American Journal of Environmental Science and Engineering
2022; 6(2): 101-111
http://www.sciencepublishinggroup.com/j/ajese
doi: 10.11648/j.ajese.20220602.13
ISSN: 2578-7985 (Print); ISSN: 2578-7993 (Online)

Soil Test Based Crop Response Phosphorus Calibration Study for Food Barely Production in Sinana District of Bale Zone, Southeastern Ethiopia

Mulugeta Eshetu[1, *], Regassa Gosa[1], Daniel Abegeja[1], Tesfaye Ketema[1], Girma Getachew[1], Tilahun Chibsa[2]

[1]Sinana Agricultural Research Center, Soil Fertility Improvement and soil and Water Conservation Team, Bale-Robe, Ethiopia
[2]Oromia Agricultural Research Institute, Natural Resource Directorate, Addis Ababa, Ethiopia

Email address:
mulugeteshetu@gmail.com (M. Eshetu)
[*]Corresponding author

To cite this article:
Mulugeta Eshetu, Regassa Gosa, Daniel Abegeja, Tesfaye Ketema, Girma Getachew, Tilahun Chibsa. Soil Test Based Crop Response Phosphorus Calibration Study for Food Barely Production in Sinana District of Bale Zone, Southeastern Ethiopia. *American Journal of Environmental Science and Engineering*. Vol. 6, No. 2, 2022, pp. 101-111. doi: 10.11648/j.ajese.20220602.13

Received: March 12, 2022; **Accepted**: May 9, 2022; **Published**: May 12, 2022

Abstract: Soil fertility decline results from different factors. Blanket fertilizer application throughout the country without considering soil types and agro-ecological are among the bottlenecks to obtain sustainable desired yield. This calls for site-specific nutrients managements and soil test based crop response fertilizer recommendations. The objective of the experiment was to determine economically optimum N, Phosphorus critical (Pc) and Phosphorus requirement factor for food barely production at Sinana district. A field trials were conducted from 2019 to 2021, using factorial combinations of four N levels (0, 23, 46 and 69 Kg/ha) and Six P levels (0, 10, 20, 30, 40, and 50 Kg/ha) chemical fertilizers, laid out in randomized complete block design with three replications. Food barely (Robera variety) with recommended seed rate of 125 kg/ha was used. 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 C'ate-Nelson diagram method. Agronomic data such as plant height; tiller, seed per spike, biomass, grain yield and thousand kernel weight were collected and subjected to two way factorial analysis of variance (ANOVA) using R software while the partial budget analysis was done using CIMMYT (1998). The results revealed that both N and combined NP fertilizer rates significantly influenced the agronomic parameters of food barely. Optimum nitrogen rate (46 N kg/ha), P critical concentration (20 ppm) and P requirement factor (4.60) for food barely production were determined at Sinana District. Therefore, uses of 46 N kg/ha fertilizer for food barely production at Sinana 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: Optimum N, Calibration, Critical P Concentration, P Requirement Factor

1. Introduction

Crop production is controlled by numerous complex interacting factors which include soil fertility, pests and diseases, climate, and farmers' resourcefulness [5]. Soil fertility decline is one of the principal factors contributing to low crop production and agricultural productivity in which this lead food insecurity in Ethiopia [41]. Soil fertility declines due to removal through crop harvest, leaching, soil erosion by water in the form of surface runoff and cereal based monocropping are among several restricting factors responsible for low crop yields and agricultural productivity.

Barley is one of the most important cereal crops in the world, ranking fourth in production area next to wheat, maize and rice [38]. However; the barley yields were influenced by different factors which is varies in spatial and temporary. Soil fertility status is dynamic and variable from locality to locality do that it is difficult to end up with a blanket recommendation these low yields of food barely due to low fertilizer application. Barely producing areas mainly located in the highlands which is susceptible to severe soil erosion, poor soil fertility, low pH, particularly deficiency of nitrogen and phosphorus which is the main factor that severely reduces the yield of barely [29]. Barley is very sensitive to insufficient nitrogen and very responsive to nitrogen fertilization [3, 25]. The barley yield was low due to due to most of the farmers in the area do not use fertilizer and few others use very much below the recommended rate [26].

Nitrogen (N) and phosphorus (P) are considered as the most deficient nutrients in soils of Ethiopia [4]. Application of a large amount of N fertilizer has been a method of increasing yield which is costly and can cause environmental pollution [17]. Diammonium phosphate (DAP) and urea have been most common chemical fertilizers used in the form of blanket application, with the understanding that N and P are the major limiting nutrients in Ethiopian soils.

Calibration is the way to establish relationship between given soil test values and yield response from adding nutrients to the soil as fertilizer [1]. The calibration curve is specific for each crop type, soil type, soil pH, climate; plant species, and crop variety [2].

Soil test based site specific nutrient management has role to replace the traditional blanket fertilizer application. Recently across Oromia the calibrations studies were conducted for major crops such as bread wheat (*Triticum aestivum*); barley (*Hordeum vulgare*); teff (*Eragrostis teff*) and *maize* (*Zea mays*) to bring our farming community towards site specific fertilizer recommendations.

In the study area, the current blanket recommendations applications causes for increase production costs; depletion of soils plant nutrients and decline crop productions. *This calls for site-specific nutrients managements and soil test based crop response fertilizer recommendations* in Sinana District.

The reliable results of soil tests be calibrated against crop response from applications of the plant nutrients in question [42]. Soil test crop response based fertilizer recommendation correlates soil nutrients to plant use and also supports to determine the most economical fertilizer rate for a given crop [39]. Supported with this idea [23] stated that site specific sound full soil test calibration is essential for successful fertilizer program and crop production. Based on this concept, soil test calibration study was conducted on food barely production at Sinana district from 2019 – 2021 with the objectives; to determine optimum N fertilizer, P-critical and P-requirement factor values for food barely production and develop soil test based P-recommendation guidelines for food barely productions in Sinana District.

