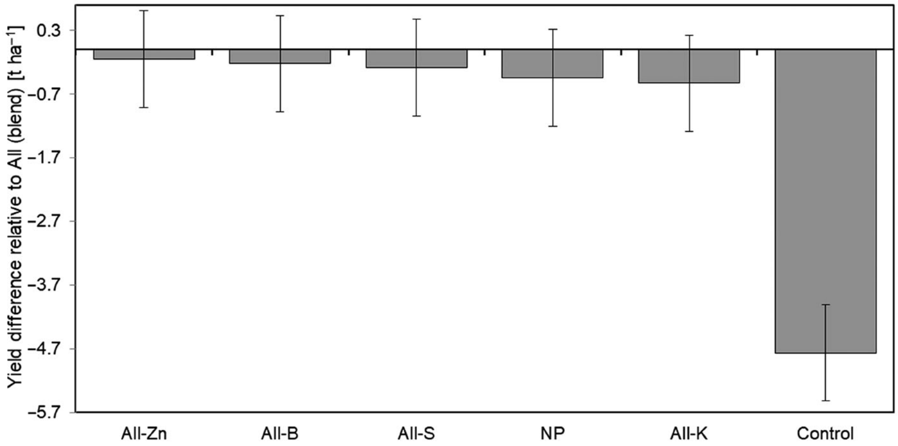


FIGURE 4 Grain yield (t ha^{-1}) differences of maize in response to applications of different nutrients relative to the application of all nutrients in a blended form.

TABLE 6 Partial budget and dominance analysis of different fertilizer treatments for maize production

	Treatments								
Partial budget	Control	NP	All (blended)	All (compound)	All (individual)	All-K	All-S	All-Zn	All-B
GY (t ha^{-1})	1.79	6.07	6.52	5.98	5.52	5.99	6.24	6.37	6.30
GB ($ ha^{-1})	785.10	2662.28	2859.65	2622.81	2421.10	2627.19	2736.84	2793.87	2763.16
N	0.00	65.35	65.35	65.35	65.35	65.35	65.35	65.35	65.35
P	0.00	61.33	26.63	26.63	26.63	26.63	26.63	26.63	26.63
K	0.00	0.00	20.47	20.47	20.47	0.00	20.47	20.47	20.47
S	0.00	0.00	6.75	6.75	6.75	6.75	0.00	6.75	6.75
Zn	0.00	0.00	1.28	1.28	1.28	1.28	1.28	0.00	1.28
B	0.00	0.00	3.51	3.51	3.51	3.51	3.51	3.51	0.00
TVC ($ ha^{-1})	0.00	126.68	124.00	124.00	124.00	103.53	117.25	122.72	120.49
NB ($ ha^{-1})	785.10	2535.65	2735.65	2498.81	2297.10	2523.66	2619.59	2671.15	2642.67
MNB ($ ha^{-1})		1750.50	1950.55	1713.71	1512.00	1738.56	1834.49	1886.05	1857.57
MRR (%)		13.82	15.73	13.82	12.19	16.79	15.65	13.37	15.42
BCR	–	21.02	23.06	21.15	19.53	25.38	23.34	22.77	22.93

Abbreviations: BCR, benefit-cost ratio; GB, gross benefit; GY, grain yield; MNB, marginal net benefit; MRR, marginal rate of return; NB, net benefit; RNP, recommended N, P, K, S, Zn, and B fertilizer; TVC, total variable cost.

The significance of soil OM in terms of improving soil biophysical and chemical properties is of paramount importance. As soil OM increases, so does soil TN content, CEC, and other soil physicochemical and biological properties, such as water-holding capacity and microbiological activity (Amede et al., 2021; Murphy, 2015). In this study, however, the soil OC was low due to the removal of crop residues, soil erosion, and a cereal-dominated cropping system (Table 3). The study of Hammad et al. (2020) indicated that the addition of organic amendments significantly improved wheat yield response to inorganic fertilizer application, soil physicochemical properties, and soil moisture content. Since soluble inorganic P is fixed by oxides and hydroxides of Al and iron (Fe) in acid soils, its availability is normally limited and uptake by plants is significantly reduced. Previous studies also indicated that the sorption of P was significantly correlated with exchangeable and extractable forms of aluminum (Al) and iron (Fe), as well as pH and OM, and Al was more important than Fe in terms of being more soluble in low pH soils and interfering with P uptake (Mamo & Haque, 1987; Sumner & Noble, 2003).

The fertility status of the experimental soils was not ideal for maize production, with initial soil pH, TC, TN, and available P as low as 5.1, 0.83%, 0.11%, and 0.05 mg kg^{-1}, respectively. Soil pH influences the availability of both macro- and micronutrients (Hazelton & Murphy, 2007) and hence crop yields (Du et al., 2024). According to the soil Zn and boron sufficiency range (Horneck et al., 2011), the concentrations of Zn and B in the soil were low, ranging between 0.14 and 1.26 mg kg^{-1} and 0.04 and 0.13 mg kg^{-1}, respectively. Zinc deficiency is common in plants growing in highly weathered acidic or calcareous soils (Alloway, 2009). The benefit of Zn application on grain quality improvements above their baseline levels will also be affected by various soil factors, such as landscape variability and soil pH. A deficiency of boron may occur if its extractable concentration is less than 0.5 in most crops, and low levels of boron may limit plant growth and yield, while high concentrations can be toxic. If the concentration of boron is greater than 2, it is excessive, and boron toxicity may occur in sensitive crops (Horneck et al., 2011). For cereal crops, grain analysis is the most reliable indicator of boron toxicity. In most cases, soils with a pH less than 5.5 are deficient in available P and exchangeable cations (Marschner, 2011), and P becomes unavailable to plants (Agegnehu et al., 2021; Marschner, 2011) unless amended with lime. Higher variability in crop yield under poor soil conditions may have been related to high variability in the less fertile environment. According to Horneck et al. (2011), S concentrations of the experimental soils were from low to very low, which is insufficient to meet the crop's demand. Studies over locations indicated that 17 kg K and 10 kg S ha^{-1} were recommended for maize (Bekele et al., 2022), and 18 kg K and 10 kg S ha^{-1} for wheat (Dargie et al., 2022), depending on soil type.

