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Original Research

Soil Test Crop Response Based Phosphorous Calibration Study for Maize in Daro Lebu district, West Hararghe Zone, East Oromia, Ethiopia

Habtamu Hailu[1*], Fereja Shaka[1], Tadele Geremu[2]

[1] Mechara Agricultural Research Center, Oromia Agricultural Research Institute, Oromia, Ethiopia
[2] Fitche Agricultural Research Center, Oromia Agricultural Research Institute, Oromia, Ethiopia

Abstract

A sound soil test-based crop response approach is critical for optimizing fertilizer application and enhancing crop productivity. Therefore, the study aimed to investigate soil phosphorus dynamics in the Daro Lebu district, West Hararghe Zone. Seventeen farmers' fields were selected for this study to determine the economically optimal nitrogen fertilizer application rate in the first year. In the subsequent second and third years, the study focused on assessing the phosphorus critical level and determining the phosphorus requirement factor. The initial findings showed that an optimum nitrogen rate of 69 kg ha^{-1} was recommended in the first year. For the second and third cropping seasons, six phosphorus levels (0, 10, 20, 30, 40, and 50 kg ha^{-1}) were tested in combination with a constant nitrogen rate of 69 kg ha^{-1}. The experiment was arranged in a randomized complete block design with three replications to determine the phosphorus critical level and the phosphorus requirement factor. The study revealed low soil phosphorus levels, ranging from 0.98 to 19.9 ppm, and identified a critical phosphorus concentration of 14 ppm along with a phosphorus requirement factor of 4.71 ppm. The maximum maize yield of 4,827 kg ha^{-1} was achieved with an application of 69 kg ha^{-1} of urea and phosphorus rates determined based on the critical phosphorus value. This approach significantly increased yields compared to the control (2,636 kg ha^{-1}) and provided a substantial economic return of 15.52 ETB for every birr invested. However, validation of these results on similar farms is recommended before broader adoption.

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***Corresponding Author:**
E-mail:
habhailu83@gmail.com

INTRODUCTION

Maize is the most cultivated cereal and source of cash in Ethiopia, with an area coverage (17%) and production (26%) of 6.5 million tons which is much lower than the world's average yield of 5.8 t ha-^{1}(CSA, 2019). However, some of the main obstacles to Ethiopia's crop production are low levels of input use and inadequate soil fertility (Abreha *et al*., 2013). This soil fertility problem is highly observed in highly populated and agricultural livelihood-based areas like the west Hararghe area. In the West Hararghe zone, agricultural crop production was challenged by soil fertility problems.

To ensure an accurate interpretation of soil test results, it is essential to consider the crop response to treatments of the necessary plant nutrients, as emphasized by Wortmann *et al*. (2013). This calibration helps to bridge the gap between laboratory soil analysis and field-level crop performance. A trustworthy soil test links nutrients in the soil to plant use, and fertilizer recommendations adjust results to specific agricultural field circumstances. The most cost-effective fertilizer rate for a specific crop may be found after the link between soil test results, fertilizer rates, and crop output is understood. This allows for the refinement of fertilizer recommendations to meet the needs of individual fields on a given farm (Seif, 2013). This comparatively easy-to-use technique might help farmers and producers boost fertilizer profitability after crucial nutrient levels and crop requirements are determined. The likelihood of a reaction from applying a particular nutrient is predicted by calibration studies; this must be confirmed empirically in the field (Dahnke and Olsen, 1990). A distinct calibration is needed for each type of crop, soil, pH of the soil, climate, plant species, and crop variance (Seif, 2013; Agegnehu and Lakew, 2013; Sonon and Zhang, 2014).

For acidic soils, the Bray II method (Bray and Kurtz, 1945) remains a widely accessible and commonly used approach for determining soil phosphorus (P) availability (Bado *et al*., 2004). Some crops have recently had studies done to determine the essential limits of available P and P demand factors for a particular soil and crop; nevertheless, many crops, including maize, still lack these critical limits. Several methods, including the Cate-Nelson graphical method (Nelson and Anderson, 1977), can be employed to analyze the relationship between soil test results and crop responses to fertilizer inputs. However, it is crucial to recognize that applying fertilizers without proper soil testing is akin to treating an illness without a diagnosis. Therefore, effective fertilizer management hinges on accurate soil test calibration, which establishes a correlation between soil test results and the corresponding crop yield response. This calibration ensures that fertilizer recommendations are tailored to the specific needs of the soil and crop, maximizing nutrient efficiency and optimizing agricultural productivity (Sonon and Zhang, 2014).

