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Response of bread wheat (*Triticum aestivum* L) to nitrogen and phosphorus nutrient on Nitisols in Yilmana Densa district Northwest Ethiopia

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Abstract

In Ethiopia the two major yield limiting nutrients are Nitrogen (N) and Phosphorus (P). Existing NP rates for the production of cereal crops, including wheat, are very old and critically need revisiting and updating the economic and biological optimum rates. Thus, this research was conducted to determine the economical optimum rate of N and P for bread wheat (*Triticum aestivum* L.) in 2023 rainy season in the Nitisols of Yilmana Densa district, Northwest Ethiopia. The treatment consisted of five levels of nitrogen (69, 115, 161, 207 and 253 kg ha⁻¹) that were factorially combined with three levels of P₂O₅ (46, 69 and 92 kg ha⁻¹). A pilot treatment with no N and P was also added as a control to evaluate the overall performance of wheat under no fertilizer input. TAY bread wheat variety, which is widely adapted to the study area, was used as a test crop. Randomized complete block design with three replications was used for treatment arrangement. Soil samples disturbed and undisturbed were collected before planting. SAS version 9.0 software was used for analyzing and LSD at $P \leq 0.05$ used for separating treatment means. The result revealed that N and P₂O₅ significantly ($P < 0.05$) increased grain yield, straw yield, and other yield components of the bread wheat. The minimum grain (349.2 kg ha⁻¹) and straw (446.8 kg ha⁻¹) yield were obtained from the unfertilized plot. The combined application of 207 kg N and 69 kg P₂O₅ ha⁻¹ gave the maximum grain (3737 kg ha⁻¹) and straw (3606 kg ha⁻¹) yield. Finally, 207 N combined 69 kg P₂O₅ ha⁻¹ is economically feasible with a net benefit of (208,612.1 ET Birr) and 898.3% MRR and is therefore recommended for the production of bread wheat in the Nitisols of Yilmana Densa district. Furthermore, the findings provide a basis for updating the N and P₂O₅ application rates and developing site-specific fertilizer recommendations, which can help farmers achieve higher economic returns while maintaining soil fertility across variable soil conditions.

Keywords Bread wheat, Economical optimum, Nitisols, Nitrogen, Phosphorus

1 Introduction

Agriculture plays a big part in boosting Ethiopian frugality making up about 34.64% on its GDP. It generates about 70% of the country's economy and 73% of rural occupation [32]. Ethiopia must increase its grain production to feed its rapidly growing population



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[68]. Nevertheless, Ethiopian agriculture performance is strongly rainfall dependent [34] and characterized by highly unbalanced input–output farming systems that cause soil fertility decline, ultimately resulting unsustainable agriculture practices [32].

Lack of the required amount, unbalanced synthetic fertilizer input, and leaching of soil elements caused nutrient reduction [41]. Soil degradation is considered one of the major environmental and developmental challenges affecting food security. [27, 35]. Various studies indicated that, despite of the unique characteristics of Nitisols, the Ethiopian highlands have a few serious soil fertility management problems [29]. Yearly, Ethiopia sees a drop of about 122 kg N, and 13 P kg ha⁻¹ [64]. In Ethiopia farming scene, the soils losing key nutrients like N and P as studies by [4, 31, 73] pointed out. However, factors such as crop type and climatic variability also influence Ethiopia's food production [12].

Therefore, data generation and updating on soil fertility is critically important for evidence-based planning and appropriate actions towards sustainable plant nutrient management. Understanding the nature of soil properties and developing site-specific fertilizers recommendations are vital for sustainable plant nutrient management, increase crop yield, and ensuring national food security. Inorganic fertilizers play a vital role in sustaining a positive nutrient balance by replenishing nutrients removed through crop uptake and losses during the cropping cycle [8]. Otherwise, there would be nutrient imbalances between the output and input that results low crop productivity in Ethiopia [41, 48].

As sufficient soil nutrient availability and balance drive yield increase, fertilization is essential for economic grain yield formation during the growing period of crops [36, 52]. Applying nitrogen (N) and phosphorus (P) nutrients improves wheat biological yield, with grain yield showing a stronger response to N and P fertilization than to other nutrients [5]. The combination of of nitrogen and phosphorous at the proper time improves wheat grain yield as well as average protein content [22, 24, 57].

Wheat strategic crop worldwide over one-third of the world's population used as their main food source [23]. It provides about 19% of daily calorie intake and 21% of human protein consumption [32]. In Africa, the demand for wheat is rising fast because of population growth [61, 65]. Ethiopia imports around one million tons of wheat, which costs more than 500 million dollars [27].

Wheat is widely grown from mid-altitudes to highland of Ethiopia mainly in the Amhara, Oromia and Southern regions of Ethiopia by the support of the rainfall. While with irrigation, it has grown all over Ethiopia, even in the lowland areas. Bread wheat makes up about 17% of all cereal grain productions [19]. In Ethiopia wheat is one of the top cereal crops grown there, coming in third place after *teff* (*Eragrostis tef*) and maize (*Zea mays L*) [19]. Ethiopia produces about 5.8 million tons of wheat annually, which works out to about 3 tons per hectare. This is lower than what could be achieved, which is roughly 5 tons per hectare [33].

Yilmana Densa in the Amhara region looks like a great spot for growing wheat. To get the most yield without hurting the environment, it's important to give the plants just the right amount of nutrients they need [36]. In the study area, the recommendations for nitrogen and phosphorus rates were established more than a decade ago and are no longer sufficient to achieve the yield potential of bread wheat. Hence, updating the nitrogen and phosphorus application rates is essential.

Therefore, this research was conducted on farmer's fields to determine optimum rates of N and P nutrient for bread wheat production under the Nitisols.

2 Materials and methods

2.1 Description of the study area

The experiment was conducted on farmers fields in Debre Mewi and Konch Kebeles of Yilmana densa district under rain-fed conditions in the 2023/2024 cropping season. Debre mawi study site is located at 11° 21' 18" North latitude, 37°25' 43" East longitude, and an altitude of 2116, and Konch study site is located at 11°13' 53.1" North latitude, 37°28' 34.1" East longitude and an altitude of 2296 m.a.s.l. The study was conducted in mid-highland agro-ecology between 1500 and 2300 m.a.s.l., locally known as the Woyna Dega agro-climatic zone. It is characterized by a long dry season extending from November to April and a rainy season, which begins in May and continues until October. The rainfall pattern is uni-modal and annual rainfall of the study site is approximately 1162 mm (EMSA). The average minimum and maximum temperatures are between 10 and 26 °C, respectively (EMSA) Fig. 2. The average monthly rainfall distribution and minimum and maximum temperature from 2021 to 2023 of the study area are shown in Fig. 2. The experimental sites are generally characterized by a flat topography. The experimental fields' soil are classified as Nitisols. Mixed farming is the dominant farming system mainly under taken in the study area. Tef (*Eragrostis tef*), bread wheat (*Triticum aestivum* L), maize (*Zea mays* L)), barley (*Hordeum vulgare*), potato (*Solanum tuberosum*), field pea (*Pisum sativum*), faba bean (*Vicia faba*), and finger millet (*Eleusine coracana*) are the major crops cultivated in the district. Wheat is cultivated with a rotation of legumes and potatoes in the study area (Figs. 1,).