4.2 | Influence of landscape position on maize yield

Our results demonstrated large variability in maize yields among landscape positions and testing sites, even within the same soil types, same treatments, and within short distances, despite similar trends of responses across landscape positions and sites. The yield of maize recorded at the FS position was the highest. Conversely, the lowest yield of maize was observed at the hill slope, with intermediate values at the MS (Table 4). This indicated that applications of similar types and amounts of nutrients along the toposequence resulted in variable yield responses. Those differences in yield along the landscape positions could be linked to the major variations in the levels of nutrients and water contents of the soils of the study areas (Amede et al., 2020; Bufebo et al., 2021; Desta et al., 2023). The three landscape positions in the Alefa and Takussa districts of the Amhara region and the Sokoru district of the Oromia region varied significantly in their soil fertility levels due to the continuous removal of essential plant nutrients from the slopes of the hill and the MS, and deposition down to the lower position. This may degrade the HS positions and make them unsuitable for crop production over time, unless appropriate intervention measures are taken to halt the removal of soils and nutrients through erosion and leaching from upper to low-lying topographic positions.

In line with our current results, previous studies conducted in the country and elsewhere showed that variations in soil fertility (Amede et al., 2020; Desta et al., 2023) and plant-available water (Afyuni et al., 1993) at different landscape positions were the most important factors controlling maize production. In this regard, Afyuni et al. (1993) reported that the FS position had the greatest amount of plant-available water on the longer transect than the other landscape positions. The relatively higher fertility (Agegnehu et al., 2023; Gedamu et al., 2023) and soil water contents (Afyuni et al., 1993) at the FS positions implied that the soil is responsive to the applied fertilizers, and water is available for the crop during the growing period, including sensitive stages to water deficit (Hall et al., 1980; Otegui et al., 1995). Hence, applying more fertilizer to the deep MS and FSs, but less to the shallow HSs, based on soil fertility status, site-specific fertilizer recommendations will improve nutrient use efficiency and crop yield, and benefit farmers. Similar results on the variances of crop yields along the landscape positions were previously reported for other crops in different areas (Desta et al., 2022; Gedamu et al., 2023).

Realizing how yield varies across different landscape positions is critical for producers to optimize nutrient use efficiency. Topographic features, such as slope and elevation, influence soil properties and moisture availability, leading to varying crop responses to fertilizer applications (Amede et al., 2020; Desta et al., 2022). Because soil fertility gradients along the topo-sequence could significantly influence nutrient use efficiency, reducing fertilizer losses and yield variability (Haneklaus & Schnug, 2000; Turner & Hiernaux, 2015). Therefore, the formulation of optimal fertilizer recommendations relying on landscape positions having clusters of similar segments of topographies, soil types, fertility classes, and moisture levels along the topo-sequence is vital. Application of manure, crop residues, green manures, and other alternative organic sources of fertilizers integrated with soil and water conservation measures is suggested, particularly to the hill slope positions, to enhance the response to the applied nutrients and sustainably intensify the productivity of the soil and crops. Applying organic fertilizers to the HS position also helps to minimize the risk of downstream nutrient movement since relatively higher doses of mineral fertilizers are usually applied to offset the lower potential of the soils in this position. Overall, optimizing fertilizer rates at the FS based on landscape positions through site-specific nutrient management and recommendations will also be crucial to enhance nutrient use efficiency, and produce and sustain higher crop yields.

Great spatial variability among landscape positions denotes that yield variability is an indicator of variation in soil fertility and its responsiveness to nutrient applications (Desta et al., 2022; Schut et al., 2018; Yao et al., 2014). The results of our study indicate that local factors are much more influential in explaining the heterogeneity in maize yield and yield response to fertilizer application. These variations are attributed to highly diverse farming systems and environmental factors such as soil, topography, and water availability that vary strongly among farms and landscape positions (Agegnehu et al., 2023; Tittonell et al., 2008; Yao et al., 2014). The spatial variability is further exacerbated by heterogeneous soil and crop management practices, such as crop rotation, intercropping, crop residue retention, and applying soil amendments, which are common among farmers' fields (Amede et al., 2020; Tamene et al., 2017).

4.3 | Influence of nutrient type and source on maize yield

The productivity of maize without external inputs was very low in this study. This signaled the need for applying fertilizer at the recommended rates to alleviate nutrient deficiencies in the soils and improve maize yield. Maize yield could be significantly increased by about 208%–264% due to fertilizer application compared to the control without fertilizer. The huge yield difference between fertilized and unfertilized treatments indicated the gap for a large potential to boost maize yield by optimizing nutrients. The most yield-limiting nutrients identified in the study areas are N and P, which agrees well with the nationwide study that confirmed N and P are highly deficient in Ethiopian soils (EthioSIS, 2015). In many areas in Ethiopia, P deficiency is associated with low P reserves, and in other areas, it is due to a high soil P absorption capacity (Nziguheba et al., 2016).

Our study revealed that the yield of maize could be reduced by about 264 compared to the control without the application of any fertilizer. The blending of K, S, Zn, and B with N and P could increase the total biomass and grain yields of maize by only 2.9% and 3.6%, respectively, indicating that the addition of all nutrients did not result in significant yield increments over the application of N and P nutrients alone (Table 5). Our result confirmed that the omission of K, S, Zn, and B did not significantly decrease maize yield in the study locations, indicating that they are not yield-limiting. Thus, N and P are the most important nutrients for maize production in the study areas. Soil survey results across the Amhara and Oromia regions (EthioSIS, 2015) also depicted that N and P are among the most yield-limiting nutrients in the maize production system, including the study areas. Amare et al. (2022) reported the nonsignificant influence of K, S, Zn, and B on maize growth and yield. Similarly, Van Eynde et al. (2023) also reported that the addition of Zn did not improve maize yield in Sub-Saharan Africa. In contrast to our current results, applying K, S, Zn, and B increased cereal crop yields in the central highlands of Ethiopia (Abebe et al., 2018; Dargie et al., 2022). The improvement in maize yield with the application of P and B was reported by Ao & Sharma (2021). Another study contradicting this finding stated that maize yield was increased through the application of K nutrient at a higher rate (Ali et al., 2020). The findings of this study showed that it will be necessary to adopt site- and context-specific fertilizer recommendations in the country to improve nutrient use efficiency and sustainable yields of crops.