2. Materials and Method

2.1. Descriptions of the Study Area

The study was conducted in Sinana District which is one of the Bale highlands Oromia Regional State, Southeastern Ethiopia. This District is bordered by Goro District in the east, Dinsho District in west, Agarfa and Gassera in the north and Goba District in northeast. Sinana district is located about 460 km from the capital city of Addis Ababa. Geographically, Sinana District is located at 6° 40' 0"to 7° 20' 0" N and 45° 55' 0" to 46° 25' 0" E. Topographically, the area consists of gently undulating plain with average slope gradient of 7%. It extends from 1700 to 3100 above mean sea level (masl).

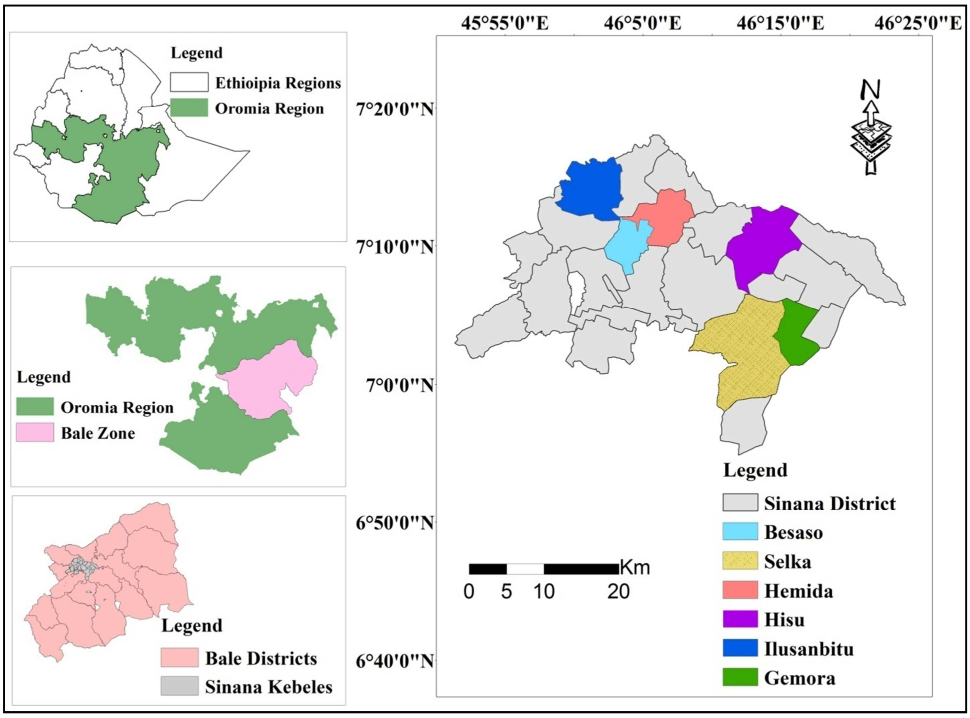

Figure 1. *Map the study site.*

2.2. Climate and Agro-ecology

Rainfall climatologically patterns of the area is a bimodal distribution having SH2 (humid sub humid to cool mild highland) agro ecology. The area is characterized by seasonal mean monthly rainfall varies from 8 to 160 mm, annual rainfall totals of between 453 mm and 1130 mm. Temperature maximum ranged from 21.9 to 23.5°C while minimum varied from 6.8 to 10.1°C. Agriculture is the main economic activity in the district, with the major sources of their livelihood income mainly from crop cultivation. Major crops grow in the district include wheat, barley, faba bean, field pea and others.

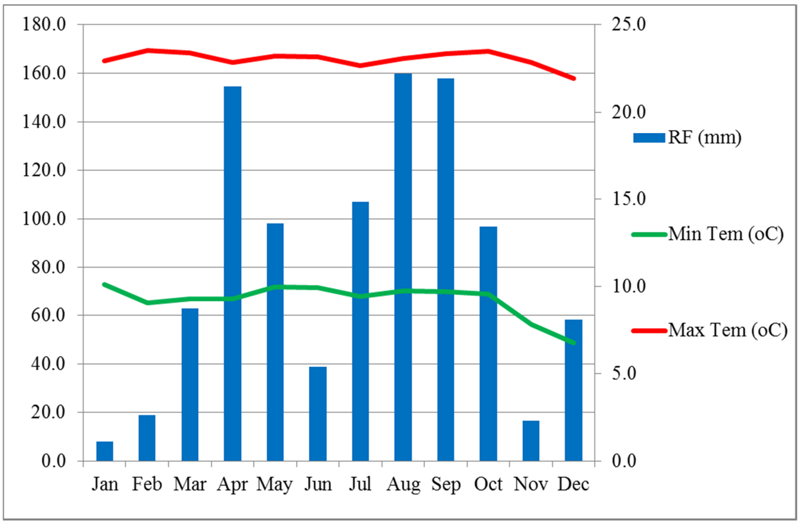

Figure 2. *Mean monthly rain fall (mm), Max and Min Temperature (°C) in three years (2019 to 2021) of Sinana District.*

2.3. Site Selection, Experimental Treatments, Design and Procedures

To select representative for experimental sites composite soil samples were collected from 22 farmers' fields in Sinana district, where food barely is a dominant crop. Based on available soil P values determined using 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 soils P were selected for the experiment in the district.

On-farm field experiments were conducted for three consecutive years (2019 to 2021) at six locations for first year and 22 sites or location for the reaming two years in Sinana District during the main cropping season (July to December) under rainfed conditions. In the first year, factorial combination of four N rates (0, 23, 46 and 69 $Kgha^{-1}$) and six P rates (0, 10, 20, 30, 40 and 50 $Kgha^{-1}$) were applied (Table 1) to determine optimum N. In the second and third years, six rates of P (0, 10, 20, 30, 40 and 50 Kg/ha) with recommended N rate (46 Kg/ha) were used to determine critical P concentration (Pc) and P requirement factor (Pf). Urea and TSP were used as N and P source; respectively.

