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Response of Hybrid Maize to NP Fertilizer Rates, Nutrient Uptake, and Nutrient Use Efficiency in the Central Rift Valley of Ethiopia

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Abstract

Maize (Zea mays L.) is the most important cereal crop in Ethiopia, but its productivity is limited by a decline in soil fertility and by inefficient use of fertilizers under rain-fed conditions. The present study looked at the reaction of the hybrid maize variety BH-546 to various rates of nitrogen (N) and phosphorus (P) fertilizers, with a focus on grain yield, biomass production, nutrient use efficiency and economic profitability in the central rift valley of Ethiopia. Field trials were carried out from 2022 to 2024 at the Negelle Arsi Research Station and on farmers' fields, employing a randomized complete block design with three replications. The experiment included five nitrogen rates (46, 69, 92, 115 and 138 kg N ha^{-1}), three phosphorus rates (10, 20 and 30 kg P ha^{-1}), together with an untreated control. The results showed that the different NP fertilizer rates had a significant effect ($p \leq 0.05$) on both grain and biomass yields. Grain yield varied between 1.45 and 4.82 t ha^{-1}, while biomass yield ranged from 7.1 to 17.3 t ha^{-1}. The combination of 69 kg N ha^{-1} and 10 kg P ha^{-1} gave the highest grain yield (4,817 kg ha^{-1}) and the highest biomass yield (17,256 kg ha^{-1}). This treatment also achieved the greatest agronomic efficiency (24.1 kg grain kg^{-1} nutrient) and the highest economic return, with a marginal rate of return of 839%. Increasing the NP rates beyond this level did not lead to higher yields and in fact reduced nutrient use efficiency. It is therefore recommended to apply 69 kg N ha^{-1} and 10 kg P ha^{-1} in a balanced manner as the most efficient and economically viable fertilizers management practice for hybrid maize production in the central rift valley of Ethiopia.

1. Introduction

Maize (Zea mays L.) is one of the most important cereal crops in Ethiopia and has a vital role in ensuring national food security as well as in supporting the livelihoods of people in rural areas. It is commonly eaten as a main food item and is also used as animal feed and as a raw material in various industries. Ethiopia is currently the largest producer of maize in Sub-Saharan Africa, maize accounting for a significant share of the total cereal production (FAO, 2022; CSA, 2023). The production of maize in Ethiopia is very dependent on rainfall, which means that it is vulnerable to climate change. Major problems include irregular rainfall distribution, rains starting later than usual, and more frequent dry periods during the key stages of growth (Kassie et al., 2015).

Smallholder farmers primarily grow maize in an rain-fed manner across different agro-ecological zones, a situation which is particularly evident in the mid-altitude sub-humid regions of Oromia, Amhara, SNNPR, and certain areas of Benishangul gumuz (Abate et al., 2015). Despite the fact that a number of high-yielding and stress-tolerant maize hybrids have been introduced, their uptake remains limited, because of the high price of the seeds, the inadequate supply, and the inefficient distribution systems (Abate et al., 2015).

Even though maize production is important, its productivity in Ethiopia is still well below its possible level. The average grain yield nationwide is about 3 to 4 t ha^{-1}, whereas research stations and demonstration plots have reached 8 to 10 t ha^{-1} (Abate et al., 2015; Tsedeke et al., 2017).

Soil fertility decline is widely seen as the biggest hindrance to maize production in Ethiopia. Continuous farming, limited use of organic matter and nutrient depletion has led to a serious loss of essential nutrients (Haileslassie et al., 2005; Agegnehu et al., 2016). Nitrogen is the most important nutrient for maximizing maize harvests (Kong et al., 2008). A lack of soil phosphorus reduces the effectiveness of nitrogen use by crops (Delve et al., 2009). Phosphorus is the second most limiting nutrient in soil after nitrogen (Balemi and Negisho, 2012) and is crucial for plant growth. In tropical agro ecosystems, phosphorus deficiency significantly hampers crop production (Mustonen et al., 2012).