The application of N and P nutrients is highly required to boost the yield of maize in Ethiopia because N and P are essential plant nutrients for maize production since they govern the most important biochemical, morphological, and physiological processes (Biswas & Ma, 2016; Yang et al., 2017). Thus, the application of optimum levels of fertilizers to the N- and P-deficient soils, adjusting their rates to the requirements of the crop, and eliminating all soil factors that restrict nutrient absorption from the soil are required to improve the efficiency of nutrients and attain higher maize yield (Barłóg et al., 2022). According to Singh et al. (2023), the forms and dynamics of nutrient uptake depend on many factors, including environmental conditions, soil type, and management practices. Phosphorus is one of the main nutrients that limit crop production in Sub-Saharan Africa. Excessive use of N and P fertilizers not only escalates the cost of production for smallholder farmers but can also bring adverse impacts on the environment (Duan et al., 2019; Liu et al., 2018) and human health due to increased concentrations of nitrogen dioxide (de Vries, 2021). On the other hand, application of N and P fertilizers lower than the optimum limit results in poor crop establishment, stunted growth, and ultimately reduced grain yield and quality. Nitrogen is the world's most widely utilized nutrient, followed by P and K. However, studies showed that crops could utilize less than 50% of applied N, the rest being lost to the environment (Govindasamy et al., 2023). Based on studies among agroecological zones in the Upper Blue Nile basin of Ethiopia, Mulualem et al. (2021) reported that the extent of TN and available P losses from the root zone of the soil through runoff, leaching, gaseous emissions, and crop harvest ranged from 40 to 56 and 4 to 6 kg ha^{-1} year^{-1}, respectively.

The results of this study revealed that the omission of all nutrients significantly negatively affected maize yield across sites. The omission of all nutrients resulted in the lowest grain and biomass yields of maize, with higher penalties indicating that the soils of the study areas are deficient in the major essential plant nutrients, especially N and P. Our results showed that the application of all nutrients in blended form gave circa 9% and 3% higher grain and biomass yields, respectively (Table 3), than the application of NP only. Overall, the application of nutrients in blend form exhibited relatively better performance compared to the application of the same nutrients in compound and individual forms in improving maize productivity. Despite those increases, the changes in yields of maize were not found to be significant. In contrast to our results, N. Li et al. (2022) reported 2.3%–12.2% higher grain yield of wheat and 8.6%–43.9% higher N use efficiency of wheat with the application of fertilizer in compound compared to blend forms.

The results also indicated that statistically significant differences were not observed in the total biomass, straw, and grain yields of maize among applications of all nutrients in the blended, compound, and individual forms (Figure 3). This implies that the fertilizer formulations (blended, compound, or individual) and sources did not result in a significant influence on maize yield as long as all the nutrients were applied. According to Wang et al. (2017), as compound fertilizers contain nutrients such as N, P, K, S, Zn, and B in each fertilizer granule, different from blended fertilizers that contain mixtures of nutrients (fertilizers) in their granules, their benefits in maize production cannot be overlooked. Owing to the higher yields, flexibility in the nutrient ratio adjustment, and nutrient release rates of blended fertilizers (Guo et al., 2021; Miserque & Pirard, 2004), their uses are encouraged. Considering the comparable yield with nutrients in blended forms, ease of use, and richness in various nutrients, nutrients in compound forms are also suggested for use by farmers. Thus, based on the results of this study and the merits they have, the use of nutrients in blended or compound forms is recommended for maize production.

The pronounced yield loss of maize in response to the omission of all nutrients could partially be attributed to very low SOC and consequently the lower N contents of the experimental soils. Soils with lower SOC contents have low water-holding and nutrient-retention capacity, resulting in poor water and nutrient uptake and low nutrient use efficiency. Previous studies proved negative SOC balance, which extended up to −3.7 t ha^{-1} $year^{-1}$, with higher depletion rates in the hilly and intensively cultivated areas of the cereal-based cropping systems (van Beek et al., 2018). Likewise, negative balances were reported for N in a range of soil types. For instance, studies conducted on nutrient balances from different periods and cropping systems in Ethiopia have also shown that the N balance in different soils varied from −20 to −185 kg N ha^{-1} in the central Ethiopian highlands (Haileslassie et al., 2006; Tulema et al., 2007), -23 ± 73 kg ha^{-1} across the high potential highlands of Ethiopia (Van Beek et al., 2016), and 39.6 to 55.5 kg ha^{-1} $year^{-1}$ in three contrasting agroecological zones of the Upper Blue Nile Basin of Ethiopia (Mulualem et al., 2021). The N outflows far exceed the inflows, indicating that the depletion rate of N is high.

One of the hypotheses of this study was that applying K, S, Zn, or B with N and P would increase the growth and yield of maize. However, our results indicated that the omission of either one or all of these nutrients had little or negligible effect on the reduction in maize yield in most study sites, except for some responses to the omission of K, S, Zn, or B in some localized maize-producing areas. For instance, maize responded to the application of K in the Gobu Sayo area and secondary and micronutrients at Adami Tullu in the Oromia Region (Balemi et al., 2019), and teff responded to the application of K on Vertisols of selected sites in Ethiopia (Demiss et al., 2020). Another study by Dargie et al. (2022) also indicated that 19% and 50% grain yield increments were observed with the application of K in some pocket wheat production areas on Vertisols in tepid moist mid-highlands agroecology, and a 20% yield increment with the application of S in tepid moist mid-highlands agroecology. Brhane et al. (2017) also reported a 29.3% yield increment of wheat due to the application of 30 kg ha^{-1} K_2O compared to the application of the recommended 8 kg K_2O with NPSZn as blended fertilizer. Thus, such localized areas need further study to assess the status of these nutrients in the soils and consider their application before reaching yield-limiting levels.