Treatments laid out in RCBD with three replications on 3 m x 3 m (9 m^2) plot size using food barely (Robera variety) as test crop. Land preparation were done both using tractors and oxen. Others agronomic managements were applied according to the recommendations, seed rate (125 kg/ha), hand weeding, herbicide, disease/pest control and row planting in 20 cm.

Table 1. *Descriptions of treatments in the first year.*

Treatments N: P (Kg/ha)	Treatments N: P (Kg/ha)	Treatments N: P (Kg/ha)	Treatments N: P (Kg/ha)
T1 = 0: 0	T7 = 23: 0	T13 = 46: 0	T19 = 69: 0
T2 = 0: 10	T8 = 23: 10	T14 = 46: 10	T20 = 69: 10
T3 = 0: 20	T9 = 23: 20	T15 = 46: 20	T21 = 69: 20
T4 = 0: 30	T10 = 23: 30	T16 = 46: 30	T22 = 69: 30
T5 = 0: 40	T11 = 23: 40	T17 = 46: 40	T23 = 69: 40
T6 = 0: 50	T12 = 23: 50	T18 = 46: 50	T24 = 69: 50

2.4. Soil Sampling, Preparation and Laboratory Analysis

Soil samples at 0- 20 cm depth from the experimental sites before (composite) and after twenty one (21) days after planting (from each plots) were taken from five (5) different auger sampling points. Composite soil samples were prepared for each sites and plots. The composite soil samples were labeled with necessary information then air dried and crushed using a mortar and pestle to passed through a 2 mm mesh sieve for most soil physicochemical properties. On the other 0.5 mm mesh sieve was used for soil organic carbon and total nitrogen. The analyses were conducted following standard laboratory procedures at Sinana and Melkasa Agricultural Research Center and Haramaya University Soil Laboratory.

Particle size distribution was determined using the Bouyoucos hydrometer method [9]. Finally, the textural class of the soil was assigned using USDA textural triangle classification system [37]. The pH of the soil was measured in the supernatant suspension of a 1:2.5 soil to water ratio using a pH meter [35]. [40] method was used for the determination of organic carbon. Total nitrogen was determined using the Kjeldahl method as described by [10]. Available P was determined following the Olsen method [34] using ascorbic acid as reducing agent.

Total exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) were extracted after leaching the soils with 1N neutral ammonium acetate (NH_4OAc) solution. Exchangeable Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrometry (AAS) while K^+ and Na^+ were determined by flame photometer [33]. Cation exchange capacity (CEC) was determined for the soil samples which were first leached with 1 M ammonium acetate (NH_4OAc), washed with ethanol and the adsorbed ammonium was replaced by Na [11]. Then, the CEC was measured titrimetrically by distillation of ammonia that was displaced by Na. Percent base saturation (PBS) was calculated as follows;

$$\text{PBS}\ (\%) = \frac{Ca^{+2} + Mg^{+2} + K^{+} + Na^{+} * 100}{CEC}$$

The available micronutrients (Fe, Mn, Cu and Zn) were extracted by diethylenetriaminepenta acetic acid (DTPA). Their contents were quantified using AAS at their wave lengths as described by [28].

2.5. Agronomic Data Collection

Agronomic data were collected on the yield and yield components such as plant height, numbers of productive tillers, seed per spike, above ground biomass yield; grain yield and thousand kernel weight were taken then finally subjected to standard statistical analysis.

2.6. Statistical Analysis

The collected food barely yields and yield component data were subjected to analyses of variance (ANOVA) using R-software computer software 4.0.3. Significant differences among treatments means were separated by least significant differences (LSD) at 5% level of probability and using linear correlation coefficient matrix. Based on these interpretations were made following the procedure described by [18].

2.7. Partial Budget Analysis

Partial budget analysis was performed to determine the economic feasibility of the treatments. Partial budget, dominance, marginal and rate of marginal return analyses were used. The average yield was adjusted downwards to reflect the difference between the experimental plot yield and the yield farmers will expect from the same treatment.

The average grain yield was also adjusted by reducing 10% to minimize the over estimation of yield when yield of small plot converted to hectare basis. The average open market price (Birr/kg) of food barely, urea (N) fertilizers were considered for analysis. The minimum acceptable rate of return (MARR) was 100% [12], which is suggested to be realistic. This enables to make farmer recommendations from marginal analysis.

2.8. Determination of Critical P Concentration

The critical P concentration (Pc) value was determined by the Cate-Nelson diagram method [32]. Where soil test P put on the X-axis and relative yield on the Y-axis based on values obtained from trials conducted at 22 sites of Sinana District. A pair of perpendicular lines drawn on it to produce four quadrants displayed the relative yield. The diagram of the results was divided into four quadrants to maximize the number of points in the positive quadrants and to 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. The optimum is indicated by the point where the vertical line crosses the x-axis and critical P (Pc) value was determined using relative grain yield against the soil test values at different rates of phosphorus fertilizer for a given of nutrient rate. The relationship between grain yield response to nutrient rates and soil test P values, relative grain yields in percent were calculated as follows:

$$\text{Relative yield}\ (\%) = \frac{\text{Yield} * 100}{\text{Maximum yield}}$$

2.9. Determination of P Requirement Factor

The P requirement factor (Pf) enables one to determine the quantity of P required per hectare to raise the soil test P 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 [32]. The value of Pf was calculated using available P values in samples taken from unfertilized and fertilized plots after 21 days starting from sowing date as below:

$$\text{Pf} = \frac{\text{kg P applied}}{\Delta\ \text{soil P}}$$

Finally, using Phosphorus requirement factor, 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:

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

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

3. Result and Discussions

3.1. Selected Soils Physicochemical Properties Before PLANTING

The results of particle size distribution, pH, OM, TN and Av.P of the soil were summarized and presented in Table 2. Accordingly; the values of soil particles size distributions ranged from 14 - 26%, 16 - 36% and 38 – 66% for percent sand, silt and clay content; respectively. As the rating suggested by [21]. Low to moderate for both soil percent sand and silt content while moderate to very high for percent clay content. According the USDA soil textural class triangle all soils of experimental site were clay textural class (Table 2).