Soil fertility research increasingly focuses on Soil Test-Based Crop Response (STBCR) fertilizer recommendations. Establishing a reliable soil test is a cornerstone of this approach, facilitating the accurate determination of phosphorus (P) needs. By calibrating soil test results against observed crop responses to fertilizer applications, researchers can refine the relationship between soil P levels and optimal fertilizer inputs. This study aimed to elucidate the critical P concentration threshold and determine appropriate P application rates for maximizing maize production in the Daro Lebu district.

Materials and Methods

Description of the Study Area

The research was conducted in the Daro Lebu district of the Oromia Regional State, Ethiopia, specifically within the West Hararghe Zone. Located approximately 434 kilometers southeast of Addis Ababa (Figure 1), Mechara-Mechata, the district's capital, experiences a mean annual temperature range of 15°C to 27°C and an average annual rainfall of 500-1300 mm (Ayala *et al*., 2018). The two primary cereal crops cultivated in the region are maize (Zea mays) and sorghum (Sorghum bicolor). Cash crops include coffee (Coffea) and khat (Catha edulis). Additionally, a variety of vegetable crops are grown, including Allium cepa L. (onion), Brassica oleracea (cabbage and broccoli), Solanum tuberosum (potato), and Lycopersicon esculentum (tomato) (Debela *et al*., 2017).

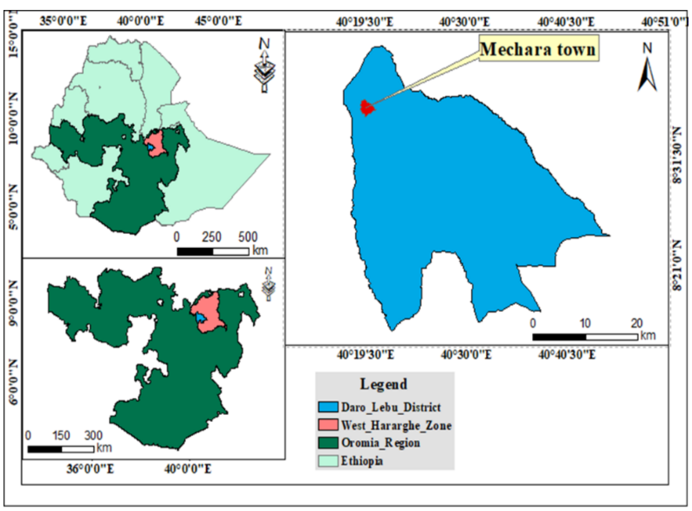

Figure 1. Map of the study area.

Site Selection, Soil Sampling, and Analysis Procedures

Maize production potential *Kebeles* (Sakina, Guddis, Sororo, Haroresa Kile, Satawa, Boido, Hamsiso, and Kortu) were selected purposively from the district. The experimental locations in the district were chosen based on the following criteria: phosphorus content ranges based on soil base test; farmers' readiness to offer land and initiative to perform the activity; accessibility for supervision; and proximity to the road. Prior to planting, twenty surface composite soil samples were taken using an auger in a zigzag pattern from 0 to 20 cm below the surface for examination. In order to facilitate additional laboratory examination, the surface soil samples that were obtained from the experimental field were ground, air-dried, and passed through a 2 mm sieve (FAO, 2008).

Experimental Design and Procedures

The study spanned four years, from 2018 to 2022. The economic rate of N determination trial was conducted on six farmer sites during the 2018/19 cropping season. Conversely, the Pc and Pf determination trials were implemented on seventeen farmer sites across the subsequent three cropping seasons: 2019/20, 2020/21, and 2021/22.

The initial year of the experiment (2018/19) employed a factorial design with four nitrogen levels (0, 46, 69, and 92 kg/ha) and three replications, arranged in a randomized complete block design (RCBD). For the subsequent three years (2019/20, 2020/21, and 2021/22), the experiment adopted a randomized complete block design (RCBD) with three replications. Six phosphorus levels (0, 10, 20, 30, 40, and 50 kg/ha) were applied, while a constant rate of 69 kg/ha urea was maintained. The Melkasa-2 maize variety, known for its early maturity, was utilized. Between plot 1m space and block, 75cm and 30cm were used as enter row and intra plant, respectively. Where all plot areas sowed were harvested and used for agronomic data collection. To ensure consistent comparability, maize grain yields were adjusted to a standard moisture content of 12.5%. The resulting yields were then expressed in kilograms per hectare (kg/ha).