The partial budget analysis indicated that the highest MNB of \$1950.55 ha^{-1} and NB of \$2735.65 ha^{-1} were recorded with the application of all nutrients in the blended form. This implies that N and P could be more efficiently utilized in maize production systems when K is applied. According to Zingore et al. (2022), the application of NPK was superior to N and P in terms of partial factor productivity of N and P for maize and rice production.

4.4 | Influence of spatial variability on maize yield

It has been assumed that fertilizer recommendations have similar responses to fertilizer application across farmers' fields of a certain landscape position. As shown in the results of this study, however, the actual crop response significantly varied with fertilizer application. This indicates that the interaction of landscape position with soil and topographic factors and agronomic practices has strongly influenced crop yield response to fertilizer application. Similar studies reported the causes of the variations in the response of crops to fertilizer applications, considering different factors (Agegnehu & Amede, 2017; Schut et al., 2018). Thus, the study of the response to applied nutrients at a local scale is advisable to capture field variations explained in soil fertility differences within short distances.

The purpose of developing site-specific fertilizer recommendations is to identify and manage spatially similar areas within a landscape that present a homogenous combination of yield-limiting factors (Córdoba et al., 2016). Thus, the largest spatial variation that was explained between landscape positions made it difficult to determine homogenous fertilizer response zones, as there are too many limiting factors. Thus, the need for understanding the relationship between the spatial variability of crop fields and yields has been important because of the growing concern for the efficient utilization of fertilizer (Yao et al., 2014). Managing soil spatial variability by applying inorganic and organic sources of nutrients is the normal approach for site-specific plant nutrient management (Reyes et al., 2019).

5 | CONCLUSIONS

The findings of our study indicated wide variability in maize yield responses to the application of different nutrients under different landscape positions, where the highest and lowest yields were observed at the FS and HS positions, respectively. This suggests the need for site-specific nutrient management for each landscape position in contrast to the existing blanket recommendations across all landscape strata. Optimization of nutrients at each landscape position is required to enhance the yield of maize. It is necessary to target nutrient sources and rates based on the responsiveness of the soil, where FSs require higher rates than the MS and HS positions, as they are more responsive to the application of inorganic fertilizers. On the other hand, as the HSs are highly degraded due to the continued soil erosion and nutrient mining, the use of organic and inorganic amendments such as animal and green manure, retention of crop residues, and lime is required to improve the overall soil biophysical and chemical properties and make it responsive to the application of mineral fertilizers. Surprisingly, maize yield differences among the nutrient forms were not significant when all nutrients were applied in blended, compound, or individual form. Significant yield differences were also not observed between applying NP only and all nutrients (NPKSZnB), implying that K, S, Zn, and B are not yield-limiting nutrients for maize production in the study areas. Thus, maize yield could be enhanced through appropriate management and application of N and P fertilizers at the required rates. Considering yield, flexibility, nutrient composition, and suitability of use, applying fertilizers in blended or compound form may be recommended for maize production. Despite the nonsignificant effects of macro- and micronutrients other than N and P on maize yield, further investigation is suggested to evaluate the benefits of these nutrients on the nutrient composition and quality of the grain, which is directly related to the nutritional quality of the grain for human consumption. Further research is also suggested to determine the optimum rates of N and P fertilizers to attain the biological and economic optimum yields of maize under each landscape position.

AUTHOR CONTRIBUTIONS

Getachew Agegnehu: Conceptualization; data curation; investigation; methodology; project administration; writing—original draft; writing—review and editing. **Zerfu Bazie**: Data curation; writing—original draft. **Gizaw Desta**: Investigation; methodology. **Kassu Tadesse**: Writing—original draft. **Gizachew Legesse**: Supervision. **Hirut Birhanu**: Data curation; supervision. **Habtamu Getnet**: Supervision. **Ayalew Addis**: Supervision. **Tarekegn Yibabie**: Supervision. **Beamlaku Alemayehu**: Data curation; supervision. **Fayisa Bulo**: Supervision. **Mulugeta Demiss**: Methodology; supervision. **Tilahun Amede**: Conceptualization; methodology. **Abiro Tigabe**: Validation. **John Wendt**: Conceptualization; methodology. **Latha Nagarajan**: Project administration; resources. **Upendra Singh**: Conceptualization; methodology. **Zachary Stewart**: Funding acquisition; resources.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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REFERENCES

Abebe, A., Abera, G., & Beyene, S. (2018). Assessment of the limiting nutrients for wheat (*Triticum aestivum* L.) growth using diagnosis and recommendation integrated system (DRIS). *Communications in Soil Science and Plant Analysis*, *49*(21), 2653–2663. https://doi.org/10.1080/00103624.2018.1526951

Afyuni, M., Cassel, D., & Robarge, W. (1993). Effect of landscape position on soil water and corn silage yield. *Soil Science*

Society of America Journal, *57*(6), 1573–1580. https://doi.org/10.2136/sssaj1993.03615995005700060030x

Agegnehu, G., & Amede, T. (2017). Integrated soil fertility and plant nutrient management in tropical agro-ecosystems: A review. *Pedosphere*, *27*(4), 662–680. https://doi.org/10.1016/S1002-0160(17)60382-5

Agegnehu, G., Amede, T., Desta, G., Erkossa, T., Legesse, G., Gashaw, T., Van Rooyen, A., Harawa, R., Degefu, T., Mekonnen, K., & Schulz, S. (2023). Improving fertilizer response of crop yield through liming and targeting to landscape positions in tropical agricultural soils. *Heliyon*, *9*, e17421. https://doi.org/10.1016/j.heliyon.2023.e17421

Agegnehu, G., Amede, T., Erkossa, T., Yirga, C., Henry, C., Tyler, R., Nosworthy, M. G., Beyene, S., & Sileshi, G. W. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: A review. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *71*, 852–869. https://doi.org/10.1080/09064710.2021.1954239

Ali, A., Adnan, M., Safdar, M., Asif, M., Mahmood, A., Nadeem, M., Javed, M. A., Ahmad, S., Qamar, R., & Bilal, H. (2020). Role of potassium in enhancing growth, yield and quality of maize (*Zea mays* L.). *International Journal of Biosciences*, *16*(6), 210–219.