The pH (pH_H_2O) values of soil of watershed varied from 6. 07 to 6.50 as indicated (Table 2). As per the pH ratings suggested by [22] for pH in soil-water ratio were rated slightly acidic media. The values of soil organic matter (OM) were ranged from 1.55 to 2.65% (Table 2). As per the ratings of [36] OM contents for soils of the experimental sites rated into low to moderate class. The values of total nitrogen (TN) content varied from 0.11 to 0.43% rated as low to moderate as ratings suggested by [27]. The values of available phosphorus (Av. P) ranged from 2.02 to 5.04 mg/kg which rated very low to low based on the critical values for determined by the Olsen method established by [13]. The very low to low categories of these major soils plant nutrients might be due to leaching, continues cereal based monocropping (mostly wheat), low or limited inputs of organic and inorganic sources fertilizers, nutrient fixation and loss as a results of soil erosions.

Table 2. *Selected soils physicochemical properties status for the experimental sites of Sinana District.*

Site Name	Soil particle size distributions			Textural Class	PH-H_2O	OM	TN	Av. P (mg/Kg)
	Sand	Silt	Clay					
	(%)					(%)		
Sambitu	14	20	66	clay	6.31	1.55	0.15	5.8
Robe Area	18	16	66	clay	6.50	2.05	0.29	2.94
Amida	18	24	58	clay	6.07	2.26	0.36	4.55
Besaso	14	24	62	clay	6.15	1.75	0.27	4.02
Jafera	26	36	38	clay	6.24	2.26	0.43	2.02
Selka Oda	18	32	50	clay	6.12	2.65	0.33	2.34
Gemora	14	32	54	clay	6.25	2.22	0.11	2.56
Hisu	14	20	66	clay	6.18	2.49	0.11	2.45

Where: OM = soil organic matter, TN = Total nitrogen, Av. P = available phosphorus.

3.2. Cation Exchange Capacity, Exchangeable Bases and Percent Base Saturation

Cation exchange capacity (CEC) values were ranged from 36.4 to 50.2 $cmol_+/kg$ according to [21] rated into high to very high (Table 3). Exchangeable Bases (Ca, Mg, K and Na) values varied 8.81 to 37.17 $cmol_+/kg$, 0.57 to 1.40 $cmol_+/kg$, 2.13 to 3.49 $cmol_+/kg$ and 0.60 to 70 $cmol_+/kg$ also as the rating stated by [14] categorized into moderate to very high, low to moderate, low to moderate and moderate for Ca, Mg, K and Na; respectively. The low class of some basic cations might be due to their leaching by relatively high rainfall.

The results indicate that exchangeable bases concentration followed in the order of; Ca > Mg > K > Na for soils of the experiential sits (Table 3). The results indicated the values of exchangeable bases were optimal for crop production it does not mean no need managements. The calculated values of percent base saturation (PBS) for soils of the experimental sites varied from 33.28 to 88.82% and as per the rating set by [21] categorized into low to moderate class with having moderately leached (Table 3).

Table 3. *Cation exchange capacity, exchangeable bases and percent base saturation status soils of experimental sites in Sinana District.*

Site Name	CEC	Ca	Mg	K	Na	PBS%
	($cmol_+/kg$)					
Sambitu	50.2	24.23	1.40	3.49	0.60	59.22
Robe Area	47.4	14.87	1.23	3.14	0.62	41.90
Amida	36.4	8.81	1.03	2.13	0.64	34.62
Besaso	49.2	11.01	1.11	3.60	0.65	33.28
Jafera	48	37.17	0.57	2.99	0.67	86.25
Selka Oda	47.2	33.62	0.59	2.89	0.69	80.06
Gemora	46.6	28.15	1.27	3.09	0.70	71.27
Hisu	41.8	31.94	1.01	3.34	0.70	88.82

3.3. Soil Micronutrients

The results of soils analyzed values for micronutrients (Fe, Mn, Cu and Zn) varied from 6.53 to 13.37 mg/kg, 1.13 to 8.53 mg/kg, 1.54 to 3.40 mg/kg and 0.14 to 0.98 mg/kg and followed in the order of Fe > Mn > Cu > Zn as presented in Table 4. Based on [22] soils micronutrients (Fe, Mn, Cu and Zn) status of experimental sites categorized as high for Fe, moderate both for Mn and Cu while very low to moderate for Zn (Table 4).

Table 4. *Soil micronutrients status of experimental sites of Sinana District.*

Site Name	Fe	Mn	Cu	Zn
	mg/kg			
Sambitu	7.77	3.90	1.84	0.14
Robe Area	9.12	6.58	2.34	0.33
Amida	12.75	4.69	2.25	0.21
Besaso	13.37	7.08	2.34	0.36
Jafera	6.53	1.24	1.54	0.24
Selka Oda	6.63	1.13	1.92	0.20
Gemora	9.22	5.90	3.40	0.92
Hisu	12.02	8.53	3.26	0.98

3.4. Determination of Optimum Nitrogen Fertilizer (N) for Food Barely Production

Plant Height (PH)

The statistical analysis for plant height shows that significantly ($p \leq 0.05$) difference among means comparison of food barley due to N rates (Table 5). The highest mean plant height (84.12 cm) was obtained from N rate of 46 $Kgha^{-1}$ while the lowest plant height (59.88 cm) was recorded under control plot or zero nitrogen application. Plant height was significantly increased in response to increasing the rate of N fertilizer from nil up to 46 N kg/ha while decline at 69 N kg/ha. Thus, the possible reason might be the optimum rate of nitrogen application may have played an essential role for plant growth and development. Additionally, low or excess dose of nitrogen also causes reduction in vegetative growth of plant. This result supported by the finding of [20, 8] who stated the increments of plant height with increasing nitrogen rate. Likewise, [15, 19] reported that highest plant of barley recorded on high N treatments applied.