2.2 Experimental set up

The experiment had sixteen treatments; a control (as a satellite or pilot treatment), five rates of nitrogen (69, 115, 161, 207, 253 kg ha⁻¹) and three rates of phosphorus (46, 69, 92 kg ha⁻¹) combined in a factorial arrangement except for the control treatment. The

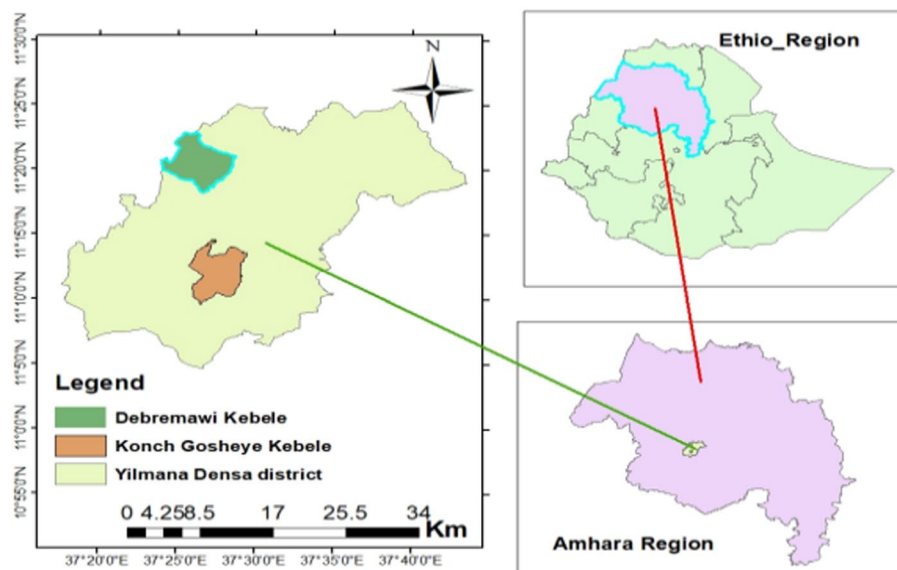


Fig. 1 Location map of the study area

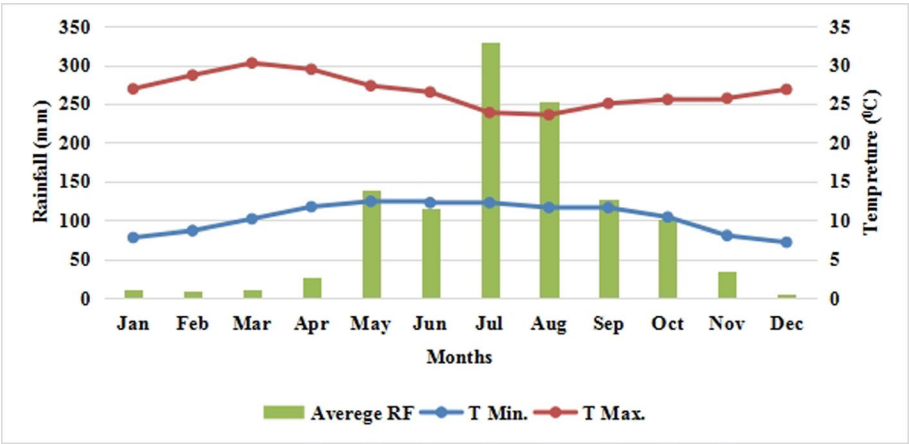


Fig. 2 Climate data of the study area from 2021 to 2023 Ethiopian Meteorological Service Agency (EMSA)

Table 1 Treatment details

Treatment	Treatment combination	
	Nitrogen (N kg ha ⁻¹)	Phosphorus (P ₂ O ₅ kg ha ⁻¹)
T1	0	0
T2	69	46
T3	69	69
T4	69	92
T5	115	46
T6	115	69
T7	115	92
T8	161	46
T9	161	69
T10	161	92
T11	207	46
T12	207	69
T13	207	92
T14	253	46
T15	253	69
T16	253	92

treatment details are shown in Table 1. The *TAY* bread wheat is nationally registered variety, which is released by Adet agriculture research center (AARC). It is well adapted to the study area [55] and was used as the test crop at a seeding rate of 150 kg ha⁻¹. Urea (46 N-0-0) and triple super-phosphate (TSP) (46 P₂O₅) were used as a source of nitrogen and phosphorus fertilizers, respectively.

2.3 Data collection preparation and analysis

2.3.1 Soil sampling and analysis before planting

The soil sample took from each test site before we started planting. The samples were taken in a zigzag pattern from 0 to 20 cm deep. Then, mixed all the samples from each site to get one combined sample. Also, some soil core samples were taken to determine the bulk density. The soil samples were dried out in the air and then pushed them through a 2 mm sieve to check all the soil parameters like soil pH, available phosphorous and CEC. A 0.5 mm was the sieve used to measure N and OC. The soil texture was determined using the Bouyoucos hydrometer method. Soil bulk density was determined

after drying the soil samples by oven drying at 105 °C. Soil bulk density was calculated by dividing the mass of oven-dried soil by the respective volume of the core sampler. In this study, a cylindrical core sampler with a diameter of 5 cm and a length of 5 cm volume approximately (98 cm³) was used. Soil pH was determined using a glass electrode pH meter in 1:2.5 soil water suspensions as described by Van Reewijk. Organic carbon was estimated by the wet digestion method of Walkley and Black. Available phosphorus was determined with the Olson method [62]. The Kjeldahl digestion method was used for determining total nitrogen [50]. Cation exchange capacity was measured after saturation the soil with 1N NH₄OAc and displacing it with 1N NaOAc [17].

2.4 Crop data collection

The number of productive tillers and seed per spike gathered from each five plants per plot. Noted plant height from near to the ground to spike starts, then measured the spike length to get an average reading. The data of plant parameters were collected according to the national standard guidelines [1]. Wheat crop was harvested from the central thirteen harvestable row. To get the straw yield, simply subtracting the grain yield from the total above ground biomass. The harvest index calculated by dividing the grain yield by the total above-ground biomass and showing it as a percentage Wheeler et al. [71].

$$\text{Harvest index (\%)} = \frac{\text{Grain yield}}{\text{Above ground Biomass}} * 100 \quad (1)$$

The moisture correction factor was calculated by using the following formula [13]

$$\text{Adjusted Yield} = \frac{100 - \text{measured moisture content\%}}{100 - 12.5\%} * \text{grain yield} \quad (2)$$

Thus, 12.5% moisture adjusted grain yield = moisture correction factors X grain yield obtained from each plot.

2.5 Data analysis

Collected data from the field for each parameter were subjected to the analysis of variance (ANOVA) using SAS software version 9.0 statistical software program. Treatment means were separated using the least significance difference test at $P \leq 0.05$.