Alloway, B. J. (2009). Soil factors associated with zinc deficiency in crops and humans. *Environmental Geochemistry and Health*, *31*(5), 537–548. https://doi.org/10.1007/s10653-009-9255-4

Amare, T., Alemu, E., Bazie, Z., Woubet, A., Kidanu, S., Alemayehu, B., Awoke, A., Derebe, A., Feyisa, T., Tamene, L., Kerebh, B., Wale, S., & Mulualem, A. (2022). Yield-limiting plant nutrients for maize production in northwest Ethiopia. *Experimental Agriculture*, *58*, e5. https://doi.org/10.1017/S0014479721000302

Amare, T., Terefe, A., G Selassie, Y., Yitaferu, B., Wolfgramm, B., & Hurni, H. (2013). Soil properties and crop yields along the terraces and toposequece of Anjeni Watershed, Central Highlands of Ethiopia. *Journal of Agricultural Science*, *5*(2), 134–144. https://doi.org/10.5539/jas.v5n2p134

Amede, T., Gashaw, T., Legesse, G., Tamene, L., Mekonen, K., Thorne, P., & Schultz, S. (2020). Landscape positions dictating crop fertilizer responses in wheat-based farming systems of East African Highlands. *Renewable Agriculture And Food Systems*, *37*, 4–16. https://doi.org/10.1017/S1742170519000504

Amede, T., Legesse, G., Agegnehu, G., Gashaw, T., Degefu, T., Desta, G., Mekonnen, K., Schulz, S., & Thorne, P. (2021). Short term fallow and partitioning effects of green manures on wheat systems in East African highlands. *Field Crops Research*, *269*, 108175. https://doi.org/10.1016/j.fcr.2021.108175

Ao, M., & Sharma, Y. (2021). Influence of lime, phosphorus and boron on performance of maize (*Zea mays* L.) in acidic soil of Nagaland. *Annals of Plant and Soil Research*, *23*(1), 54–60. https://doi.org/10.47815/apsr.2021.10029

Assefa, B. T., Chamberlin, J., Reidsma, P., Silva, J. V., & van Ittersum, M. K. (2020). Unravelling the variability and causes of smallholder maize yield gaps in Ethiopia. *Food Security*, *12*, 83–103. https://doi.org/10.1007/s12571-019-00981-4

Balemi, T., Rurinda, J., Kebede, M., Mutegi, J., Hailu, G., Tufa, T., Abera, T., & Sida, T. S. (2019). Yield response and nutrient use efficiencies under different fertilizer applications in maize (*Zea mays* L.) in contrasting agro ecosystems. *International Journal of Plant & Soil Science*, *29*(3), 1–19.

Barłóg, P., Grzebisz, W., & Łukowiak, R. (2022). Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. *Plants*, *11*(14), 1855. https://doi.org/10.3390/plants11141855

Bekele, I., Lulie, B., Habte, M., Boke, S., Hailu, G., Mariam, E. H., Ahmed, J. S., Abera, W., & Sileshi, G. W. (2022). Response of maize yield to nitrogen, phosphorus, potassium and sulphur rates on Andosols and Nitisols in Ethiopia. *Experimental Agriculture*, *58*, e11. https://doi.org/10.1017/S0014479722000035

Belete, T. (2016, June 27–July 1). *The role of DSM in transforming agriculture: The case of Ethiopian Soil Information System (EthioSIS)* [Paper presentation]. 7th Global DSM Workshop, Aarhus, Denmark.

Biswas, D. K., & Ma, B.-L. (2016). Effect of nitrogen rate and fertilizer nitrogen source on physiology, yield, grain quality, and nitrogen use efficiency in corn. *Canadian Journal of Plant Science*, *96*(3), 392–403. https://doi.org/10.1139/cjps-2015-0186

Brhane, H., Mamo, T., & Teka, K. (2017). Potassium fertilization and its level on wheat (*Triticum aestivum*) yield in shallow depth soils of Northern Ethiopia. *Journal of Fertilizers and Pesticides*, *8*(02), 8–10.

Bufebo, B., Elias, E., & Agegnehu, G. (2021). Effects of landscape positions on soil physicochemical properties at Shenkolla Watershed, South Central Ethiopia. *Environmental Systems Research*, *10*(1), Article 14. https://doi.org/10.1186/s40068-021-00222-8

Carter, M., & Stewart, B. (1996). *Structure and organic matter storage in agricultural soils*. CRC Press Inc.

CIMMYT. (1988). *From agronomic data to farmer recommendations: An economics training manual* (Completely revised edition). CIMMYT.

Córdoba, M. A., Bruno, C. I., Costa, J. L., Peralta, N. R., & Balzarini, M. G. (2016). Protocol for multivariate homogeneous zone delineation in precision agriculture. *Biosystems engineering*, *143*, 95–107. https://doi.org/10.1016/j.biosystemseng.2015.12.008

CSA. (2021). *Report on area, production and yield of crops for private peasant holdings for main crop season 2020/21* (Statistical Bulletin no. 589). Central Statistical Authority (CSA).

Dargie, S., Girma, T., Chibsa, T., Kassa, S., Boke, S., Abera, A., Haileselassie, B., Addisie, S., Amsalu, S., Haileselassie, M., Soboka, S., Abera, W., & Weldesemayat, S. G. (2022). Balanced fertilization increases wheat yield response on different soils and agroecological zones in Ethiopia. *Experimental Agriculture*, *58*, e23. https://doi.org/10.1017/S0014479722000151

Demiss, M., Mamo, T., Beyene, S., & Kidanu, S. (2020). Effect of potassium levels on teff (*Eragrostis tef* (*Zucc.*) *Trotter*) growth and yield in Central Highland Vertisols of Ethiopia. *Eurasian Journal of Soil Science*, *9*(2), 105–118.