Number of Fertile Tillers

The analysis of variance indicated that number of tillers was highly significant ($p \leq 0.05$) influenced by N rates (Table 2). The highest mean number of tiller (3.90) was obtained from N fertilizer rate (46 N kg ha^{-1}) while the minimum number of tillers (1.79) was recorded from control (with zero nitrogen fertilizer). This might be due to nitrogen is an essential nutrient for growth and development of the plant as well improve the plant tillers. Several authors [3, 39, 8, 16] also reported applying optimum N rate was produced highest number of fertile tillers.

Spike Length

Table 5. *Responses of food barely plant height; number of tiller and seed per spike to N fertilizer application at Sinana District.*

N Rate ($Kgha^{-1}$)	PH (cm)	NT	SL (cm)	SPS
0	59.88^{d}	1.79^{d}	3.83^{c}	22.43^{d}
23	72.33^{c}	2.92^{c}	5.08^{b}	27.19^{c}
46	84.12^{a}	3.90^{a}	5.93^{a}	38.65^{a}
69	78.50^{b}	3.35^{b}	5.29^{b}	34.06^{b}
Mean	73.71	2.99	5.03	30.58
LSD (<0.05)	3.90	0.23	0.26	2.21
CV (%)	19.80	28.65	19.07	26.99

Where, PH: plant height, NT: number of tiller, SL: spike length, SPS: seed per spike, CV: Coefficient of Variation, LSD: least significant difference, Means followed by the same letter in the column and rows are not significantly different at 5% level of significance.

The statistical analysis among the means comparison of spike length were significantly ($p \leq 0.05$) influenced by N fertilizer rates (Table 5). The highest (5.93 cm) and the lowest (3.83 cm) spike length were obtained from 46 $kgha^{-1}$ N rate and control plot; respectively (Table 5). This implies that spike length considered as a yield contributing factor as larger spikes have more grains as compared to shorter spikes which ultimately effect better grain yield. This result supported with the finding of [8, 25] who reported spike length became higher at the optimum doses of nitrogen source fertilizer.

Biomass Yield

As the result indicated that biomass yield was very highly significantly ($p \leq 0.05$) influenced by N rate (Table 6). The maximum of biomass yield (6936.21 kg/ha) was obtained from 46 kg/ha while the minimum of biomass yield was recorded at control treatment which produced 3834.80 kg/ha (Table 6). This might be significant increases in plant height, number of tillers, spike length, number of seed per spike and grain yield from optimum N rate application ultimately contributed to the increased crop biomass yield. This result is confirmed with the studies of [39, 6, 16] those reported the significance increased in total biomass yield as compared to treatment received zero nitrogen rate. This means biomass yield has positive correlation with food barley growth parameters such as total number of plants, tillers per unit area and final plant height. Besides this result also agreed with the finding of [25] who obtained the highest biomass yield from plot receiving different rates of while the lowest biomass yield from control plot (zero nitrogen rate).

Grain Yield

The means comparison of food barely grain yield were significantly ($p \leq 0.05$) difference as influenced by N fertilizer rates (Table 6). Accordingly, the highest of grain yield (4267.91 kg/ha) was obtained from 46 kg/ha while lowest of grain yield of food barely was recorded at control treatment which produced 1921.22 kg/ha. Thus indicated that application of optimum nitrogen enhanced the grain yields of all food barley while excess uses might causes for economic loss and possible for lodging of the crop. Improvement in food barley yield with optimum N fertilizer application can be attributed due to the stimulating effects of nutrients on plant growth that provides ideal condition for crop as the supply to plants need. The current result agreement with the achievements of [6, 7, 16, 25] those obtained significant highly grain yield as a results of optimum N application due to positive effects of N on crop growth conditions. Grain yield is a complex character depending upon a large number of yield components such as number of tiller, spike length, seed per spike and biomass yield that might be the reason for highest grain yield at 46 N kg/ha rate applications. This finding supported by [23, 24] who obtained optimum nitrogen rate (46 N kg/ha) for teff and bread wheat productions; respectively.

Thousand kernels weight

Thousand kernels weight of food barely was significantly ($P \leq 0.05$) influenced by main effect of N fertilizer rate. The highest thousand kernels weight (36.13 g) was obtained from 46 N kg/ha however the lowest thousand kernels weight (24.87 g) was obtained from control plot (Table 6). Thousand kernels weight is an important yield determining component which is mostly genetic character that is influenced least by environmental factors. This result supported with the finding of [8, 25] who obtained the increasing rate of nitrogen application were increased thousand kernel weights. Thus, suggest that optimum application of N fertilizer may led to an increased in photosynthesis process and accumulations of carbohydrate in kernel to produce heavy kernels and consequently increased thousand kernels weight of food barely.

Table 6. *Responses of food barely biomass; grain yield and thousand kernel weight to N fertilizer application at Sinana District.*

N Rate ($Kgha^{-1}$)	BM ($kgha^{-1}$)	GY ($kgha^{-1}$)	TKW (g)
0	3834.80^{d}	1921.22^{d}	24.87^{d}
23	4954.55^{c}	2636.38^{c}	29.64^{c}
46	6936.21^{a}	4267.91^{a}	36.13^{a}
69	5923.06^{b}	3697.62^{b}	33.03^{b}
Mean	5412.00	3130.80	31.23
LSD (<0.05)	433.43	170.08	0.79
CV (%)	29.94	20.31	9.59

Where, BM: above ground biomass, GY: grain yield, TKW: Thousand kernel weights, CV: Coefficient of Variation, LSD: least significant difference, Means followed by the same letter in the column and rows are not significantly different at 5% level of significance.

Responses of Plant Height, Number of Tillers and Seed

Per Spike component to combined applications of different NP Fertilizer rates.

Plant height was significantly (P ≤ 0.05) affected by different rates of NP application (Table 7). The maximum plant height (87.47 cm) was recorded from application of 46:50 NP kg/ha and zero application of NP result the minimum (51.21 cm) plant height, which was significantly lower than the effect of other rates. This increment of plant height with increased NP rates might be due to related to the response of optimum nitrogen and phosphorus promotes vegetative growth as other growth factors are in conjunction with it. This result is in line with the report of [39, 29] who stated that plant height of barely was increase with increasing rates of NP up to optimum level. The probable reason might be that optimum NP supply played an essential role in plant growth and development.

