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Research Article

Soil Test Based Crop Response Phosphorus Calibration Study for Bread Wheat (*Triticum aestivum* L.) Production in Agarfa District Bale Highland, Oromia, Ethiopia

Girma Getachew*, Mulugeta Eshetu, Regassa Gosa, Tesfaye Ketama

Soil Fertility Improvement Research Team, Sinana Agricultural Research Center, Bale-Robe, Ethiopia

Abstract

Ethiopia faces a wide set of soil fertility loss issues which are declining of soil fertility due to biological and environmental factors as well as blanket fertilizer application throughout the country without considering soil types and agro-ecological are among the factors that pronounced in low yielding of food crop production like bread wheat. To tackle this problem, site specific nutrients managements and soil test-based crop response fertilizer recommendations was conducted for three consecutive years during the main cropping seasons of (2015 – 2017 E.C). The objective of the experiment was to determine economically optimum Nitrogen, Phosphorus critical (Pc) and Phosphorus requirement factor (Prf) for bread wheat production in Agarfa district. The treatments consisted of factorial combinations of three levels of TSP (0, 100, and 200) kg ha^{-1} with five levels of nitrogen (0, 23, 46, 69, and 92 kg ha^{-1}) that gave a total of fifteen treatments. However, in the second two consecutive years, the experiment was conducted to determine phosphorus critical (Pc) and phosphorus requirement factor (Pf), and the treatments consisted of six levels of phosphorus (0, 10, 20, 30, 40, and 50) kg ha^{-1} combined with a single level of nitrogen (69 kg ha^{-1}). Composite soil sample before plating and intensive soil samples after 21 days of sowing were taken from each plot and analyzed for selected physicochemical properties following standard laboratory procedures. Phosphorus critical level (Pc) determination was done using Cate-Nelson diagram method. Agronomic data such as above ground biomass and grain yield was collected then subjected to two-way factorial analysis of variance (ANOVA) using R software while the partial budget analysis was done using CIMMYT procedure. The results indicate that combined NP fertilizer rates significantly influenced the agronomic parameters of bread wheat. Optimum nitrogen rate (69 N kg/ha), P critical concentration (28.0 ppm) and P requirement factor (4.15) for bread wheat production were determined at Agarfa District. Therefore, uses of 69 N kg/ha fertilizer for bread wheat production at Agarfa District and areas having similar soil conditions and agro-ecology is advisable. Farther verification of the result on farm land could be a pre request before disseminating the technology to the user.

Keywords

Phosphorus, Bread Wheat, Cate and Nelson Graph, Nitrogen, Phosphorous Critical (Pc) Phosphorus Requirement Factor (Pf), Soil and Yield

*Correspondence: Girma Getachew (girmageta40@gmail.com)

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1. Introduction

Wheat is a type of cereal crop cultivated for its grain and used worldwide as a staple food. Ethiopia is also one of the largest wheat producers in Sub-Saharan Africa and approximately 80% of the wheat area is planted to bread wheat [1]. According to data published by [2], wheat is mostly farmed in Ethiopia's highlands, which are located between 6 and 16 °N latitude and 35 and 42 °E longitude, with elevations ranging from 1500 to 2800 m above sea level and mean minimum temperatures of 6 °C to 11 °C. Wheat production is crucial for both food security and economic stability in many emerging countries, particularly those like Ethiopia where falling soil fertility continues to impede agricultural productivity. However, severe deficits in soil nutrients are the main reason Ethiopia's wheat yield is still below its potential [3].

Due to erosion, leaching, and the lack of nutrient recycling, the majority of Ethiopian soils, particularly those in the highlands, have poor nutrient contents [4]. In Ethiopia's highlands, degradation of soil fertility is one of the main problems affecting wheat production [5, 6]. Ethiopian soils are thought to be particularly lacking in nitrogen (N) and phosphorus (P) [7, 8]. Particularly in highland soils, phosphate (P) deficiency is a major problem that hinders grain formation, tillering, and root development. Similarly, using a lot of N fertilizer has been a way to boost yield, but it can be expensive and pollute the environment [9]. Nowadays, a balanced fertilizer recommendation is of paramount importance in order to confirm the security and sustainably increase crop productivity for farmers and other stakeholders.