Desta, G., Amede, T., Gashaw, T., Legesse, G., Agegnehu, G., Mekonnen, K., & Whitbread, A. (2022). Sorghum yield response to NPKS and NPZn nutrients along sorghum-growing landscapes. *Experimental Agriculture*, *58*, e10. https://doi.org/10.1017/S0014479722000072

Desta, G., Legesse, G., Agegnehu, G., Tigabie, A., Nagaraji, S., Gashaw, T., Degefu, T., Ayalew, B., Addis, A., & Getachew, T. (2023). Landscape-based nutrient application in wheat and teff mixed farming systems of Ethiopia: Farmer and extension agent demand driven approach. *Frontiers in Sustainable Food Systems (TSI)*, *7*, 01–19. https://doi.org/10.3389/fsufs.2023.1241850

de Vries, W. (2021). Impacts of nitrogen emissions on ecosystems and human health: A mini review. *Current Opinion in Environmental Science & Health*, *21*, 100249. https://doi.org/10.1016/j.coesh.2021.100249

Du, L., Zhang, Z., Chen, Y., Wang, Y., Zhou, C., Yang, H., & Zhang, W. (2024). Heterogeneous impact of soil acidification on crop yield reduction and its regulatory variables: A global meta-analysis. *Field Crops Research*, *319*, 109643. https://doi.org/10.1016/j.fcr.2024.109643

Duan, J., Shao, Y., He, L., Li, X., Hou, G., Li, S., Feng, W., Zhu, Y., Wang, Y., & Xie, Y. (2019). Optimizing nitrogen management to achieve high yield, high nitrogen efficiency and low nitrogen emission in winter wheat. *Science of the Total Environment*, *697*, 134088. https://doi.org/10.1016/j.scitotenv.2019.134088

Du Prel, J.-B., Röhrig, B., & Blettner, M. (2009). Critical appraisal of scientific articles: Part 1 of a series on evaluation of scientific publications. *Deutsches Arzteblatt International*, *106*(7), 100. https://doi.org/10.3238/arztebl.2009.0100

Erenstein, O., Jaleta, M., Sonder, K., Mottaleb, K., & Prasanna, B. (2022). Global maize production, consumption and trade: Trends and R&D implications. *Food Security*, *14*(5), 1295–1319.

Erkossa, T., Laekemariam, F., Abera, W., & Tamene, L. (2022). Evolution of soil fertility research and development in Ethiopia: From reconnaissance to data-mining approaches. *Experimental Agriculture*, *58*, e4. https://doi.org/10.1017/S0014479721000235

Eshett, E., Omueti, J., & Juo, A. (1989). Soil properties and mineralogy in relation to land use on a sedimentary toposequence in south-eastern Nigeria. *The Journal of Agricultural Science*, *112*(3), 377–386. https://doi.org/10.1017/S0021859600085828

EthioSIS. (2015). *Fertilizer recommendation atlas of the Amhara and Oromia Regional States*. The Ethiopian Soil Information System (EthioSIS).

Fabozzi, F., Focardi, S., Rachev, T., & Arshanapalli, B. (2014). Appendix E: Model selection criterion: AIC and BIC. In *The basics of financial econometrics: Tools, concepts, and asset management applications* (pp. 399–403). Wiley.

FAOStat. (2021). *FAOSTAT*. FAO. http://www.fao.org/faostat

Gao, Y., Li, J., Ning, R., Zheng, Y., Song, W., Hou, P., Zhu, L., Jia, X., Zhao, Y., Song, W., Guo, R., & Guo, J. (2024). Evaluation of grain moisture content at maturity and screening for identification indexes of maize inbred lines. *Agronomy*, *14*(7), 1480. https://doi.org/10.3390/agronomy14071480

Gedamu, S. A., Aragaw, K. S., Abush, H. T., & Agegnehu, G. (2023). Response of Teff ((*Eragrostis tef* (*Zucc*.) *Trotter*) to nitrogen and phosphorus applications on different landscapes in eastern Amhara. *Heliyon*, *9*(7), e17813. https://doi.org/10.1016/j.heliyon.2023.e17813

Govindasamy, P., Muthusamy, S. K., Bagavathiannan, M., Mowrer, J., Jagannadham, P. T. K., Maity, A., Halli, H. M., Sujayanand, G. K., Vadivel, R., Das, T. K., Raj, R., Pooniya, V., Babu, S., Rathore, S. S., Muralikrishnan, L., & Tiwari, G. (2023). Nitrogen use efficiency—A key to enhance crop productivity under a changing climate. *Frontiers in Plant Science*, *14*, 1121073. https://doi.org/10.3389/fpls.2023.1121073

Guo, J., Fan, J., Zhang, F., Yan, S., Zheng, J., Wu, Y., Li, J., Wang, Y., Sun, X., Liu, X., Xiang, Y., & Li, Z. (2021). Blending urea and slow-release nitrogen fertilizer increases dryland maize yield and nitrogen use efficiency while mitigating ammonia volatilization. *Science of the Total Environment*, *790*, 148058. https://doi.org/10.1016/j.scitotenv.2021.148058

Haile, G., Gebru, C., Lemenih, M., & Agegnehu, G. (2024). Soil property and crop yield responses to variation in land use and topographic position: Case study from southern highland of Ethiopia. *Heliyon*, *10*(3), e25098. https://doi.org/10.1016/j.heliyon.2024.e25098

Haileslassie, A., Priess, J. A., Veldkamp, E., & Lesschen, J. P. (2006). Smallholders' soil fertility management in the Central Highlands of Ethiopia: Implications for nutrient stocks, balances and sustainability of agroecosystems. *Nutrient Cycling in Agroecosystems*, *75*(1–3), 135–146. https://doi.org/10.1007/s10705-006-9017-y

Hall, A., Ginzo, H., Lemcoff, J., & Soriano, A. (1980). Influence of drought during pollen-shedding on flowering, growth and yield of maize [*Zea mays*]. *Zeitschrift fuer Acker-und Pflanzenbau*, *149*(4), 287–298.