Number of fertile tillers was significant (P ≤ 0.05) influenced to the interaction effects of both nitrogen and phosphorus fertilizer (Table 7). Accordingly; the highest (4.56) and the lowest (0.88) number of fertile tillers were obtained from 46: 40 NP kg/ha and 0: 0 NP kg/ha (control plot); respectively. This might be due to nitrogen stimulate the plant growth and phosphorus improve nitrogen availability. This result supported with the work of [39, 29] who reported the significant increase number of fertile tillers due to interaction effects of N and P fertilizer levels.

The values seeds per spike were significantly (P ≤ 0.05) influenced by the interactions of different NP fertilizer application rates (Table 7). Accordingly; the highest (43.20) and the lowest (18.56) number of fertile tillers were obtained from 46: 40 NP kg/ha and 0: 0 NP kg/ha (control plot); respectively. This might be due to nitrogen and phosphorus responsible for plant growth through the translocation of food materials in plants therefore it play vital role in grain setting as well as in producing higher number of grains. Supporting with this finding [29] reported the significant increase number of seeds per spike response to different rates of NP fertilizers.

Table 7. *Responses of plant height, number of tillers and seed per spike to combined application of different nitrogen and phosphorus levels for food barely production at Sinana District.*

Treatments	P Rates (kg/ha)					
	0	10	20	30	40	50
N Rates (kg/ha)	Plant height (cm)					
0	51.21[j]	60.02[ij]	64.50[ghi]	59.87[ij]	62.87[hi]	60.82[ij]
23	72.50[defgh]	71.04[efgh]	73.39[defg]	69.11fghi	72.96[defg]	74.98[cdef]
46	81.14[abcd]	83.73[abc]	83.07[abc]	84.64[ab]	84.66[ab]	87.47[a]
69	78.10[abcdef]	80.36[abcde]	78.14[abcdef]	77.79[bcdef]	78.73[abcdef]	77.90[abcdef]
CV (%)	20.00					
LSD (<0.05)	9.66					
N Rates (kg/ha)	Number of productive tiller					
0	0.88[h]	2.63[fg]	2.90[cdefg]	2.68[efg]	2.74[defg]	2.17[g]
23	3.71[abcd]	3.16[bcdefg]	3.68[abcd]	3.80[abc]	3.56[abc]	3.80[abc]
46	3.62[abcde]f	3.79[abc]	3.60[abcdef]	3.84[abc]	4.56[a]	3.99[ab]
69	3.67[abcde]	3.46[bcdef]	4.07[ab]	3.82[abc]	4.08[ab]	3.77[abc]
CV (%)	44.29					
LSD (<0.05)	0.99					
N Rates (kg/ha)	Seed per spike					
0	18.56[l]	22.23 [kl]	22.94[jkl]	24.81[hijk]	23.03[ijkl]	22.98[jkl]
23	29.53[efgh]	24.17[hijk]	27.64[ghij]	26.36g[hijk]	27.03[ghijk]	28.41[fghi]
46	38.09[abc]	33.83[cde]	38.72[abc]	39.54[ab]	43.20[a]	38.52[abc]
69	33.42[cdef]	34.70[bcde]	30.87[defg]	35.48[bcd]	35.31[bcd]	34.61[bcde]
CV (%)	26.85					
LSD (<0.05)	5.38					

Response of Biomass, Grain yield and thousand kernel weights to different nitrogen and phosphorus fertilizer rates.

Biomass yield was significantly (P ≤ 0.05) affected by different rates of NP application (Table 8). The maximum plant height (8774.98 kg/ha) was recorded from application of 46:40 NP kg/ha and zero application of NP result the minimum (3238.93 kg/ha) biomass yield, which was significantly lower than the effect of other rates. This might be because of the biomass the complex character depending upon a large number of food barely components such as number of tiller, spike length, seed per spike and grain yield that might be the reason for highest biomass yield at 46 N kg/ha rate applications. Similarly; [39, 29] reported the significantly increment of total above ground biomass response to N and P fertilizer interactions. Thus current study indicated that optimum application of nitrogen leads to high photosynthetic activity, vigorous vegetative growth and dark green color and finally improves the utilization of carbohydrates while adequate or optimum of phosphorus increases tiller emergence especially secondary tillers and proper regulation of carbohydrates translocation which it helps in increasing the biomass yield through.

Grain yield values were statistical significantly (p ≤ 0.05) influenced by the interactions of N and P fertilizers rates application for food barely production. Accordingly; the highest (4877.73 kg/ha) was recorded from application of 46:40 NP kg/ha and zero application of NP (control plot) result the lowest (1700.11 kg/ha) grain yield (Table 8). This might be because of the grain yield the complex character depending upon a large number of food barely components such as number of tiller, spike length and seed per spike that might be the reason for highest gain yield at 46:40 NP kg/ha rate applications. The mean grain yield of food barely response to optimum NP fertilizer application was 65.15% as compared to the unfertilized or control plot. Similarly; [30, 31] reported significant difference in grain yield due the optimum phosphorus and nitrogen fertilization application in which yield increased from control (without fertilizer) up to optimum combination of these fertilizers.

Thousand seed weight was significantly influenced different rates of NP application (Table 8). The highest thousand kernels weight (38.14 g) was recorded at application of 46:40 NP kg/ha while the lowest thousand kernels weight (22.14 g) was observed at control plot which is below the standard thousand kernels weight (35 – 40 g).