2.6 Economic analysis

Partial budget analyses were carried out to see if mixing different N and P fertilizers makes sense for growing wheat, using the methods mentioned in the document [18]. To account for any difference that might occur between how researcher and farmers manage fields, the grain and straw amounts adjusted down by 10%.

3 Result and discussion

3.1 Soil physical and chemical properties of the experimental fields before planting

3.1.1 Bulk density

The bulk density of the study area was 1.28 g cm⁻³ for Debremawi and 1.25 g cm⁻³ for Konch. As a result, the bulk density of both experimental sites was in a suitable range for crop production [39, 43]. A bulk density between 1.0 and 1.7 g cm⁻³ is less compaction and not limit water movement in most case good for growing crops [40].

3.1.2 Texture

The soil of the experimental sites was classified as clay in textural (Table 2). The result is supported by Eyasu Elia and Agegnehu [29], who found a significant concentration of clay in the Nitisols of the Ethiopian highland soils.

3.1.3 Soil reaction (pH)

The experimental sites had pH of 5.58 Debremawi and 5.54 Konch (Table 2) and marked moderately acidic based on [50, 67] report. This could be lower organic matter content due to contentious cultivation.

3.1.4 Soil organic carbon

The soil organic carbon for the study field was 1.82 and 1.94% at Debremawi and Konch, respectively, as shown in Table 2. According to the rating of [50, 54] the organic carbon content in the soils was pretty low. This finding was like what [26, 37] also reported low SOC levels in the cultivated Nitisols soils.

3.1.5 Available phosphorous (P-Olson)

The soil analysis result of available P for experimental sites showed 3.63 mg kg⁻¹ for Debremawi and 4.24 mg kg⁻¹ for Konch (Table 2). Depending on Landon [38, 50] report available P rating of the experimental sites is very low. Negassa and Gebrekidan [60] stated that notable of the Ethiopian soils possessed low levels of available phosphorus. This could be related low organic matter inputs as observed the organic carbon result of the two sites.

3.1.6 Total nitrogen (TN)

The total nitrogen contents for both experimental sites were 0.17% (Table 2). The TN content was placed as low according to the ratings of Metson [54]. The farming systems of Ethiopia is low total soil N content as reported by Negassa and Gebrekidan [60], which is under rating for bread wheat production.

3.1.7 Cation exchangeable capacity (CEC)

CEC values of the study farmer fields were varied between 31.86 cmol₍₊₎ kg⁻¹ soil for Konch and 33.32 cmol₍₊₎ kg⁻¹ for Debremawi. The CEC at the experimental sites was high, based on Landon's [50] rating. This matches what [26] found in regarding the

Table 2 Selected soil physical and chemical proprieties of the experimental fields before sowing

Soil parameters	Debremawi	Konch	Status	References
pH (H ₂ O)	5.58	5.54	Moderately acidic	Tekalign [67]
CEC cmol ₍₊₎ kg ⁻¹	31.86	33.32	High	Landon [50]
SOC (%)	1.82	1.94	Very low	Metson [54]
TN (%)	0.17	0.17	Low	Metson [54]
Av. P (mg kg ⁻¹)	3.63	4.24	Very low	Olson (1954)
Bulk Density (g cm ⁻³)	1.28	1.25	Low/suitable	Hazelton and Murphy [39]
Sand (%)	8	4		
Silt (%)	30	22		
Clay (%)	62	74		
Textural class	Clay	Clay		USDA classification

pH = Power of Hydrogen, CEC = Cation Exchange Capacity, SOM = Soil Organic Matter, TN = Total Nitrogen, Av. P = Available Phosphorus

Nitisols in Jabitehinan and Achefer in Western Gojam. Soils of both study sites are characterized with clay texture and that could be accountable for the high CEC of the experimental sites.

3.2 Nitrogen and phosphorus effect on yield and yield attributes of bread wheat

3.2.1 Plant height

The application of nitrogen (N) and phosphorus (P_2O_5) rates significantly influenced the wheat plant height at both experimental site ($P < 0.05$) (Table 5). The maximum plant heights 72.8 cm in Debremawi and 71.6 cm in Konch were recorded from plots receiving 207 kg N ha^{-1} combined with 69 kg P_2O_5 ha^{-1} . The next highest values were obtained from the combination of 207 kg N ha^{-1} and 46 kg P_2O_5 ha^{-1} at both locations. The overall mean across sites further confirmed that the rate of 207 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} substantially enhanced plant height, with the tallest plants reaching 76 cm (Fig. 3). In contrast, the shortest plant heights 52.5 cm in Debremawi and 50.9 cm in Konch were observed in the unfertilized control plots (Tables 3, 4). The results clearly indicate that increasing the application of N and P_2O_5 generally promotes wheat plant height. However, plant height declined when N and P_2O_5 rates exceeded 207 kg N ha^{-1} and 69 kg P_2O_5 ha^{-1} , likely due to nitrogen toxicity, which can inhibit vegetative growth and overall plant development. Excessive N application has been reported to reduce wheat plant height compared with optimal N rates [74], Muhammad [58]. Nevertheless, several studies in Ethiopia have shown that wheat plant height generally increases with incremental applications of optimal N doses [20, 30, 49].

Similarly, Khan et al. [47] reported that nitrogen applied at appropriate rates linearly enhances plant height, indicating a direct relationship between nitrogen availability and vegetative growth. Consequently, the combined application of N and P plays a crucial role in improving wheat vegetative development, as their synergistic interaction enhances nutrient uptake and utilization. Assefa et al. [10, 11] also observed significant improvements in wheat plant height due to the interaction of nitrogen and phosphorus at optimum level.

3.2.2 Spike length

The main effect of phosphorus on wheat spike length was not significant ($P > 0.05$). However, when 207 kg N ha^{-1} was combined with either 69 or 92 kg P_2O_5 ha^{-1} , spike length

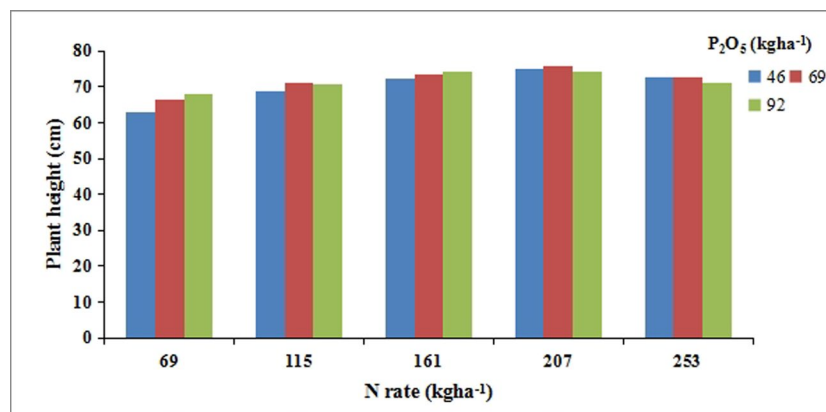


Fig. 3 Response of bread wheat height to the applied nitrogen and phosphorous

Table 3 Response of wheat yield and yield components to Nitrogen and phosphorous for Debremawi