In the Bale Highlands of Oromia, including the Agarfa District, wheat faces unique challenges due to variable soil fertility and climatic conditions. Farmers in the study area uses blanket recommendations application which exposing farmers to increased production costs and cause depletion of soils plant nutrients. This calls for site-specific soil test-based Crop Response Phosphorus Calibration Study in Agarfa District of for bread wheat production. Each kind of plant has an ideal range of nutrients as well as a minimum essential quantity. Below this threshold, plants start to show symptoms of nutrient shortages. Poor growth can also be caused by toxicity from consuming too many nutrients. The proper application and arrangement of nutrients is therefore essential [10]. Furthermore, according to [11], soil test calibration varies depending on the type of crop, climate, and crop variety. It also relates soil test measurement in terms of crop response [12]. It is crucial that the results of soil tests be calibrated against crop responses from applications of the plant nutrients in question because this is the final indicator of a fertilization program. Instead of using the soil test-based crop response fertilizer application method, farmers in the majority of the country and the study area specifically applied fertilizers based on the blanket recommendation (100 kg ha^{-1} urea and 100 kg TSP ha^{-1}). Therefore, this soil test-based crop response phosphorus calibration this study was undertaken with the following objectives:

Specific Objectives

1) To determine economically optimum N fertilizer for bread wheat production in Agarfa District.
2) To determine Phosphorus critical and phosphorus requirement factor for bread wheat production in Agarfa District.

2. Materials and Methods

2.1. Description of the Experimental Site

The study was conducted at Agarfa District which is one of the Bale highlands Oromia Regional State, Southeastern Ethiopia. Agarfa District is located in the northwestern corner of the Bale Zone, and bordered on the south by Sinana and Dinsho, on the west-by-west Arsi zone, on the north by the Shabelle River which separates it from the Arsi Zone, and on the east by Gaserana and Gololcha districts. Agarfa district is located about 460 km from the capital city of Finfine. Geographically, Agarfa District is located at 7 °11' 0" to 7 °28' 0" N and 39 °35' 0" to 46 °0' 30" E. Topographically, the elevation of Agarfa district ranges from 1400 m to 3800 m above mean sea level (a.m.s.l). About 61% of the district is plain with slope ranging from 0 to 8 degrees and the majority of this area lies in the southeastern and western parts of the study area [13].

2.2. Climate and Agro-ecology

Agarfa District is characterized by bimodal rain fall patterns. The area is characterized by seasonal mean monthly rainfall varies from 6.11 to 155.11 mm, annual rainfall totals of between 661 mm and 1045 mm. Temperature maximum ranged from 17.31 to 22.5 °C while minimum varied from 7.60 to 10.56 °C. Agarfa District is predominantly dependent on rainfed, subsistence agriculture along with rearing of livestock. Agriculture is the main economic activity in the district, with the major sources of their livelihood income mainly from crop cultivation. The major crops produced in the area are barley, wheat, teff, maize, beans, field pea and others.