Nitrogen plays a key role in leaf development and chlorophyll production, which gives maize its vibrant green color. It promotes vegetative growth, kernel formation, and overall grain yield. Phosphorus is vital for protein synthesis that strengthens plant tissues. Low organic matter in the soil further decreases nutrient availability and water retention, negatively impacting maize growth and yield (Tilahun et al., 2018).

Fertilizer recommendations in Ethiopia have traditionally been based on blanket application rates of DAP and urea, without considering soil type, agro-ecology, or specific crop needs. This method has led to poor nutrient use efficiency and subpar maize yields (Gete et al., 2010). Nutrient losses due to volatilization, leaching, and fixation, especially phosphorus fixation in acidic and Vertisol soils, are common (Agegnehu & Lakew, 2013). Poor timing and placement of fertilizers worsen these inefficiencies.

Climate change projections suggest rising temperatures and increased rainfall variability. These changes could further hinder maize productivity unless adaptation measures are put in place (Tesfaye et al., 2017). Smallholder farmers often use recycled seeds, which result in lower yield potential and greater vulnerability to pests and diseases. Different varieties have shown varying yields across farms. The productivity of maize varieties in order of yield on farms around Bako Tibe, Western Ethiopia is BH-661, BH-660, BH-540, BH-543, and BH-140 (Tolera et al., 2017). However, little research has been done on the response of the improved maize variety BH-546 to varying rates of phosphorus and nitrogen in balanced fertilization under rain-fed conditions at Negelle Arsi, in the central rift valley of Ethiopia. This study aims to explore the optimal combinations of nitrogen and phosphorus fertilizer rates for the BH-546 maize variety at Negelle Arsi, in the Central Rift Valley of Ethiopia.

2. Experimental Design and Treatment

The experiment took place at Negelle Arsi station and on two farmers' fields in the main maize production areas of the Central Rift Valley of Ethiopia from 2022 to 2024. It was designed as an incomplete factorial arrangement with a complete block layout, repeated three times. Five levels of nitrogen (46, 69, 92, 115, 138 kg N ha^{-1}) were combined with three levels of phosphorus (10, 20. 30 kg P ha^{-1}) for the experimental plots. This resulted in a total of 15 treatment combinations. Maize variety BH-546 without fertilizer served as the control treatment. The test crop was maize variety BH-546 from a sub-humid mid-altitude area.

The plot size was 4.0 m wide and 3.75 m long (15 m²), containing five rows of maize plants. Yield and yield component data were collected from the three middle rows, while the outer two rows acted as border rows. Improved seeds of the variety were planted in rows spaced 75 cm apart and 25 cm (30 cm) between plants. The specified nitrogen rates were applied in two parts: half at planting and the rest when the plants reached knee height. The three phosphorus rates (10, 20, and 30 kg P ha^{-1}) were uniformly applied to all treatments at planting. Urea was the source of nitrogen, while triple superphosphate (TSP) provided phosphorus. All other agronomic management practices followed the recommendations for the variety.

3. Materials and Methods

3.1 Site and Experimental Conditions

The experiment was carried out in Negelle Arsi district, located in the central rift valley of Ethiopia. The area lies at an altitude of 1,500–2,000 meters above sea level, with an average annual rainfall of 800-1,200 mm, primarily concentrated between June and September. The mean daily temperature varies between 12 and 25°C, providing favorable conditions for maize cultivation. The soils of the district are predominantly Nitisols and Vertisols, moderately fertile but increasingly depleted due to continuous cultivation without adequate nutrient replenishment.

The study was conducted using hybrid maize variety BH-546, which is well adapted to the agro-ecology of the central rift valley. The experimental design consisted of a randomized complete block design (RCBD) with three replications. Treatments included varying rates of nitrogen and phosphorus fertilizers, with the optimum rate identified as 69 kg N/ha and 10 kg P/ha. Fertilizers were applied in split doses: nitrogen was applied half at planting and half at knee-height stage, while phosphorus was applied at planting. Standard agronomic practices such as recommended plant density (53,000–66,000 plants/ha), timely weeding, and pest control were followed to ensure uniform crop management. Data were collected on plant growth, yield components, and grain yield to evaluate the response of BH-546 to NP fertilizer rates under local conditions.