N level (kg ha ⁻¹)	PH (cm)	SL (cm)	PT (5 plt)	SE (5 plt)	GY (kg ha ⁻¹)	SY (kg ha ⁻¹)	BM Y (kg ha ⁻¹)	HI (%)
69	68.4 ^a	7.4 ^b	2.7 ^d	43.4 ^c	1796 ^c	1918 ^c	3714 ^c	47.1 ^a
115	70.6 ^a	7.9 ^{ab}	3.4 ^c	48.6 ^b	3033 ^b	3112 ^b	6146 ^b	49.3 ^a
161	71.1 ^a	8.2 ^a	4.2 ^b	51.8 ^a	3423 ^a	3485 ^a	6908 ^a	49.5 ^a
207	70.8 ^a	8.4 ^a	5.2 ^a	53.6 ^a	3725 ^a	3758 ^a	7483 ^a	49.8 ^a
253	68.4 ^a	7.8 ^{ab}	3.6 ^c	43.4 ^c	3062 ^b	3128 ^b	6190 ^b	49.4 ^a
Sig	NS	*	**	**	**	**	**	NS
SEm	0.7	0.1	0.1	0.6	79.0	79.3	152.6	0.774
LSD (5%)	2.0	0.4	0.4	2.0	229.0	229.8	442.0	2.243
<i>P2O5 level (kg ha⁻¹)</i>								
46	68.8 ^b	7.9 ^{ab}	3.8 ^a	48.3 ^a	2765 ^b	2902 ^b	5667 ^b	47.6 ^b
69	71.2 ^a	8.1 ^a	3.8 ^a	48.6 ^a	3095 ^a	3125 ^a	6220 ^a	49.9 ^a
92	69.5 ^b	7.7 ^b	3.9 ^a	47.6 ^a	3163 ^a	3215 ^a	6377 ^a	49.5 ^a
Sig	*	NS	NS	NS	**	*	**	*
N*P	NS	**	*	**	**	*	**	*
SEm	0.5	0.1	0.1	0.5	61.2	61.5	118.2	0.6
LSD (5%)	1.6	0.3	0.3	1.5	177.4	178.0	342.4	1.7
Control	52.5	4.4	1.5	31.0	350.7	532.7	883.4	39.5

PH=Plant height, SL=Spike length, SE=Number of seed per spike, PT=Number of productive tiller, plt=plant, BM Y=biomass yield, GY=Grain yield, SY=Straw yield, HI=Harvest index, SEm=Standard error of the mean

Means are significantly different at $P \leq 0.05$. **Means are significantly different at $P \leq 0.01$. Mean values followed by different letters along the same column are significantly different at $**P \leq 0.01$, $*P \leq 0.05$

Table 4 Response of wheat yield and yield components to Nitrogen and phosphorous for Konch

N level (kg ha ⁻¹)	PH (cm)	SL (cm)	PT (5 plt)	SE (5 plt)	GY (kg ha ⁻¹)	SY (kg ha ⁻¹)	BM Y (kg ha ⁻¹)	HI (%)
69	63.1 ^d	6.8 ^c	2.8 ^d	37.4 ^d	1446 ^d	1484 ^d	2931 ^d	49.4 ^{ab}
115	70.0 ^c	7.5 ^c	3.6 ^c	47.7 ^c	2296 ^c	2485 ^c	4781 ^c	47.8 ^{ab}
161	75.6 ^b	7.9 ^b	3.9 ^b	50.8 ^b	3014 ^b	2879 ^b	5893 ^b	51.0 ^a
207	79.2 ^a	8.3 ^a	4.5 ^a	54.2 ^a	3492 ^a	3273 ^a	6765 ^a	51.5 ^a
253	75.9 ^b	7.3 ^d	3.4 ^c	50.9 ^b	2774 ^b	2902 ^b	5676 ^b	46.0 ^b
Sig	**	**	**	**	**	**	**	*
SEm	0.4	0.08	0.05	0.3	65.7	61.8	113.2	1.2
LSD (5%)	1.4	0.2	0.16	1.0	190.3	179.1	328.0	3.5
<i>P2O5 level (kg ha⁻¹)</i>								
46	71.8 ^b	7.4 ^b	3.5 ^b	46.9 ^c	2399 ^a	2434 ^b	4833 ^b	49.4 ^a
69	72.7 ^b	7.5 ^b	3.6 ^a	48.2 ^b	2663 ^b	2637 ^a	5301 ^a	49.9 ^a
92	73.8 ^a	7.7 ^a	3.7 ^a	49.6 ^a	2751 ^b	2743 ^a	5494 ^a	48.2 ^a
Sig	*	*	*	**	**	**	**	NS
N*P	**	*	**	**	*	**	**	NS
SEm	0.3	0.06	0.04	0.2	50.9	47.9	87.7	0.9
LSD (5%)	1.0	0.18	0.13	0.8	147.4	138.8	254.1	2.7
CV%	2.0	3.3	4.8	2.3	7.6	7.1	6.5	7.5
Control	50.9	4.6	1.3	21.0	347.7	360.8	708.5	49.3

PH=Plant height, SL=Spike length, SE=Number of seed per spike, PT=Number of productive tiller, plt=plant, BM Y=biomass yield, GY=Grain yield, SY=Straw yield, HI=Harvest index, SEm=Standard error of the mean

*Means are significantly different at $P \leq 0.05$

**Means are significantly different at $P \leq 0.01$. Mean values followed by different letters along the same column are significantly different at $**P \leq 0.01$, $*P \leq 0.05$

increased at both locations (Fig. 4). The longest spike (9.0 cm) was recorded at Debre-mawi with 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹. This was followed by an 8.6 cm spike with the same nitrogen rate but only 46 kg P₂O₅ ha⁻¹. At Konch, the interaction of 207 kg N ha⁻¹ with 92 kg P₂O₅ ha⁻¹ produced the highest spike length (8.6 cm), while 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹ resulted in the second highest (8.3 cm). The site-mean data showed that the longest average spike length (8.7 cm) was achieved with the combination of 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹, representing a 45.9% increase over the control, which produced the smallest spike length (4.5 cm) (Table 5). Furthermore, nitrogen and phosphorus application influenced spike formation and overall plant vigor. Plants in the control plots had thin stems, small spikes, short stature, and lighter coloration, whereas fertilized plants exhibited thick, robust stems, large green spikes, and enhanced growth Fig 7 and 8. These findings are consistent with those of Amjadian [6], who reported that nitrogen and phosphorus application increased stem and spike length by 13.8% and 25.2%, respectively, over the control. Similar increases in spike length due to combined N and P application were also reported by Alemayehu et al. [3] and Abera [2].