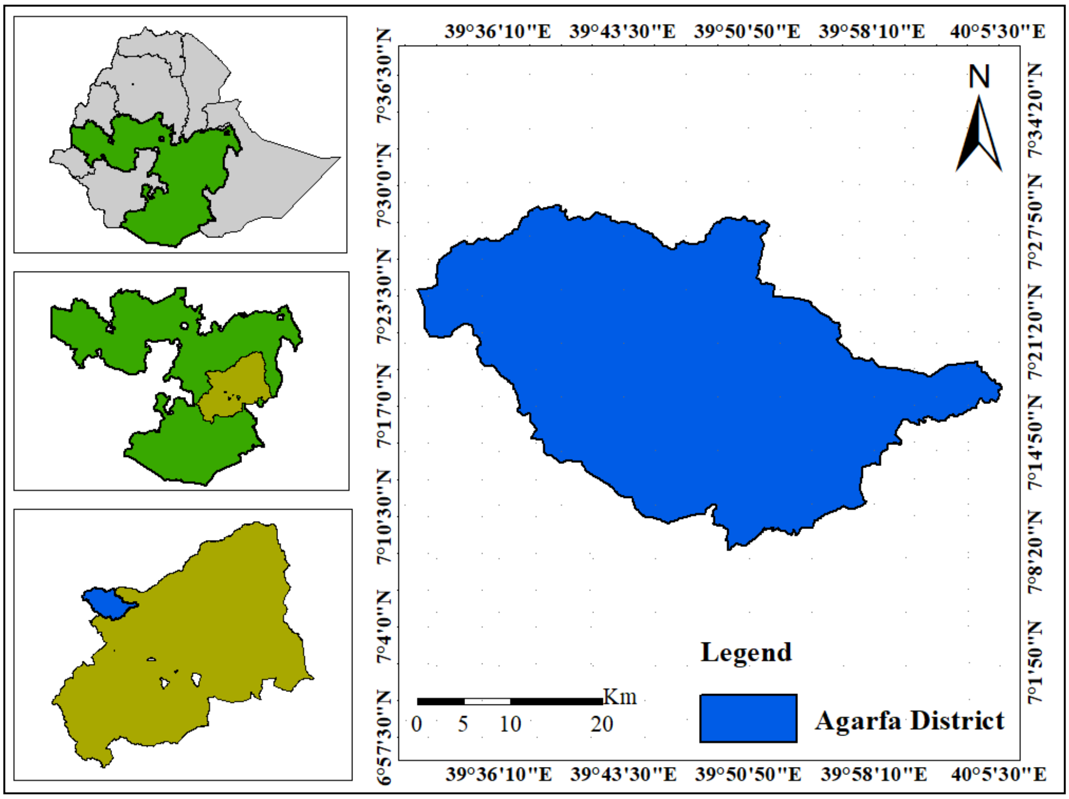

Figure 1. Location Map of Agarfa District.

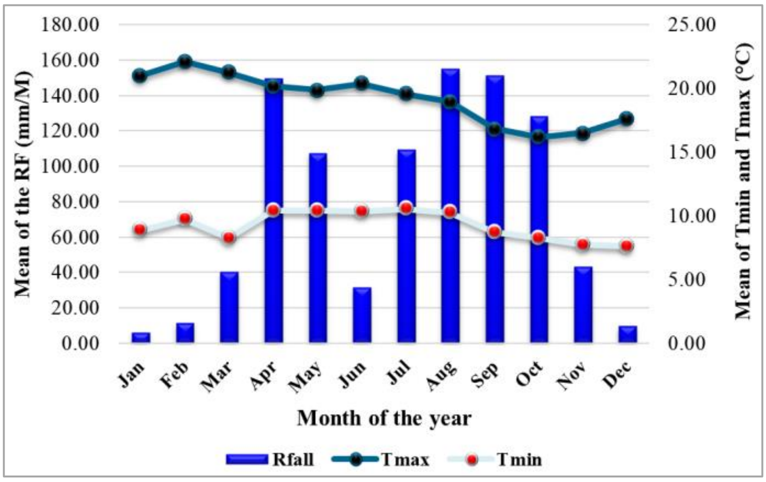

Figure 2. Mean monthly rain fall (mm), Max and Min Temperature (℃) in ten years (2014 to 2024) of Agarfa District.

2.3. Land Use and Farming System

Agriculture serves as the primary economic activity within the district, with crop cultivation being the principal source of livelihood for the local population. About 87.36% of the population lives in rural areas whose livelihood is pre dominantly dependent on rain-fed, subsistence agriculture along with rearing of livestock. Farmers in this region engage in a mixed farming approach that incorporates both crop production and livestock rearing. The predominant crops cultivated include cereals such as barley, wheat, maize, and teff, alongside pulses like chickpeas, soybeans, and lentils. Additionally, spices such as coriander and fenugreek, as well as vegetables including onions, potatoes, tomatoes, and peppers, are grown utilizing both rain-fed and irrigated methods. Cereal mono-cropping is particularly prevalent in the area [13].

2.4. Experimental Materials

1) Test Crop - bread wheat variety (*Boku*) was used as test crops.

2) TSP (46% P_2O_5) and Urea (46% N) was used as source of inorganic fertilizer.