To accurately characterize the experimental soils and determine their phosphorus critical levels (Pc) and phosphorus fertilizer requirements (Pf), intensive soil sampling was conducted at a 0-20 cm depth within three weeks of sowing during the three primary cropping seasons preceding the experiment. Soil pH was determined using a pH meter on supernatant suspensions prepared at a 1:2.5 soil-to-water ratio (Rhoades, 1982). Organic carbon content was quantified using the Walkley-Black method (Walkley and Black, 1934), while total nitrogen was assessed with the Kjeldahl method. Available phosphorus (P) was calculated using the Olsen method (Nelson and Sommers,1982).

Determination of Critical P (Pc) Concentration and P Requirement Factor (Pf)

To analyze the relationship between soil test phosphorus (P) levels and crop yield, the Cate-Nelson graphical method (Nelson and Anderson, 1977) was employed. Relative yield, calculated as a percentage of the maximum yield achieved, was plotted on the Y-axis against soil test P values on the X-axis. This graphical representation facilitated the identification of critical P levels and the estimation of fertilizer requirements

$$\text{Relative yield} = Yield * \frac{100}{maximum\ yield}$$

Pf was determined from the control and plots treated with different rates of fertilizer after three weeks from the sowing time.

$$Pf = \frac{Kg\ P\ applied}{\Delta\ soil\ P}$$

Generally, using the Pf, Pc, and initial P values, the rate of required P fertilizer to be applied was calculated by multiplying Pf by a difference of Pc and Pi as follows:

$$Rate\ of\ P\ fertilizer\ to\ be\ applied\ =\ (Pc - P\ i)\ \times\ Pf$$

Data Collection and Analysis

Growth performance parameters of maize such as plant height, number of cobs per plant, and grain yields were collected. The experimental data was analyzed using R statistical software. Differences between treatment means were evaluated at a 5% significance level using the Least Significant Difference (LSD) test. To assess the marginal rate of return (MRR) in farmer-managed experiments compared to researcher-managed trials, a partial budget analysis was conducted following CIMMYT methodologies (CIMMYT, 1988). This analysis incorporated a 10% reduction in grain yield to account for potential variations in crop management and postharvest losses.

RESULT AND DISCUSSIONS

Initial Selected Soils Physicochemical Properties

The soils at the study site were classified as clay loam, according to the United States Department of Agriculture (USDA) soil texture triangle, as described by Rowell (1994) (Table 1). Pre-planting soil analyses indicated that the majority of the study sites had pH values ranging from 5.3 to 7.34, falling within the moderately acidic to neutral range. Additionally, the measured electrical conductivity (EC) values suggested low salinity levels, indicating that excessive salt content was not a limiting factor for plant growth or seed germination. The available phosphorus (P) content in the experimental soils ranged from 0.98 to 19.9 ppm, aligning with the observations reported by Horneck *et al*. (2007).

Soil organic matter (SOM) levels varied between 1.55% and 2.65% (Table 1). Based on the classification system by Tadesse et al. (1991), these SOM concentrations were categorized as low to moderate. Total nitrogen (TN) concentrations ranged from 0.11% to 0.43%, also classified as low to moderate according to the guidelines provided by Landon (1991).

Table 1. Some physicochemical chemical properties of the experimental site of soil before planting at Daro Lebu district.