3. Results and Discussion

3.1 Grain Yield of Hybrid Maize

An analysis of variance indicated that treatments significantly affected grain yield of hybrid maize under RCBD. Mean grain yield across treatments ranged from very low-performing treatments to high-performing treatments exceeding 4.8 t ha^{-1}, demonstrating substantial variability in treatment response.

Treatments with superior performance produced grain yields above the national average maize yield of Ethiopia (≈ 3–4 t ha^{-1}), indicating the effectiveness of improved management and/or nutrient supply under experimental conditions. Conversely, the lowest-yielding treatments produced less than 2.0 t ha^{-1},

reflecting suboptimal growth conditions likely associated with nutrient stress or poor biomass accumulation.

The wide yield range observed suggests that grain yield response was strongly influenced by treatment differences, rather than random field variation, confirming the suitability of the RCBD layout in controlling block effects.

3.2 Biomass Yield of Hybrid Maize

Total aboveground biomass yield was significantly influenced by treatments. Mean biomass yield varied from as low as approximately 4.3 t ha^{-1} to more than 18 t ha^{-1}, indicating large differences in vegetative growth among treatments.

Treatments that produced higher biomass generally corresponded with higher grain yield, suggesting that biomass production was a major determinant of grain yield in hybrid maize. This is consistent with the physiological requirement of maize for sufficient leaf area development and dry matter accumulation prior to grain filling.

However, some treatments produced relatively high biomass with only moderate grain yield, indicating possible inefficient assimilate partitioning to grain or nutrient imbalance, particularly under excessive vegetative growth conditions.

3.3 Relationship between Grain Yield and Biomass Yield

Grain yield showed a positive association with biomass yield, confirming that treatments enhancing overall plant growth also improved reproductive output. This relationship highlights the importance of a balanced nutrient supply that supports both vegetative and reproductive stages.

Nevertheless, the relationship was not perfectly linear. Some treatments with high biomass did not translate proportionally into grain yield, suggesting differences in harvest index among treatments. This implies that management practices or nutrient combinations promoting excessive vegetative growth without adequate grain filling may reduce yield efficiency.

Similar findings have been reported in maize studies in Ethiopia, where improved nutrient supply increased biomass. Grain yield response depended on nutrient balance and timing (Agegnehu et al., 2016; Abate et al., 2015).

3.4 Mean Separation and Treatment Performance

Mean separation (LSD at 5%) grouped treatments into distinct performance categories for both grain and biomass yield (Table 1). The highest-yielding treatments were statistically superior to the lowest-yielding group, confirming real agronomic differences among treatments. The significant variation in grain and biomass yield observed in this study aligns with previous findings that hybrid maize responds strongly to improved soil fertility and nutrient management in Ethiopia (Gete et al., 2010; Agegnehu et al., 2016).

Table 1
Mean separation (LSD, 5%) for grain yield and biomass yield of hybrid maize (HB-546)

Treatment (NP rate kg/ha)	**Grain Yield (kg/ha**	**Biomass (kg/ha)**
0 (control)	2911^{de}	11383^{de}
46N-10P	3461^{abc}	14011^{abc}
46N-20P	2567^{ef}	11856^{ef}
46N-30P	3828^{ab}	16400^{ab}
69N-10P	**4817^{a}**	**17256^{a}**
69N-20P	3294^{bcd}	13883^{bcd}
69N-30P	3450^{abc}	16894^{abc}
92N-10P	3439^{abc}	14867^{abc}
92N-20P	**1450^{g}**	**7106^{g}**
92N-30P	3356^{bcd}	13617^{bcd}
115N-10P	3694^{ab}	15506^{ab}
115N-20P	3017^{de}	12556^{de}
115N-30P	2100^{fg}	9239^{fg}
138N-10P	3272^{cd}	13086^{cd}
115N-20P	3017^{de}	12556^{de}
115N-30P	2100^{fg}	9239^{fg}
CV (%)	**22.95**	**19.48**
LSD (0.05)	**680**	**2150**

Means followed by the same letter(s) within a column are not significantly different at P ≤ 0.05.