2.5. Treatments, Experimental Design and Procedures

To obtained representative for experimental sites composite soil samples were collected from 22 farmers' fields in Agarfa district, where bread wheat is a dominant crop. Based on available soil P values determined by the Olsen method, fields were categorized into very low, low, and moderate available soil P contents. Based on this classification, sites with low or below critical available P were selected for the experiment in the district. On-farm field experiments were conducted in Agarfa District for the three consecutive years during the main cropping seasons under rainfed (July to December) from 2015 to 2017 E.C. In the first year, factorial combination of five levels of N rates (0, 23, 46, 69 and 92 $Kgha^{-1}$) and three rates of P (0, 30, and 40 $Kgha^{-1}$) to determine optimum N rate that gave a total of fifteen treatments as shown in Table 1. However, by using the determined optimum Nitrogen (69 kg ha^{-1}) at the first year; phosphorus critical (Pc) and phosphorus requirement factor (Pf) were determined in the second two consecutive years. So, the treatments consisted of six levels of phosphorus (0, 10, 20, 30, 40, and 50) kg ha^{-1} combined with a single level of nitrogen (69 kg ha^{-1}) that gave a total of six treatments. The experiments were laid out in randomized complete block design (RCBD) with three replications and the gross plot size was 3 m x 4 m (12 m^2) were used. Totally, 18 experimental unit was evaluated.

Table 1. *Description of first year treatment combinations.*

Treatments N:P (Kg/ha)
T1=0:0
T2=0:0
T3=0:0
T4=23:0
T5=23:30
T6=23:40
T7=46:0
T8=46:30
T9=46:40
T10=69:0
T11=69:30
T12=69:40
T13=92:0
T14=92:30
T15=92:40

2.6. On Farm Management of the Experiment

Land preparation was done both using tractors and oxen. As per the specification of the design, a field layout was prepared. The land was leveled and made suitable for crop establishment. Sowing was done in mid-August from 2015 to 2017 E.C. at seed rate (150 kg/ha). Others agronomic managements like hand weeding, herbicide, disease/pest control and row planting in 20cm was done as recommended for the crop. A full dose of Triple supper phosphate (TSP or P_2O_5) and one-third of N alone was applied at sowing time as per the treatment. The remaining two-thirds of N alone was top-dressed at the mid-tillering crop stage.

2.7. Soil and Agronomic Data Collection and Measurement

2.7.1. Yield and Yield Component Parameters

Above ground dry biomass yield: The aboveground dry biomass yield was determined from plants harvested from the net plot area after sun drying to a constant weight and expressed in kg ha^{-1}.

Grain yield: The grain yield was taken by harvesting and threshing the grain yield from net plot area. The yield was adjusted to 12.5% moisture content and expressed as yield in kg ha^{-1}.

2.7.2. Soil Sample Collection and Analysis

After 21 day's composite soil samples were collected from each plot by using soil auger from a depth of 0-20cm and selected soil physicochemical parameter was analyzed following laboratory standard protocol.

2.7.3. Determination of Critical P Concentration

The diagram of the results is divided into four quadrants that maximize the number of points in the positive quadrants and minimize the number of points in the negative quadrants. The observations in the upper left quadrant overestimate the fertilizer P requirement while the observations in the lower right quadrant underestimate the fertilizer requirement. That means, critical phosphorus concentration is below which there is a response while above phosphorus was not respond. After 21 days to planting, the applied phosphorus during sowing is assumed to be ready to be utilized by the crop. Pc was determined by Cate-Nelson graphical methods where by putting phosphorus soil values on the X-axis (yield×100/maximum yield). Cate-Nelson graphical methods are based on driving the Y-X scatter diagram in to four quadrants and increasing the points in the positive quadrants and reducing the number of points in the negative quadrants [14].

$$Relative\ \ Grain\ \ Yield\ \ = \frac{Yield\ \ x100}{Maximum\ \ Yield}$$

2.7.4. Determination of Phosphorous Requirement Factor

The P requirement factor (Pf) enables one to determine the quantity of P required per hectare to raise the soil test by 1 mg/kg (1 part per million), and to determine the amount of fertilizer required per hectare to bring the level of available P above the critical level [14].