Parameter	Value	Rating	Reference
pH	6.54	Moderately acidic to neutral	(D.A. Horneck, *et al*., 2007)
EC (dS/m)	0.05	Low	(D.A. Horneck, *et al*., 2007)
P Ave. (ppm)	14.6	Low	(D.A. Horneck, *et al*., 2007)
K Ave. (ppm)	154.6	Medium	(D.A. Horneck, *et al*., 2007)
SOM	2.07	Low to moderate	(Tekalign,1991)
OC	1.2	Low	(Landon, 1991)
TN %	0.09	Low to moderate	(Landon, 1991)
CEC meq/100 g	16.7	Low	(Landon, 1991)
Texture %			
Sand	43		(USDA - NRCS 2008)
Clay	37		
Silt	20	Clay loam	
Class			

pH= Power of Hydrogen SOM= Soil Organic Matter OC=Organic Carbon TN=Total Nitrogen CEC=Cation Exchange Capacity

Plant Height (cm)

The application of varying nitrogen (N) rates had a significant effect on plant height, with observed differences being statistically significant ($p < 0.05$). The data indicated a marked response to increased N fertilizer rates, with the tallest plants reaching 172.9 cm and the shortest measuring 152.9 cm. These findings align with those of Kandil (2013), who reported that plant height increases with higher nitrogen application rates. A significant difference in plant height ($p \leq 0.05$) was also observed due to the combined application of urea and phosphorus fertilizers, highlighting the synergistic effect of these nutrients on plant growth. Phosphorus fertilizer application levels resulted in significant variations in plant height, with the highest value (190.98 cm) observed at an application rate of 69 kg ha^{-1} of urea and 92 kg ha^{-1} of phosphorus, while the lowest height (170 cm) was recorded in the control treatment. The observed increase in plant height can be attributed to nitrogen's role in promoting cell multiplication and elongation. Similar findings were reported by Ahmad et al. (2018), who noted that nitrogen application enhances stem elongation and increases the number of internodes in maize. Likewise, Sharifi (2016) concluded that the number of internodes rises with increasing nitrogen levels

Table 2. Responses of plant height, height to girth, number of cobs per hectare, and yield to applied treatments

Treatments (N, P)	PH (cm)	HG (cm)	NCPP	YH (Kg/ha)
T1 (0,0)	170b	76.37b	1.19d	4,916 d
T2 (69,23)	181a	83.91ab	1.27cd	6,062 c
T3 (69,46)	184a	85.80ab	1.34bc	6,426 bc
T4 (69,69)	188.8a	88.29ab	1.39ab	6,526 bc
T5 (69,92)	190.98a	90.63a	1.40ab	7,157 ab
T6 (69,115)	190a	90.32a	1.466a	7,422 a
Mean	184.32	85.88	1.34	64.9
CV	14.69	25.14	19.66	10
LSD	10.55	12.32	0.10	8.7

PH=Plant height, HG=Height to girth, NCP= Number of cobs per plant, YH=Yield per hectare

Grain Yield (Kg/ha)

Statistical analysis indicated that maize grain yield was significantly influenced ($p \leq 0.05$) by the combined application of urea and phosphorus fertilizers. The highest grain yield (7,157 kg ha^{-1}) was achieved with 69 kg ha^{-1} of urea and 92 kg ha^{-1} of phosphorus, whereas the lowest yield (4,916 kg ha^{-1}) was recorded in the control plot (Table 2). This variation in yield is attributed to the effects of nitrogen and phosphorus fertilizers on plant growth. The results align with the findings of Fana et al. (2012), Haile et al. (2012), and Chimdessa et al. (2023), who reported that varying rates of nitrogen and phosphorus fertilizers significantly influence the yield and yield components of maize.

Partial Budget and Marginal Rate Analysis

In the year 2014, the prices were as follows: maize was priced at 32 ETB per kg, DAP at 24 ETB per kg, and urea at 22 ETB per kg. Economic analysis revealed that the highest net income of 196,621.6 ETB was achieved with the application of 69 kg ha^{-1} of nitrogen and 92 kg ha^{-1} of phosphorus. This treatment yielded a marginal rate of return (MRR) of 1552%, which significantly exceeds the minimum MRR threshold of 100% as specified by CIMMYT (1988).

Table 3. Partial budget and marginal rate analysis for combined applications of different P Fertilizer rates with 69kg/ha urea at Daro Lebu District.

TRT	Ave. Yield kg /ha	Adj. Yield kg /ha	(TVC) in ETB	Income in ETB	Net benefit in ETB	MRR%
T1 (0,0)	4,919	4,427	1,500	141,667.2	141,667.2	
T2 (69,23)	6,062	5,455	6,200	174,585.6	168,385.6	568.48
T3 (69,46)	6,426	5,783	7,300	185,068.8	177,768.8	853.02
T4 (69,69)	6,526	5,873	8,400	187,948.8	179,548.8	161.82
T5 (69,92)	7,157	6,441	9,500	206,121.6	196,621.6	1,552.07
T6 (69,115)	7,422	6,679	10,600	213,753.6	203,153.6	593.82

MRR= Marginal rate of return, ha=hectare, Qt=Quantal, TRT= Treatments TVC= total variable cost, ETB= Ethiopian Birr.