3.5 Partial budget Analysis

A partial budget analysis was carried out in order to examine the economic viability of the various treatments after first checking whether there was a significant difference among them in the mean adjusted grain yields of maize (Table 2). Dominance and marginal analyses were also conducted. The

average yields were reduced by 10 per cent to take into account the difference between the yield obtained on the experimental plots and the yield that farmers expect from the same treatment. The average open market prices for maize (30.00 ETB per kg), for TSP (70.00 ETB per kg) and for urea (85.00 ETB per kg) were used. Fertilizer inputs were treated as variable costs and all the other costs as constant costs for all the treatments. The minimum acceptable marginal rate of return (MRR) was fixed at 100 per cent in accordance with the recommendation of CIMMYT (1988).

Table 2
Partial budget analysis of the effect of Nitrogen and Phosphorus fertilizers on Hybrid maize at Negelle Arsi

N/P rate	Yield kg/ha	Adj10% kg/ha	Field benefits kg/ha	Net benefits Et birr	TVC Et birr	Net income Et birr	MRR (%)
0/0	2911	291.1	2619.9	78597	0	78597	-
46/10	3461	346.1	3114.9	93447	11650	81797	27.5
46/20	2567	256.7	2310.3	69309	15900	53409	D
46/30	3828	382.8	3445.2	103356	20150	83206	700
69/10	4817	481.7	4335.3	130059	15550	114509	839
69/20	3294	329.4	2964.6	88938	19800	69138	D
69/30	3450	345	3105	93150	24850	68300	D
92/10	3439	343.9	3095.1	92853	20250	72603	D
92/20	1450	145	1305	39150	24500	14650	D
92/30	3356	335.6	3020.4	90612	28750	61862	D
115/10	3694	369.4	3324.6	99738	24150	75588	D
115/20	3017	301.7	2715.3	81459	28400	53059	D
115/30	2100	210	1890	56700	32650	24050	D
138/10	3272	327.2	2944.8	88344	28050	60294	D
138/20	4000	400	3600	108000	32300	78597	362.5
138/30	3558	355.8	3202.2	96066	36550	75700	D

The application of 69 kg of N per hectare together with 10 kg of P per hectare yielded the highest net benefit (130059 ETB ha^{-1}), a net income of 114509 ETB ha^{-1} and a marginal rate of return (MRR) of 839%. The application rate of 69 kg of N and 10 kg of P per hectare also gave the highest net benefit (130059 ETB ha^{-1}), a net income of 114509 ETB ha–1 and an MRR of 839%. The use of 46 kg of N and 30 kg of P per hectare likewise resulted in the highest net benefits (103356 ETB ha^{-1}), a net income of

83206 ETB ha^{-1} and an MRR of 700%. Therefore, for every birr invested in the production of maize, farmers could earn 8.39 birr and 7.00 birr after having recovered their production costs, and these treatments were found to be significantly higher than the agronomic control at the $P < 0.05$ level.

The economic advantage of moderate NP application observed in this study agrees with findings by Ayub et al. (2002) **and** Onasanya et al. (2009), who reported that maize profitability declines beyond optimal fertilizer rates. Similarly, Gete et al. (2010) and Agegnehu et al. (2016) emphasized that excessive fertilizer use often reduces economic returns in Ethiopian maize systems. These results further support the principle that economic optimum fertilizer rates are lower than agronomic maximum rates, particularly under rain-fed production systems.

Based on partial budget analysis, application of 69 kg N ha^{-1} combined with 10 kg P ha^{-1} was the most economically profitable option for hybrid maize production in the study area. This treatment maximized net income while minimizing production risk and fertilizer cost.

3.6 Agronomic Efficiency of NP rates

The agronomic efficiency of the NP rates of each treatment is depicted in Table 3. The treatment involving 69 kg N together with 10 kg P/ha achieved the highest agronomic efficiency (24.1 kg of grain per kg of nutrient), which shows a high degree of nutrient use efficiency. Although moderate rates of nitrogen and phosphorus gave rise to positive but decreasing agronomic efficiency, this reflects the phenomenon of diminishing returns. When high rates of nitrogen and phosphorus (equal to or greater than 115 kg N and 20 kg P respectively) were used, the agronomic efficiency was low or even negative, indicating that nutrients had been wasted and an imbalance. The fact that the agronomic efficiency values were negative means that yield losses took place even though fertilizer had been applied, probably because of Nutrient imbalance (excess N or P), Induced micronutrient deficiencies, such as zinc and moisture or soil organic matter limits.