Table 8. *Responses of biomass, grain yield and thousand kernel weight to combined application of different nitrogen and phosphorus levels for food barely production at Sinana District.*

Treatments	**P Rates (kg/ha)**					
N Rates (kg/ha)	**0**	**10**	**20**	**30**	**40**	**50**
	Biomass (kg/plot)					
0	3238.93^{l}	3776.99 ^{kl}	3976.67^{jkl}	3891.79 ^{jkl}	3949.55^{jkl}	4052.65^{ijkl}
23	4806.20^{ghijk}	4306.91^{hijkl}	5130.55^{fghi}	4737.39^{ghijk}	5302.79^{efgh}	5693.490^{defg}
46	4917.78^{fghij}	6301.33^{de}	7828.99^{ab}	7454.08^{bc}	8774.98^{a}	8070.119 ^{ab}
69	6447.43^{cd}	5726.27^{defg}	5943.75^{def}	5851.85^{defg}	5591.26^{defg}	5783.33^{defg}
CV (%)	31.47					
LSD (<0.05)	1.97					
N Rates (kg/ha)	Grain Yield (kg/ha)					
0	1700.11^{k0}	1775.94^{k}	1764.51^{k}	2072.19^{jk}	2115.42^{jk}	2099.14^{jk}
23	2251.50^{ij}	2625.63^{hi}	2592.73^{hi}	2748.33^{h}	3290.27^{fg}	5 2865.39^{gh}
46	3709.61^{def}	3881.32^{cd}	4309.23^{bc}	4495.09^{ab}	4877.73^{a}	4334.47^{b}
69	3408.49^{ef}	3516.49^{def}	3728.93^{de}	3744.89^{de}	3745.88^{de}	3679.93^{def}
CV (%)	21.06					
LSD (<0.05)	433.16					
N Rates (kg/ha)	Thousand kernel weight (g)					
0	22.14^{h}	25.03^{g}	29.95^{f}	25.66^{g}	25.39^{g}	25.49^{g}
23	29.91^{f}	29.32^{f}	25.50^{g}	28.94^{f}	29.58^{f}	30.15^{f}
46	34.31^{cd}	35.90^{bc}	35.66^{bc}	37.34^{ab}	38.14^{a}	35.40^{c}
69	32.79^{de}	32.35^{e}	34.19^{cde}	32.92^{de}	33.16^{de}	32.767^{de}
CV (%)	9.31					
LSD (<0.05)	1.89					

3.5. Partial Budget Analysis for Optimum N Rate

The results of economic analysis showed that the highest economic net return 44293.43-birr ha^{-1} with acceptable MRR (1857.84%) was obtained from 46 kgha^{-1} nitrogen rate application (Table 9). Thus, application of nitrogen fertilizer for Food Barley had positive net benefit over the control treatment (zero nitrogen) which implies that improvement in crop nutrient management strategy increase in farmers' income. Therefore, application of 46 N Kgha^{-1} is economically profitable and recommended for farmers in Sinana district and other areas with similar soil types and agro-ecological conditions.

Table 9. *Partial budget analysis for optimum nitrogen rate determination for food barely productions in Sinana district.*

N rates (Kgha^{-1})	**UGY (Kgha^{-1})**	**AGY (Kgha^{-1})**	**GB (Birr ha^{-1})**	**TVC (Birr ha^{-1})**	**NB (Birr ha^{-1})**	**MRR (%)**
0	1921.22	1729.098	20749.176	0.00	20749.18	0.00
23	2636.38	2372.742	28472.904	900.00	27572.90	758.19
46	4267.91	3841.119	46093.428	1800.00	44293.43	1857.84
69	3697.62	3327.858	39934.296	2490.00	37444.30	D

Where, UGY = unadjusted grain yield, AGY = adjusted grain yield, GB= Gross benefit; TVC = Total variable cost; NB = Net benefit; MRR = Marginal rate of return.

3.6. Critical P Concentration (Pc) for Food Barely

The critical P concentration (Pc) was determined from the scatter diagram drawn using relative grain yields of food barely and the subsequent soil test P values for all P rates (0-50 P kg/ha). The Pc defined by the Cate Nelson method in this study was 20 mg/kg P with mean relative yield response of about 65% as indicated Figure 3. When the soil test value is below the critical value additional information is needed on the quantity of P required to elevate the soil P to the required level. At values of greater than or equal to 20 mg/kg, the crop achieved about 65% of its maximal yield in the absence of P fertilizer application (Figure 3). This implies that P fertilizer application could be recommended for a buildup of the soil P to this critical value, or maintaining the soil P at this level. Increasing P beyond this level, the cost of additional P fertilizer to produce extra yield would likely be greater than the value of the additional yield.

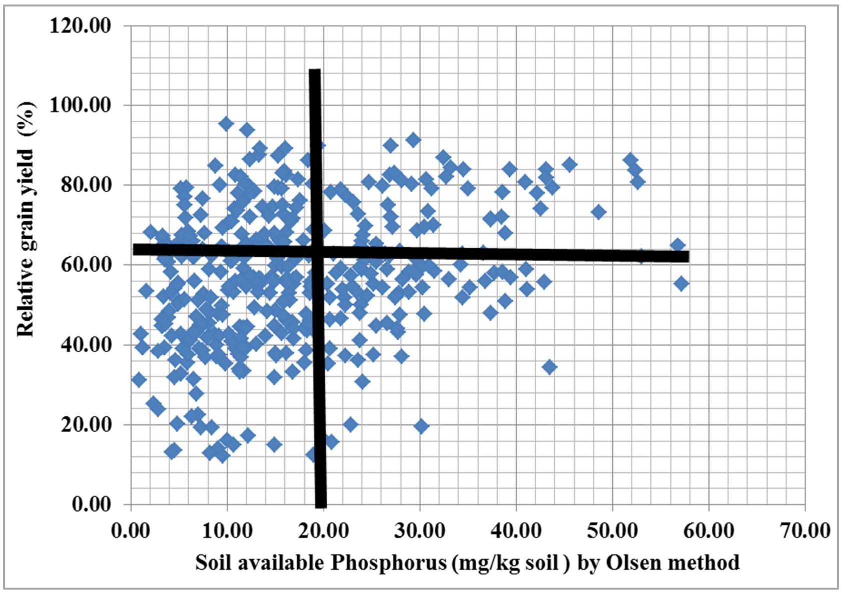

Figure 3. *Relationships between soil extractable P measured using Olsen method and relative grain yield of food barely according to this Nelson and Anderson graphical method critical limit determined was 22 P mg/kg.*

3.7. P requirement Factor (Pf) for Food Barely

Calculated phosphorus requirement factor (Pf), which is the amount of P in kg needed to raise the soil test P by 1ppm food barley production at Sinana District was 4.60 (Table 10). This factor enables one to determine the quantity of P required per hectare to raise the soil test by 1 mg/kg P (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. It was calculated using available P values in samples collected from unfertilized and fertilized plots.