3.2.3 Productive tiller

The number of productive tillers per plant was significantly increased ($P < 0.05$) at both experimental sites by the application of nitrogen and phosphorus. The highest numbers of productive tillers, 5.8 and 4.7, were obtained with 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹, whereas the control plots in Debre-mawi and Konch recorded the lowest values, 1.5 and 1.3, respectively. The combined analysis across locations indicated that the application of 207 kg N ha⁻¹ with 69 kg P₂O₅ ha⁻¹ produced the maximum average number of productive tillers (5.3) (Fig. 5). The observed increase in productive tillers can be attributed to the synergistic effect of nitrogen and phosphorus, likely mediated through the stimulation of plant hormone synthesis, which promotes cell division and elongation. These findings are consistent with Arzu et al. [9], who reported a substantial improvement in tiller productivity when nitrogen and phosphorus were applied in combination. Similarly, Muhammad Tahir et al. [58] observed that the number of productive tillers increased with increasing nitrogen rates until the optimum level was reached. Other studies have indicated that wheat responds positively to high nitrogen rates in terms of productive tillers, although the response may be inconsistent across different

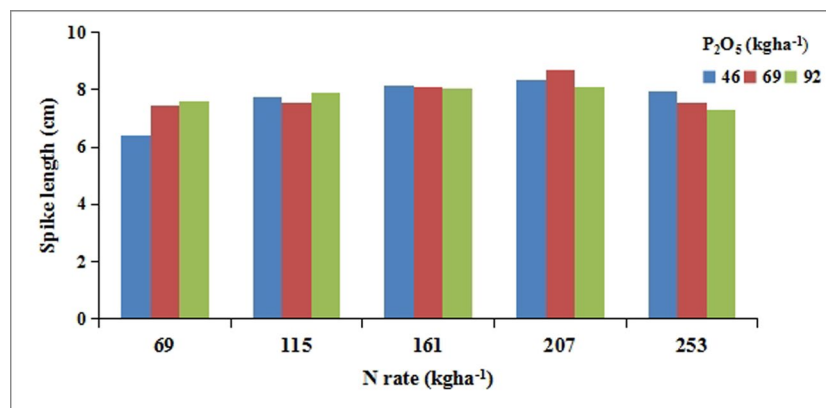


Fig. 4 Response of spike length of bread wheat to applied nitrogen and phosphorous

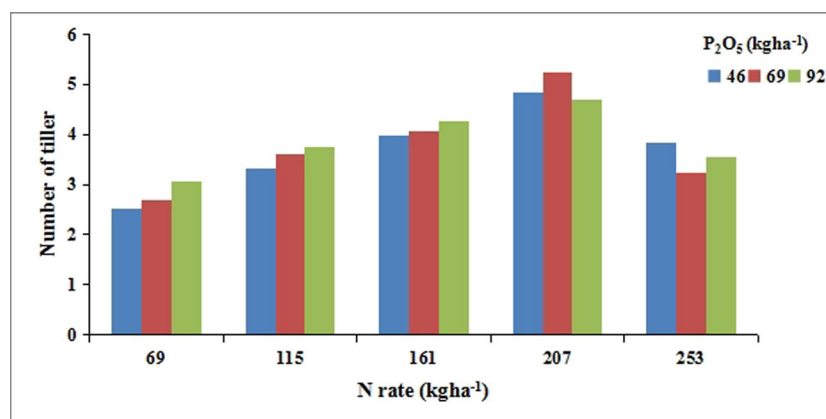
Table 5 Response of wheat yield and yield components to Nitrogen and phosphorous over location

N level (kg ha ⁻¹)	PH (cm)	SL (cm)	PT (5 plt)	SE (5 plt)	GY (kg ha ⁻¹)	SY (kg ha ⁻¹)	BMV (kg ha ⁻¹)	HI (%)
69	65.8 ^c	7.1 ^d	2.8 ^d	40.5 ^c	1621 ^d	1701 ^d	3322 ^d	48.3 ^a
115	70.3 ^b	7.7 ^{bc}	3.6 ^c	48.2 ^b	2665 ^c	2799 ^c	5463 ^c	48.6 ^a
161	73.4 ^{ab}	8.1 ^{ab}	4.1 ^b	51.4 ^a	3218 ^b	3182 ^b	6400 ^b	50.3 ^a
207	75.1 ^a	8.4 ^a	4.9 ^a	54.0 ^a	3609 ^a	3515 ^a	7124 ^a	50.7 ^a
253	72.2 ^{ab}	7.6 ^c	3.5 ^c	47.2 ^b	2918 ^c	3015 ^{bc}	5933 ^{bc}	47.8 ^a
Sig	**	**	**	**	**	**	**	NS
SEm	0.4	0.08	0.07	0.3	61.3	56.1	111.5	0.7
LSD (5%)	1.2	0.2	0.2	1.1	173.5	158.8	315.7	2.1
<i>P₂O₅ level (kg ha⁻¹)</i>								
46	70.4 ^a	7.7 ^a	3.7 ^a	47.7 ^a	2582 ^a	2668 ^b	5250 ^b	48.6 ^a
69	72.0 ^a	7.9 ^a	3.8 ^a	48.4 ^a	2879 ^b	2881 ^a	5760 ^a	49.9 ^a
92	71.7 ^a	7.8 ^a	3.9 ^a	48.6 ^a	2957 ^b	2979 ^a	5936 ^a	48.9 ^a
Sig	NS	NS	NS	NS	**	**	**	NS
N*P	*	**	**	**	**	**	**	NS
SEm	0.3	0.06	0.06	0.3	47.5	43.5	86.4	0.5
LSD (5%)	0.9	0.1	0.1	0.8	134.4	123.0	244.5	1.6
CV%	2.6	4.9	8.7	3.4	9.3	8.4	8.4	6.5
Control	52.4	4.5	1.4	26.0	349.2	446.7	795.9	44.4

PH=Plant height, SL=Spike length, SE=Number of seed per spike, PT=Number of productive tiller, plt=plant, BMV=Biomass yield, GY=Grain yield, SY=Straw yield, HI=Harvest index, SEm=Standard error of the mean

*Means are significantly different at $P \leq 0.05$

**Means are significantly different at $P \leq 0.01$. Mean values followed by different letters along the same column are significantly different at ** $P \leq 0.01$, * $P \leq 0.05$

**Fig. 5** Response of bread wheat productive tillers to applied nitrogen and phosphorous

environments [24]. The combined application of nitrogen and phosphorus was found to significantly increase the number of productive tillers ($P < 0.05$), in agreement with the results reported by Abera [2].

3.3 Number of seeds per spike

The number of seeds per spike was significantly affected ($P < 0.01$) by the interaction of nitrogen (N) and phosphorus (P_2O_5) fertilizer rates at both experimental sites (Tables 3, 4). Increasing nitrogen rates up to 207 kg N ha⁻¹ across all levels of P_2O_5 consistently increased the number of seeds per spike. However, the main effect of phosphorus was not significant at Debremaawi (Table 3). The lowest numbers of seeds per spike were

recorded in the control plots, with 31 seeds at Debremawi and 21 seeds at Konch. The highest values 56.2 and 55.7 seeds per spike were obtained from 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹ at Debremawi and 207 kg N ha⁻¹ with 92 kg P₂O₅ ha⁻¹ at Konch, respectively.