Hammad, H. M., Khaliq, A., Abbas, F., Farhad, W., Fahad, S., Aslam, M., Shah, G. M., Nasim, W., Mubeen, M., & Bakhat, H. F. (2020). Comparative effects of organic and inorganic fertilizers on soil organic carbon and wheat productivity under arid region. *Communications in Soil Science and Plant Analysis*, *51*(10), 1406–1422. https://doi.org/10.1080/00103624.2020.1763385

Haneklaus, S., & Schnug, E. (2000). Decision-making strategies for the variable-rate application of compound fertilizers. *Communications in Soil Science and Plant Analysis*, *31*(11–14), 1863–1873. https://doi.org/10.1080/00103620009370543

Hazelton, P., & Murphy, B. (2007). *Interpreting soil test results: What do all the numbers mean?* CSIRO Publishing. https://doi.org/10.1071/9780643094680

Horneck, D. A., Sullivan, D. M., Owen, J. S., & Hart, J. M. (2011). *Soil test interpretation guide*. Oregon State University.

Horwitz, W. (2000). *Official methods of analysis of AOAC International. Volume I, agricultural chemicals, contaminants, drugs*. AOAC International.

ICRISAT. (2017). *Feeding degraded soils in Ethiopia to feed the people and the environment*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). https://oar.icrisat.org/10363/1/Flyer%20on%20wheat%20based%20farming%20systems%20in%20Ethiopia.pdf

Li, N., Yang, Y., Wu, Y., Liu, B., Tao, L., Zhan, Y., Ni, X., & Yang, Y. (2022). Better performance of compound fertilizers than bulk-blend fertilizers on reducing ammonia emission and improving wheat productivity. *Agriculture, Ecosystems & Environment*, *335*, 108018.

Li, Z., Zhang, Q., Wei, W., Cui, S., Tang, W., & Li, Y. (2020). Determining effects of water and nitrogen inputs on wheat yield and water productivity and nitrogen use efficiency in China: A quantitative synthesis. *Agricultural Water Management*, *242*, 106397. https://doi.org/10.1016/j.agwat.2020.106397

Liu, W., Wang, J., Wang, C., Ma, G., Wei, Q., Lu, H., Xie, Y., Ma, D., & Kang, G. (2018). Root growth, water and nitrogen use efficiencies in winter wheat under different irrigation and nitrogen regimes in North China Plain. *Frontiers in Plant Science*, *9*, 1798. https://doi.org/10.3389/fpls.2018.01798

Mamo, T., & Haque, I. (1987). Phosphorus status of some Ethiopian soils. *Plant and Soil*, *102*(2), 261–266. https://doi.org/10.1007/BF02370713

Marschner, H. (2011). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, *15*(12), 1409–1416. https://doi.org/10.1080/00103628409367568

Miserque, O., & Pirard, E. (2004). Segregation of the bulk blend fertilizers. *Chemometrics and Intelligent Laboratory Systems*, *74*(1), 215–224. https://doi.org/10.1016/j.chemolab.2004.03.017

Mulualem, T., Adgo, E., Meshesha, D. T., Tsunekawa, A., Haregeweyn, N., Tsubo, M., Ebabu, K., Kebede, B., Berihun, M. L., Walie, M., Mekuriaw, S., & Masunaga, T. (2021). Exploring the variability of soil nutrient outflows as influenced by land use and management practices in contrasting agro-ecological environments. *Science of the Total Environment*, *786*, 147450. https://doi.org/10.1016/j.scitotenv.2021.147450

Murphy, B. (2015). Impact of soil organic matter on soil properties—A review with emphasis on Australian soils. *Soil Research*, *53*(6), 605–635. https://doi.org/10.1071/SR14246

Negasa, T., Ketema, H., Legesse, A., Sisay, M., & Temesgen, H. (2017). Variation in soil properties under different land use types managed by smallholder farmers along the toposequence in southern Ethiopia. *Geoderma*, *290*, 40–50. https://doi.org/10.1016/j.geoderma.2016.11.021

Nziguheba, G., Tossah, B. K., Diels, J., Franke, A. C., Aihou, K., Iwuafor, E. N. O., Nwoke, C., & Merckx, R. (2009). Assessment of nutrient deficiencies in maize in nutrient omission trials and long-term field experiments in the West African Savanna. *Plant and Soil*, *314*, 143–157. https://doi.org/10.1007/s11104-008-9714-1

Nziguheba, G., Zingore, S., Kihara, J., Merckx, R., Njoroge, S., Otinga, A., Vandamme, E., & Vanlauwe, B. (2016). Phosphorus in smallholder farming systems of sub-Saharan Africa: Implications for agricultural intensification. *Nutrient Cycling in Agroecosystems*, *104*, 321–340. https://doi.org/10.1007/s10705-015-9729-y

Otegui, M. E., Andrade, F. H., & Suero, E. E. (1995). Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Research*, *40*(2), 87–94. https://doi.org/10.1016/0378-4290(94)00093-R

Posner, J. L., & Crawford, E. W. (1992). Improving fertilizer recommendations for subsistence farmers in West Africa: The use of agro-economic analysis of on-farm trials. *Fertilizer Research*, *32*(3), 333–342. https://doi.org/10.1007/BF01050371

Reyes, J., Wendroth, O., Matocha, C., & Zhu, J. (2019). Delineating site-specific management zones and evaluating soil water temporal dynamics in a farmer's field in Kentucky. *Vadose Zone Journal*, *18*(1), 1–19. https://doi.org/10.2136/vzj2018.07.0143

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, R. J., Izac, A.-M. N., Mokwunye, A. U., Kwesiga, F. R., Ndiritu, C. G., & Woomer, P. L. (1997). Soil fertility replenishment in Africa: An investment in natural resource capital. In R. J. Buresh, P. A. Sanchez, & F. Calhoun (Eds.), *Replenishing soil fertility in Africa* (pp. 1–46). SSSA Special Publication 51. SSSA. https://doi.org/10.2136/sssaspecpub51.c1