Table 3
Agronomic Efficiency of NP fertilizer treatments in maize

NP rate(kg ha⁻¹)	Grain yield (kg ha⁻¹)	Yield increase over control (kg ha⁻¹)	Total nutrient applied (kg ha⁻¹)	AE (kg grain kg⁻¹ nutrient)
69N–10P	4817	1906	79	**24.1**
46N–10P	3461	550	56	9.8
46N–30P	3828	917	76	12.1
69N–20P	3294	383	89	4.3
69N–30P	3450	539	99	5.4
92N–10P	3439	528	102	5.2
92N–30P	3356	445	122	3.6
92N–20P	1450	−1461	112	**-13.1**
115N–10P	3694	783	125	6.3
115N–20P	3017	106	135	0.8
115N–30P	2100	−811	145	**-5.6**
138N–10P	3272	361	148	2.4
138N–20P	4000	1089	158	6.9
138N–30P	3558	647	168	3.9

3.7 Implications of improving Agronomic Efficiency

As indicated in Table 4, The treatment which used 69 kg N and 10 kg P per hectare achieved the highest agronomic efficiency (24.1 kg of grain per kg of nutrient), showing a high degree of efficiency in the use of nutrients. Although moderate rates of nitrogen and phosphorus gave a positive but decreasing agronomic efficiency, this reflects the phenomenon of diminishing returns. When high rates of nitrogen and phosphorus (equal to or greater than 115 kg N and 20 kg P respectively) were applied, the agronomic efficiency was very low or even negative, which points to wastage of nutrients and an imbalance. The fact that the agronomic efficiency values were negative means that there were yield losses even though fertilizer had been applied, probably because of nutrient imbalance (such as excess nitrogen or phosphorus), induced deficiencies of micronutrients (for example, zinc) and limitations caused by soil moisture or soil organic matter.

Table 4
Combined NUE and Economic Performance of Selected NP Rates

NP rate kg/ha	AE (kg kg^{-1})	Net benefits (birr per ha)	MRR (%)	Overall performance)
69N-10P	24.1	114509	838.8	Best/agronomic +economic
46N-10P	9.8	81797	27.5	Agronimically fair, Economically weak
46N-30P	12.1	83206	< 100	Moderate AE, Economically dominated
138N-20P	6.9	75700	< 100	Yield oriented, low efficiency
>-115N->-20P	<-1	Low	Negative/low	In efficient

3.8 Conclusion

The combination of 69kgN and 10kgP/ha gave the highest grain yield of hybrid maize(BH-546) with yield increases of 20–30% compared to unfertilized plots when NP fertilizers were applied at Negelle Arsi in the central rift valley of Ethiopia. The strong association between biomass and grain yield indicates that balanced nutrient supply is critical for hybrid maize. Fertilizer management should not focus on nitrogen alone but should include phosphorus and other limiting nutrients based on soil test results. Overall, the study confirms that optimized management practices can markedly improve maize productivity and contribute to closing the yield gap in Ethiopia. Applying 69 kg N/ha and 10 kg P/ha to hybrid maize BH-546 in Negelle Arsi maximized grain yield (4,817 kg/ha), achieved high NUE (69.8 kg grain/kg N), the best PFP (61.0 kg grain/kg NP), and delivered strong economic returns with a benefit–cost ratio of 28.6. This rate is therefore recommended as the most efficient, productive, and profitable fertilizer management practice for BH-546 under local conditions.

Declarations

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Author Contribution

Mesfin Hundessac onceived and designed the study, coordinated the research, and wrote the main manuscript text. Gelmessa contributed to the field experiments and data collection, and reviewed and edited the manuscript. Both authors reviewed and approved the final manuscript.

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