Over location analysis indicated that the application of 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹ produced the highest average number of seeds per spike (55.3), representing a 51.6% increase over the control (Fig. 6). These results demonstrate that wheat yield components, including the number of seeds per spike, are enhanced by the combined application of nitrogen and phosphorus. This finding is consistent with Assefa et al. [10, 11], who reported that nitrogen and phosphorus application increased the number of seeds per spike proportionally until the optimum nutrient levels were reached. Other studies have reported that increasing nitrogen and phosphorus (NP) fertilizer levels significantly increased the number of seeds per spike under certain level [44, 45]. The application of optimum nitrogen and phosphorus improves nutrient translocation to developing florets, thereby increasing the number of fertile florets and supporting spikelet initiation. This enhanced floret development ultimately leads to a higher number of seeds per spike [63] (Figs. 7, 8).

3.3.1 Grain yield

The main and interaction effects of nitrogen (N) and phosphorus (P₂O₅) on bread wheat grain yield were highly significant ($P < 0.01$) at both experimental sites. Grain yield increased consistently with N application up to 207 kg N ha⁻¹, after which a decline was observed across all P₂O₅ levels (Tables 3, 4). This suggests that grain yield responds positively to increasing N and P rates only up to an optimum point. The decline in yield beyond 207 kg N ha⁻¹ may be attributed to reduced grain number per spike, fewer productive tillers, delayed senescence, and ultimately lower grain filling efficiency.

Regression analysis further confirmed the strong responsiveness of wheat grain yield to applied nutrients, with coefficients of determination (R^2) of 0.96 for N and 0.99 for P₂O₅ (Fig. 9). All treated plots were higher grain yield as compared to the control plot. The highest grain yields 3,852 kg ha⁻¹ at Debremawi and 3,725 kg ha⁻¹ at Konch were obtained from the combined application of 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹. These represent yield advantages of 90.9% and 90.6% over the control, respectively. The second-highest yields, 3,763 kg ha⁻¹ at Debremawi and 3,543 kg ha⁻¹ at Konch, resulted

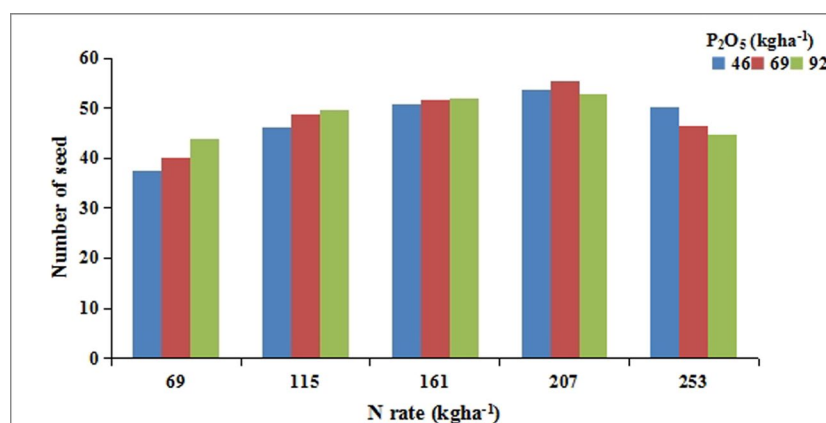


Fig. 6 Responses of bread wheat seed per spike to applied nitrogen and phosphorus



Fig. 7 Performance of bread wheat at Debremawi during growing period



Fig. 8 Performance of bread wheat at Konch during growing period

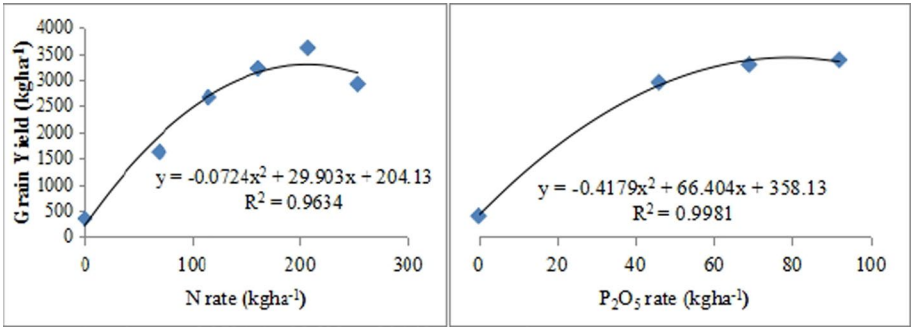


Fig. 9 Response of wheat grain for the applied N and P_2O_5

from 207 kg N ha⁻¹ combined with 92 kg P₂O₅ ha⁻¹. In contrast, the unfertilized control plots produced only 350 kg ha⁻¹ at Debremaawi and 348 kg ha⁻¹ at Konch.

Combined analysis across both sites indicated that the maximum grain yield (3,737 kg ha⁻¹) was obtained from 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹, representing an 81.3% increase over the control (Fig. 10). This substantial improvement can be attributed to the synergistic role of nitrogen and phosphorus in enhancing root development, which in turn promotes nutrient uptake, stimulates metabolic activity, and improves assimilate translocation to reproductive tissues.

These findings align with previous studies. Nakachew et al. [59] reported that combined N and P fertilization significantly increased wheat grain yield. Similar results were documented by Hundessa et al. [42] and Wogayehu Worku et al. [72], who found that appropriate N and P rates produced the highest yields. Amare et al. [5] also noted that optimal nitrogen and phosphorus application enhanced crop productivity more than other nutrients. Additional studies by Dai et al. [21], Anas et al. [7], Assefa et al. [10], and Arzu et al. [9] similarly emphasize the crucial role of N and P management in maximizing wheat productivity. According to Lakew [49] and Abera [2], adequate nitrogen strengthens photosynthetic capacity and supports efficient carbohydrate translocation to the grains, whereas phosphorus enhances root growth, spike development, and energy transfer essential for grain filling.

3.3.2 Straw yield

Straw yield was significantly influenced by the main and interaction effects of nitrogen (N) and phosphorus (P₂O₅) across both sites ($P < 0.05$). Strong linear relationships were observed between straw yield and N and P₂O₅ application, with R² values of 0.97 and 0.99, respectively (Fig. 12). The highest straw yields were obtained from 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹ at Debremaawi (3,948 kg ha⁻¹) and with 92 kg P₂O₅ ha⁻¹ at Konch (3,382 kg ha⁻¹). In contrast, unfertilized plots produced the lowest yields (533 kg ha⁻¹ at Debremaawi and 361 kg ha⁻¹ at Konch).

The interaction of N and P₂O₅ increased straw yield by 86.4% and 89.3% over the control at Debremaawi and Konch, respectively. Pooled analysis confirmed a highly significant interaction ($P < 0.01$), with the maximum over-location straw yield (3,609 kg ha⁻¹) achieved at 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹, representing a 91.1% improvement over the control (Fig. 11).