Critical Phosphorus (Pc) Level Determination

Collected soil samples were analyzed for phosphorous concentration. Soil samples were collected from the experimental plots twenty-one days after planting. Pc was determined from 17 experimental sites conducted at Daro Lebu using the Cate-Nelson diagram system arranging available soil P on the X-axis whereas the relative yield of maize on the Y-axis. The distributed plots using the Cate-Nelson diagram method displayed that (14 ppm) was a Pc level for maize production in the Daro Lebu. Accordingly, the P-critical concentration above the response of the crop to the applied P-is (14 ppm) as shown in the below graph and relative Grain yield (%).Pf was determined using available P values in the samples collected from control and treated plots (Figure 2).

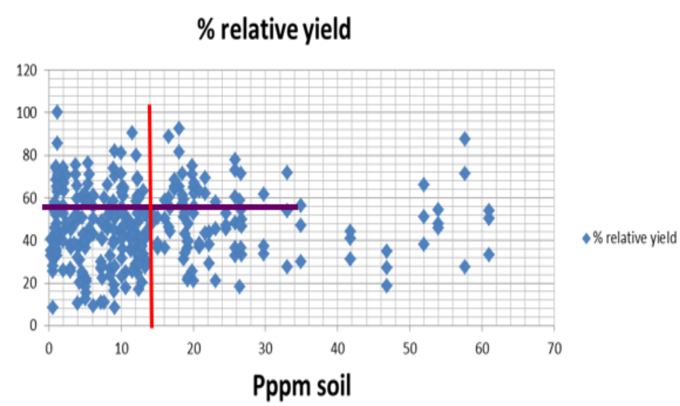

Figure 2. Scattered plot of relative grain yield (%) of maize and soil test phosphorus (Olsen) in Daro Lebu District.

Phosphorus Requirement Factor Determination

The amount of P increased above control applying P fertilizer 10, 20, 30, 40, and 50 Kg//ha was 3.14, 3.09, 7.78, 9.08, and 8.90 respectively. From this, there is the possibility to summarize that the mean of the Pf for maize production in Daro Lebu district was found to be 4.71 Kg P/ha (Table 4).

Table 4. Pf Calculation for maize production in Daro Lebu District.

P fertilizer applied	Olsen ppm (Average)	P level increase over the control (Olsen Method)	P requirement factor (pf)
0	8.39	___	___
10	11.53	3.14	3.18
20	11.48	3.09	6.47
30	16.17	7.78	3.85
40	17.47	9.08	4.40
50	17.29	8.90	5.62
Mean			4.71

CONCLUSION

A STBCR-based study was conducted in the Daro Lebu district of Oromia Regional State, Ethiopia, from 2018 to 2022, to determine optimal nitrogen (N) fertilizer rates and establish the phosphorus critical level (Pc) and phosphorus fertilizer requirement (Pf) for maize production. The results indicated that grain yield was significantly influenced ($p \leq 0.05$) by the interactions between N and P fertilizer rates. Economic analysis revealed that the highest grain yield of 7,157 kg ha^{-1} was achieved with the application of 69 kg ha^{-1} of nitrogen and 92 kg ha^{-1} of phosphorus. These fertilizer rates were identified as economically optimal for maize production in the Daro Lebu district, resulting in a net benefit of 196,621.6 Ethiopian Birr. The study also successfully determined the critical phosphorus level (Pc) and phosphorus fertilizer requirement (Pf) for maize. The Pc was established at 14 parts per million (ppm), and the Pf was identified as 4.71 kg ha^{-1}. These values are essential for optimizing phosphorus fertilizer applications in the region. To ensure practical application and validation of these recommendations, on-farm verification and demonstration trials should be conducted in the Daro Lebu district. These trials will help confirm the economic feasibility of the recommended fertilizer rates under varying local conditions, including soil variability, climate, and farming practice.

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Data Availability

All data generated are included within the article. Furthermore, datasets are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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