Finally, the value of P requirement factor (Pf) was calculated using available P values in samples taken from unfertilized and fertilized plots after 21 days starting from sowing date. The phosphorous requirement factor was expressed as:

$$Pf = \frac{Kg\ \ P\ \ applied}{Change\ \ of\ \ soil\ \ P}$$

Lastly, using Phosphorus requirement factor (Pf), Phosphorus critical level and initial P values (soil P value from composite soil sample before fertilization) rate of P fertilizer to be applied was calculated as follows:

Rate of P fertilizer to be applied= (Pc –Pi) × Pf.

Where, Pc=critical P concentration, Pi=initial P values and Pf=P requirement factor.

2.8. Data Analysis and Interpretation

All Collected soil and agronomic data were subjected to statistical analysis of variance using a generalized linear model (GLM) in R statistical software version 4.2.2 [15]. Whenever the ANOVA detects significant differences at a 5% level between treatments, mean separation was conducted using fisher's least significant difference test [16].

2.9. Economic Analysis

To identify economic feasibility of treatments, partial budget analysis was implemented and calculated the marginal rate of return (MRR) [17]. Note only MRR was considered but also proper interaction effects of treatments were selected according to its highest net benefit obtained.

3. Result and Discussion

3.1. Status of Selected Soil Chemical Properties Before Planting

The research area's soil pH varied from 6.10 to 6.60 (Table 2), suggesting a reaction that was slightly acidic to almost neutral. [18, 19] assessed the soil organic matter (OM) level as low to moderate, with a range of 1.67% to 2.15% (Table 2). Available phosphorus (Av. P) levels varied from 2.72 to 8.12 mg/kg (Table 2). According to [20], the Olsen method established a rate for soils that ranged from very low to low.

Table 2. *Selected soils physicochemical properties of Agarfa district.*

Parameters	Mean	Min	Max	Rates	References
pH (H_2O)	6.37	6.10	6.60	slightly acidic to near-neutral	Jones (2003
OM (%	1.89	1.67	2.15	Low to Moderate	Tekalign (1991)
AvP (mg/kg)	5.19	2.72	8.12	very low to low	Cottenie (1980)

Where: OM = soil organic matter, Av.P = available phosphorus, Min = minimum, Max = maximum

3.2. Response of Bread Wheat Production to Combined Applications of Different NP Fertilizer Rates

The analysis of variance showed highly significantly ($P<0.05$) difference the total aboveground biomass yield of wheat due to combined application of phosphorus and nitrogen. The overall aboveground biomass production of wheat was significantly affected by the interaction between nitrogen and phosphorus fertilizer (Table 3). The interaction effect of 30 P (Kg ha^{-1}) and 69 N (kgha^{-1}) produced the highest aboveground biomass (15.26 t ha^{-1}), while the control treatment produced the lowest aboveground biomass (10.93t ha^{-1}) (Table 3). The result is in agreement with the report of [21] who reported that, the highest (10.705-ton ha^{-1}) and the lowest (7.365-ton ha^{-1}) biomass yields were recorded by application of (40 kg P ha^{-1}) with 69 N (kgha^{-1}) and control plots respectively.

Table 3. *Interaction effect of nitrogen and phosphorous (P_2O_5) fertilizers on bread wheat mean aboveground biomass (t/ha).*

N (kgha-1)	Mean Aboveground Biomass (t ha-1) P (kgha-1) 0	30	40
0	11.00bc	10.93c	14.40abc
23	12.00abc	12.46abc	14.00abc
46	13.53abc	12.93abc	13.23abc
69	15.13a	15.26a	15.06ab
92	14.66abc	14.46abc	14.33abc
Mean	13.56		
LSD (0.05)	4.11		
CV	18.14		

Additionally, the analysis of variance showed that during the years of the calibration study, the combination effect of phosphorus fertilizer application rates with nitrogen had a highly significant ($p < 0.05$) impact on grain production (kgha^{-1}) (Table 4). The combined application of 40 kg P ha^{-1} with N (69 kgha^{-1}) produced the highest mean grain yield (5592.83) and control plots the lowest (2717.50 kg ha^{-1}). The outcome is consistent with the observation that the combined application of 69/92 kg ha^{-1} nitrogen and phosphorus fertilizer, respectively, produced the highest grain production (5657.28 kg ha^{-1}) [21].