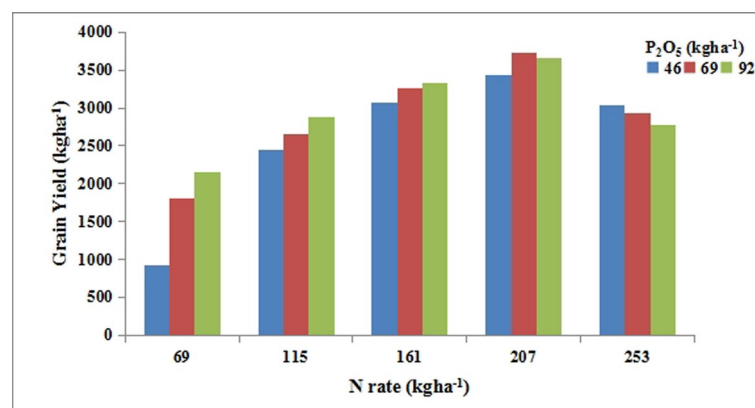


Fig. 10 Responses of bread wheat grain to the applied nitrogen and phosphorous

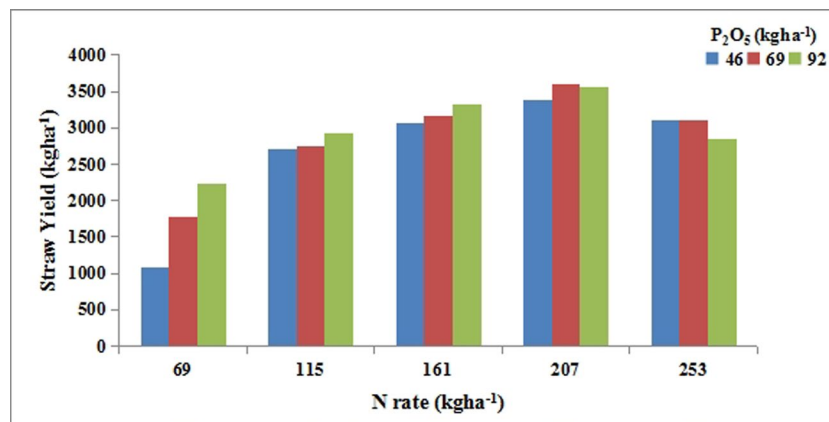


Fig. 11 Response of bread wheat straw to the applied Nitrogen and Phosphorous

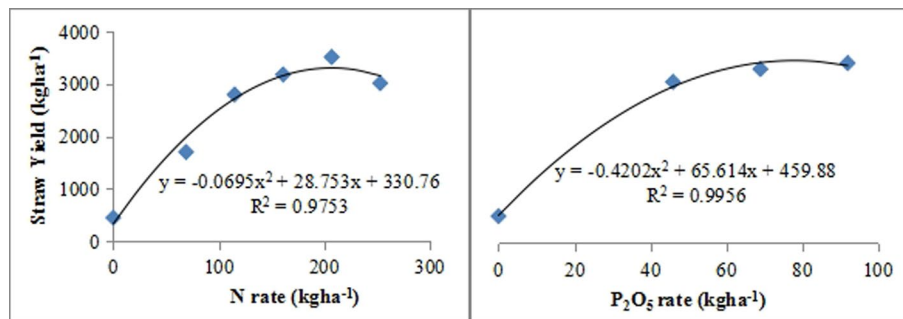


Fig. 12 Response of wheat straw for the applied N and P₂O₅

Nitrogen plays a crucial role in chlorophyll formation, enzymatic activity, and structural tissue development, while phosphorus enhances root growth, nutrient absorption, and energy transfer. Thus, the marked improvement in straw yield can be attributed to the complementary physiological roles of N and P. These findings highlight the importance of balanced fertilization for maximizing biomass production. The results of this study are consistent with previous reports indicating that combined applications of N and P significantly enhance wheat straw yield. Similar trends were reported by Dai et al. [21], Hundessa et al. [42], and Mohsen Jahan and Amiri [56], who observed higher straw yields under integrated N and P fertilization. Additional studies [9, 20, 30, 44–46] likewise confirmed that the synergistic application of N and P fertilizers increased wheat straw yield. Straw yield peaked at 207 kg N ha⁻¹ before declining, and increased significantly with P₂O₅ application (Tables 3, 4, 5), consistent with Arzu et al. [9], who reported optimal wheat straw yields at adequate phosphorus levels. The strong straw yield response to phosphorus also reflects the very low soil P availability identified before planting (Table 2), indicating that P was a key limiting nutrient at both sites (Fig. 12).

3.3.3 Harvest index

The analysis of variance (ANOVA) showed that wheat harvest index (HI) was highly significantly affected ($P < 0.01$) by nitrogen (N) and phosphorus (P₂O₅) rates at Debremaawi, whereas the effect was insignificant ($P > 0.05$) at Konch (Tables 3, 4). At Debremaawi, the highest HI (54.05%) was achieved with 69 kg N ha⁻¹ and 46 kg P₂O₅ ha⁻¹, whereas the lowest HI (39%) occurred in the unfertilized control. At Konch, the maximum HI

(52.53%) was obtained under 207 kg N ha⁻¹ combined with 69 kg P₂O₅ ha⁻¹, while the minimum (40.04%) was recorded at 253 kg N ha⁻¹ and 92 kg P₂O₅ ha⁻¹. Combined analysis across both sites revealed the highest HI (51%) from 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹, representing a 13.3% improvement over the control.

The enhanced HI under optimal N and P₂O₅ supply may be attributed to improved vegetative growth, efficient dry matter accumulation, and greater partitioning of assimilates into the grain. In contrast, the unfertilized control plots exhibited poor growth and minimal biomass allocation. Overall, the results highlight the critical importance of balanced N and P nutrition in regulating dry matter distribution and optimizing wheat productivity. Proper nutrient management thus remains essential for improving crop performance and achieving higher yields. Studies have consistently shown that combined N and P fertilization results in a higher HI compared to unfertilized or unbalanced nutrient applications [10, 11, 53]. Duan et al. [25] and Kabato et al. [44, 45] also reported that balanced applications of nitrogen and phosphorus improve assimilate production and distribution, thereby enhancing grain filling and increasing the harvest index.

3.4 Combined correlation between yield and yield components of wheat at the experimental sites

The combined correlation analysis was done for experiments and the Pearson's correlation indicated that plant height ($r = 0.57$), productive tillers ($r = 0.74$), number of seed per spike ($r = 0.77$), biomass yield ($r = 0.99$) and harvest index ($r = 0.37$) highly, significantly correlated ($P \leq 0.01$), which suggests that an increasing thus parameters tended with positive impact on improving of wheat grain yield (Table 6).