Schut, A. G., Traore, P. C. S., Blaes, X., & de By, R. A. (2018). Assessing yield and fertilizer response in heterogeneous smallholder fields with UAVs and satellites. *Field Crops Research*, *221*, 98–107. https://doi.org/10.1016/j.fcr.2018.02.018

Sileshi, G. W., Kihara, J., Tamene, L., Vanlauwe, B., Phiri, E., & Jama, B. (2022). Unravelling causes of poor crop response to applied N and P fertilizers on African soils. *Experimental Agriculture*, *58*, e7. https://doi.org/10.1017/S0014479721000247

Singh, R., Sawatzky, S. K., Thomas, M., Akin, S., Zhang, H., Raun, W., & Arnall, D. B. (2023). Nitrogen, phosphorus, and potassium uptake in rain-fed corn as affected by NPK fertilization. *Agronomy*, *13*(7), 1913. https://doi.org/10.3390/agronomy13071913

Spielman, D. J., Kelemwork, D., & Alemu, D. (2013). Seed, fertilizer, and agricultural extension in Ethiopia. In P. Dorosh & S. Rashid (Eds.), *Food and agriculture in Ethiopia: Progress and policy challenges* (pp. 84–122). University of Pennsylvania Press. https://doi.org/10.9783/9780812208610

Sumner, M. E., & Noble, A. D. (2003). Soil acidification: The world story. In Z. Rengel (Ed.), *Handbook of soil acidity* (pp. 1–28). Marcel Dekker.

Sun, S., Zhang, G., He, T., Song, S., & Chu, X. (2021). Effects of landscape positions and landscape types on soil properties and chlorophyll content of citrus in a sloping orchard in the three gorges reservoir area, China. *Sustainability*, *13*(8), 4288. https://doi.org/10.3390/su13084288

Tamene, L. D., Amede, T., Kihara, J. M., Tibebe, D., & Schulz, S. (2017). *A review of soil fertility management and crop response to fertilizer application in Ethiopia: Towards development of site-and context-specific fertilizer recommendation*. CIAT Publication.

Tittonell, P., Vanlauwe, B., Corbeels, M., & Giller, K. E. (2008). Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant and Soil*, *313*, 19–37. https://doi.org/10.1007/s11104-008-9676-3

Tulema, B., Aune, J. B., & Breland, T. A. (2007). Availability of organic nutrient sources and their effects on yield and nutrient recovery of tef [*Eragrostis tef* (*Zucc*.) *Trotter*] and on soil properties. *Journal of Plant Nutrition and Soil Science*, *170*(4), 543–550. https://doi.org/10.1002/jpln.20052

Turner, M. D., & Hiernaux, P. (2015). The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. *Agriculture, Ecosystems & Environment*, *211*, 73–83.

Van Beek, C., Elias, E., Yihenew, G., Heesmans, H., Tsegaye, A., Feyisa, H., Tolla, M., Melmuye, M., Gebremeskel, Y., & Mengist, S. (2016). Soil nutrient balances under diverse agro-ecological settings in Ethiopia. *Nutrient Cycling in Agroecosystems*, *106*, 257–274.

van Beek, C. L. C., Elias, E., Selassie, Y. G., Gebresamuel, G., Tsegaye, A., Hundessa, F., Tolla, M., Mamuye, M., Yemane, G., & Mengistu, S. (2018). Soil organic matter depletion as a major threat to agricultural intensification in the highlands of Ethiopia. *Ethiopian Journal of Science and Technology*, *11*(3), 271–285.

Van Eynde, E., Breure, M. S., Chikowo, R., Njoroge, S., Comans, R. N., & Hoffland, E. (2023). Soil zinc fertilisation does not increase maize yields in 17 out of 19 sites in Sub-Saharan Africa but improves nutritional maize quality in most sites. *Plant and Soil*, *490*, 67–91.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L., & Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, *39*(1), 17–24.

Wang, Z.-B., Chen, J., Mao, S.-C., Han, Y.-C., Chen, F., Zhang, L.-F., Li, Y.-B., & Li, C.-D. (2017). Comparison of greenhouse gas emissions of chemical fertilizer types in China's crop production. *Journal of Cleaner Production*, *141*, 1267–1274. https://doi.org/10.1016/j.jclepro.2016.09.120

Yamauchi, M. (1992). Growth of rice plants in soils of toposequence in Nigeria. *Japanese Journal of Tropical Agriculture*, *36*(2), 94–98. https://doi.org/10.11248/jsta1957.36.94

Yang, X., Lu, Y., Ding, Y., Yin, X., Raza, S., & Tong, Y. (2017). Optimising nitrogen fertilisation: A key to improving nitrogen-use efficiency and minimising nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). *Field Crops Research*, *206*, 1–10. https://doi.org/10.1016/j.fcr.2017.02.016

Yao, R.-J., Yang, J.-S., Zhang, T.-J., Gao, P., Wang, X.-P., Hong, L.-Z., & Wang, M.-W. (2014). Determination of site-specific management zones using soil physico-chemical properties and crop yields in coastal reclaimed farmland. *Geoderma*, *232*, 381–393. https://doi.org/10.1016/j.geoderma.2014.06.006

Zelleke, G., Agegnehu, G., Abera, D., & Rashid, S. (2010). *Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system*. International Food Policy Research Institute (IFPRI).

Zingore, S., Adolwa, I. S., Njoroge, S., Johnson, J.-M., Saito, K., Phillips, S., Kihara, J., Mutegi, J., Murell, S., Dutta, S., Chivenge, P., Amouzou, K. A., Oberthur, T., Chakraborty, S., & Sileshi, G. W. (2022). Novel insights into factors associated with yield response and nutrient use efficiency of maize and rice in sub-Saharan Africa. A review. *Agronomy for Sustainable Development*, *42*(5), 82. https://doi.org/10.1007/s13593-022-00821-4

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