Table 4. *Responses of grain yield (kgha^{-1}) the combination of Nitrogen and Phosphorus.*

N (kgha-1)	P (kgha-1) 0	30	40
0	2717.50h	2862.33h	3114.67g
23	3441.50f	3628.67f	3828.83e
46	3826.17e	4164.50d	4641.67c
69	4243.43d	4851.00b	5592.83a
92	4488.83c	5013.17b	4231.67d
Mean	4043		
LSD (0.05)	194.65		
CV	12.90		

3.3. Partial Budget Analysis

Table 5 summarized the profit from the production of bread wheat using integrated rates of fertilizer application of nitrogen and phosphorus. Marginal analysis was used on non-dominated treatments to determine which ones offered the best return on the farmer's investment. A treatment's 100% marginal rate of return (MRR) was thought to be the lowest acceptable rate of return for farmers to find it beneficial [17]. Farmers must have access to information on treatment costs and benefits before they can embrace technological innovation. In order to create recommendations based on the agronomic data, this study evaluated the treatments' economic benefits. This helps farmers in the study area choose the optimal mix of resources.

The result in this study indicated that the treatments that received 40 kg ha^{-1} phosphorus with 69 kg ha^{-1} of nitrogen resulted in higher net benefits than control (Table 5). The highest net benefit of 218,510 ETB ha^{-1} with MRR of 1356% was obtained from the plot received 40 kg ha^{-1} phosphorus with 69 kg ha^{-1} of nitrogen, while the lowest net benefit of 110,059 ETB ha^{-1} was recorded from control treatment (Table 5).

Table 5. *Partial budget Analysis of N rates for bread wheat.*

N	P	AGY	GB	TVC	NB	MRR
0	0	2446	110059	-	110059	0
0	30	2576	115925	1500	114425	291
0	40	2803	126144	2000	124144	704
23	0	2827	127231	2000	125231	759
23	30	3266	146961	3500	143461	954
23	40	3356	151018	4000	147018	924
46	0	3084	138760	4000	134760	618
46	30	3748	168662	5500	163162	966
46	40	4178	187988	6000	181988	1199
69	0	3819	171859	6000	165859	930
69	30	4366	196466	7500	188966	1052
69	40	5034	226510	8000	218510	1356
92	0	4040	181798	8000	173798	797
92	30	4512	203033	9500	193533	879
92	40	3809	171383	10000	161383	513

Whereas: P- phosphorus, N- Nitrogen, AGY - adjusted grain yield, GB – Gross Benefit, MRR=marginal rate of return, TVC- total variable costs, NB - Net Benefit

3.4. Determination of Phosphorus Critical Concentration and P-Requirement Factor

Critical phosphorus (Pc): The phosphorus critical point for bread wheat production in Agarfa District was calculated using the Cate-Nelson graphical approach. As a result, the scatter diagram created using the relative grain yields of bread wheat and the subsequent soil test P values for all P rates (0-50 kg P ha^{-1}) was used to calculate the critical P concentration (Pc). Therefore, for bread wheat production in the district where crops reached roughly 80% of their maximum, the P-Critical concentration above which crop response became minimum was 28.0 ppm (Figure 3). The quantity of phosphorus in kilograms needed to elevate the soil p by one part per million is known as the phosphorus demand factor. For the study region, the district's P requirement factor (Pf) was 4.76.