3.5 Partial budget analysis

Partial budget analysis for bread wheat production is given in Table 7. The maximum net benefit (208,612.4 ET Birr) was obtained from combined application of 207 kg N with 69 kg P₂O₅ ha⁻¹. Minimum net benefit (11,491.3 ET Birr.) was recorded from the control plot. Application of 207 N with 92 kg P₂O₅ ha⁻¹, 253 kg N with 46 kg P₂O₅ ha⁻¹, 253 N with 69 kg P₂O₅ ha⁻¹, 253 N with 92 kg P₂O₅ ha⁻¹ were dominated by the rest treatments, and they were excluded from further economic analysis. The data regarding the marginal rate of return (MRR) revealed that maximum MRR (3,414.8%) was obtained when 115 N combined with 46 P₂O₅ kg ha⁻¹ followed by 69 N with 69 kg P₂O₅ ha⁻¹ (2,861.1%). Minimum MRR was 251.1% recorded in treatment where application of 69 N combined with

Table 6 Combined Pearson's correlation matrix between wheat yield and yield components

	PH	SL	PT	SE	GY	SY	BMV	HI
PH	1							
SL	0.46**	1						
PT	0.45**	0.68**	1					
SE	0.77**	0.66**	0.73**	1				
GY	0.57**	0.72**	0.74**	0.77**	1			
SY	0.52**	0.70**	0.74**	0.76**	0.96**	1		
BMV	0.554*	0.72**	0.75**	0.78**	0.99**	0.99**	1	
HI	0.17 ^{ns}	0.30**	0.23*	0.17 ^{ns}	0.37**	0.23*	0.30**	1

Ns = Non-significant, PH = Plant height, SL = Spike length, GY = Grain yield, SY = Straw yield, PT = Number of productive tiller, HI = Harvest index, SE = Seed number per spike and BMV = Biomass yield

*Significant different at $P < 0.05$

**Significant different at $P < 0.01$

Table 7 Partial budget analysis for Nitrogen and Phosphorous

Treatments	Adj.GY	Adj.STY	GBGY	GBTY	TGB	TVC	NB	MRR
Control	314.3	402.1	21,999.6	1491.7	23,491.3	12,000.0	11,491.3	–
N69 P ₂ O ₅ 46	825.0	979.5	57,750.0	3633.9	61,383.9	22,650.0	38,233.9	251.1
N69 P ₂ O ₅ 69	1620.2	1607.2	113,412.6	5962.8	119,375.4	24,600.0	94,025.4	2861.1
N69 P ₂ O ₅ 92	1931.9	2006.5	135,231.6	7444.2	142,675.8	26,550.0	115,125.8	1082.1
N115 P ₂ O ₅ 46	2202.8	2444.8	154,194.6	9070.3	163,264.9	27,150.0	135,614.9	3414.8
N115 P ₂ O ₅ 69	2397.0	2477.5	167,792.1	9191.6	176,983.7	29,100.0	147,133.7	590.7
N115 P ₂ O ₅ 92	2594.7	2633.8	181,631.1	9771.5	191,402.6	31,050.0	159,352.6	626.6
N161 P ₂ O ₅ 46	2766.5	2752.3	193,653.6	10,211.1	203,864.7	31,650.0	171,714.7	2060.4
N161 P ₂ O ₅ 69	2933.1	2844.3	205,319.1	10,552.2	215,871.3	33,600.0	181,521.3	502.9
N161 P ₂ O ₅ 92	2989.5	2995.2	209,267.1	11,112.1	220,379.2	35,550.0	183,829.2	118.4
N207 P ₂ O ₅ 46	3092.4	3039.4	216,470.1	11,276.2	227,746.3	36,150.0	191,096.3	1211.2
N207 P ₂ O ₅ 69	3363.0	3248.1	235,412.1	12,050.3	247,462.4	38,100.0	208,612.4	898.3
N207 P ₂ O ₅ 92	3287.9	3203.8	230,153.7	11,886.1	242,039.8	40,050.0	200,990	D
N253 P ₂ O ₅ 46	2732.5	2788.9	191,272.2	10,346.8	201,619	40,650.0	160,469.0	D
N253 P ₂ O ₅ 69	2643.5	2787.1	185,045.7	10,340.1	195,385.8	42,600.0	152,035.8	D
N253 P ₂ O ₅ 92	2502.1	2564.9	175,144.2	9515.9	184,660.1	44,550.0	139,110.1	D

Adj GY = Adjusted Grain Yield (kg ha⁻¹), Adj STY (kg ha⁻¹) = Adjusted Straw yield (kg ha⁻¹), GBGY = Gross Benefit of Grain Yield (ET Birr), GBTY = Gross benefit of Straw Yield (ET Birr), TGB = Total Gross Benefit (ET Birr), TVC = Total Variable Cost (ET Birr), NB = Net Benefit (ET Birr), MRR = Marginal rate of return (%)

46 P₂O₅ kg ha⁻¹. The economic analysis clearly indicated that the non-dominated treatments associated with MRR are greater than 100% implies this are economically feasible. Generally, treatment combination of 207 N combined with 69 P₂O₅ kg ha⁻¹ gave the MRR value 898.3% relative to the other non-dominated treatments record the maximum net benefit (208,612.4 ET Birr) is profitability for wheat crop produce.

4 Conclusion

The overall results of this study demonstrated that the application of 207 kg N ha⁻¹ and 69 kg P₂O₅ ha⁻¹ significantly increased bread wheat productivity to 3737 kg ha⁻¹, representing more than a tenfold increase compared to the unfertilized plot. This has a great implication for the food and nutritional security of the nation. Nitrogen and phosphorous significantly affected the grain yield, straw yield, plant height and other yield component parameters. The harvest index was also improved to about 51% using nitrogen and phosphorous, which was about 13.3% greater than the control plot. The rate of positively affected most of the yield and yield related components to the extent of 207 kg N ha⁻¹ while the response to phosphorous was only up to 69 kg ha⁻¹ for most of the yield related parameters, which is below previous recommendations and could probably be due to the accumulation of phosphorous over the years. This research proved again that nitrogen is a key nutrient for the production of wheat and hence proportional attention should be paid to nitrogen containing fertilizers. Generally, the production of wheat on the Nitisols of the study area demands the judicious application of nitrogen and phosphorous containing fertilizers, as it was clearly verified with the findings of the current research. The optimum levels of nitrogen and phosphorous that affect the grain and straw yield and high net benefit were identified to be 207 N and 69 P₂O₅ kg ha⁻¹ is recommended for bread wheat production in Yilmana Densa district and similar soil and agro ecologies. The findings demonstrate that nitrogen and phosphorus are essential nutrients for wheat production, underscoring the importance of revising and updating their application rates. But since this finding is based 1 year data further studies

concerning on nitrogen and phosphorus rate combination needed to be done for wheat on different soil types for increased bread wheat production.

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Author contributions

Conceptualization: Bitewelegn kerebeh, Tadele amare Data Curation: Bitewelegn kerebeh, Tadele Amare, Eyayu Molla Formal Analysis: Bitewelegn kerebeh, Tadele Amare, Eyayu Molla Investigation: Bitewelegn kerebeh, Tadele Amare Methodology: Bitewelegn kerebeh, Tadele Amare Project Administration and Software: Bitewelegn kerebeh, Tadele Amare Resource: Bitewelegn kerebeh, Tadele Amare Supervision And validation: Bitewelegn kerebeh, Tadele Amare, Eyayu Molla Writing—Original Draft: Bitewelegn kerebeh Writing—review and editing: Bitewelegn kerebeh, Tadele Amare, Eyayu Molla.

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Data availability

Datasets used for analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The plant parameter measured in accordance with the guideline for agronomy data collection in Ethiopia: National standard.

Consent to publication

Not applicable.

Competing Interests

The authors declare no competing interests.

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