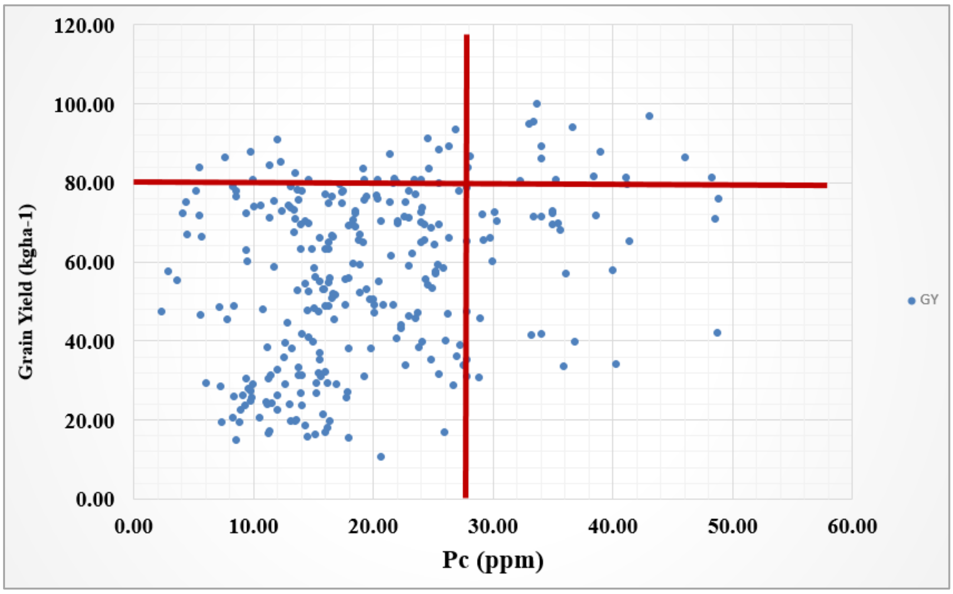

Figure 3. *Graph of critical phosphorus (Pc) for bread wheat production.*

Phosphorus Requirement Factor (Pf): The amount of phosphorus in kilograms required to increase the soil P by one part per million is known as the phosphorus requirement factor (Pf). After 21 days of each applied P-treatment, the average Olsen P-ppm and the phosphorus increase over the control were determined. The difference between the available soil test P values from plots that received 0-50 kg P ha^{-1} is used to calculate the P requirement factor (Pf). For 0 and 50 kg P ha^{-1}, the available p vs. p fertilizer applied ranges from 14.01 to 24.85 ppm. At Agarfa District, the Pf of the treatment ranged from 4.56 to 5.03 and the overall average Pf of all treatments for bread wheat production was 4.15 (Table 6). This factor enables to determine the quantity of P required per hectare to raise the soil test by 1 ppm, and to determine the amount of fertilizer required per hectare to bring the level of available P above the critical level [8].

Table 6. *Phosphorus requirement factor (Pf) for Bread wheat Production.*

P Applied	Average Soil P	PI	Pf
0	14.01	-	-
10	16.2	2.19	4.56621
20	21.17	7.16	2.793296
30	22.03	8.02	3.740648
40	21.95	7.94	5.037783
50	24.85	10.84	4.612546
Average		4.15	

4. Conclusion and Recommendation

Wheat is a type of cereal crop cultivated for its grain and used worldwide as a staple food. Ethiopia is also one of the largest wheat producers in Sub-Saharan Africa and approximately 80% of the wheat area is planted to bread wheat. However, wheat productivity in Ethiopia remains below its potential, largely due to widespread deficiencies in soil nutrients. Spatially, nitrogen (N) and phosphorus (P) are considered as the most deficient nutrients in soils of Ethiopia. Particularly in highland soils, phosphate (P) deficiency is a major problem that hinders grain formation, tillering, and root development.

In the Bale Highlands of Oromia, including the Agarfa District, farmers were used blanket fertilizer recommendations which exposing farmers to increased production costs and cause depletion of soils plant nutrients. To solve the problem of crop production and soil productivity decline because site specific soil test-based crop response phosphorus calibration studies was conducted for three consecutive years (2015-2017 E.C.) among the good alternatives and basic option. The optimum N (69 N kgha^{-1}), Pc (28 ppm) and Pf (4.15) determined during this studied advisable for bread wheat production in Agarfa district as well as extrapolation areas having the same soil conditions and agro-ecology recommended. Farther verification of the result on farmers' field could be a prerequisite before disseminating the technology to the end user.

Abbreviations

RCBD	Randomized Complete Block Design
TSP	Triple Supper Phosphate
GLM	Generalized Linear Model
ANOVA	Analysis of Variance
MRR	Marginal Rate of Return
OM	Organic Matter
pH	Potential of Hydrogen
LSD	Least Significant Different
CV	Coefficient of Variation
Pc	Critical Phosphorus
Pf	Phosphorus Requirement Factor

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Author Contributions

Girma Getachew: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft

Mulugeta Eshetu: Methodology, Software, Validation, Writing – review & editing

Regassa Gosa: Supervision, Project administration, Writing – review & editing

Tesfaye Ketama: Data curation, Investigation, Validation, Visualization

Conflicts of Interest

The authors declare no conflict of interests.

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