Table 10. *Determination of P requirement factor (Pf) for food barely production in Sinana. District.*

P rate (kg ha^{-1})	Range (mg/kg)	Average	PI	Pf
0	0.827 - 43.526	12.00		
10	2.066 - 37.328	15.49	3.49	2.87
20	3.444 - 37.741	15.93	3.93	5.09
30	3.306 - 57.163	17.97	5.97	5.03
40	2.810 - 52.617	20.04	8.04	4.98
50	3.361 - 56.749	21.95	9.95	5.03
Average				4.60

4. Conclusion and Recommendations

Absence of soil test based site specific fertilizer recommendations the major causes for crop production and soil productivity decline in the study area. In order to solve such problems soil test based crop response phosphorus calibration study for food barely production in Sinana District was conducted for three consecutive years (2019 - 2021). Accordingly, the optimum nitrogen rate (46 N kg/ha) have been determined for food barely production. Therefore, application of 46 N kg/ha fertilizer advisable for food barley productions in Sinana district as well as other areas having the same soil conditions and agro-ecology.

Phosphorus critical (pc) concentration (4.60 ppm) and phosphorus requirement factor (pf) with the value (20) were determined for food barely production during this soil test based crop response phosphorus calibration study. Therefore; farther verification of the result on farmer's field could be a prerequisite before disseminating the technology to the end users.

Generally it can be concluded that the results of soil test crop response based application of optimum nitrogen and calibrated phosphorus were significantly improve yield and yield component of food barely. Thus show that both nitrogen and phosphorus are the most yield limiting nutrients in the study area.

Acknowledgements

The authors would like to thanks to Oromia Agricultural Research Institute and Sinana Agricultural Research Center for allocate logistic and vehicle during this research experimental implemented. Special thank also forwarded to all Soil Fertility Improvement Research Team staff members for active participations, especially to laboratory analysis team for their support and unreserved effort during soil samples analysis and providing results on time.

References

[1] Abdurahman Husien, Tilahun Firomsa, Tilahun Abera. 2021. Soil test crop response based phosphorus calibration study for bread wheat in Kofele District, West Arsi Zone Oromia, Ethiopia, *Journal of Scientific Agriculture*, 5: 20-25.

[2] Agegnehu, G., and Lakew, B. 2013. Soil test phosphorous calibration for malting barley (*Hordium vulgare L.*) production on Nitisols of Ethiopian highlands. Tropical Agriculture, 90, 177-187.

[3] Alam, M. Z., Haider, S. A. and Paul, N. K. 2007. Yield and Yield Components of Barley (*Hordeum vulgare* L.) cultivars in Relation to Nitrogen Fertilizer. Journal of Applied Sciences Research. 3 (10): 1022-1026.

[4] Alemu Dugassa, Ketema Belete, Tesfaye Shimbir. 2019. Response of Wheat (Triticum aestivum L.) to Different Rates of Nitrogen and Phosphorus at Fiche-Salale, Highlands of Ethiopia. *International Journal of Plant Breeding and Crop Science,* 6 (1), 474-480.

[5] Altieri, M. A. 2018. Agroecology: the science of sustainable agriculture. CRC Press.

[6] Amare A and Adane L. 2015. Grain quality and yield response of malt barley varieties to nitrogen fertilizer on brown soils of Amhara Region, Ethiopia. World J Agric Res 11: 135-143.

[7] Bekalu Abebe and Mamo Manchore. 2016. Effect of the Rate of N-Fertilizer Application on Growth and Yield of Wheat (Triticum aestivum L.) at Chencha, Southern Ethiopia. *International Journal of Plant, Animal and Environmental Sciences* 6 (3): 168-175.

[8] Biruk, G. and Demelash, K. 2016. Effect of Nitrogen Fertilizer Level on Grain Yield and Quality of Malt Barley (Hordeum vulgare L.) Varieties in Malga Woreda, Southern Ethiopia. *Food Science and Quality Management*, 52, 8–16.

[9] Bouyoucos, G. J., 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*, 54 (5): 464-465.

[10] Bremner JL and Mulveny CS., 1982. Nitrogen Total, In: AL Page (ed). Methods of Soil Analysis, Part Two, Chemical and Microbiological properties, 2nd ed. Am. Soc. Agron. Wisconsin pp. 595-624.

[11] Chapman, H. D., 1965. Cation exchange capacity. In: Black, C. A. (Ed.), Methods of Soil Analysis. *American Society of Agronomy, Madison* 9: 891-901.

[12] CIMMYT. 1988. From Agronomic Data to Farmer Recommendations: An Economics Training Manual. Completely Revised Edition, Mexico, DF., 79 pp.

[13] Cottenie, A., 1980. Soil and plant testing as a basis of fertilizer recommendations. FAO soil bulletin 38/2. Food and Agricultural Organization of the United Nations, Rome.

[14] FAO (Food and Agriculture Organization). 2006. Plant Nutrition for Food Security: A guide for integrated nutrient management. *Fertilizer and Plant Nutrition Bulletin* 16, Rome, Italy.

[15] Fazal, J., Mohammad, S., Jehan, B., Mohammad, A. and Sabir Gul, K. 2012. Effect of Different Levels of Inorganic Fertilizer N on the Yield and Yield Components of Barley Varieties at KPK Agricultural University, Peshawar, Pakistan. *Pakistan. Journal of. Botany*, 43 (3): 1471-1475.

[16] Franklin, O., Cambui, C. A., Gruffman, L., Palmroth, S., Oren, R. and Näsholm, T., 2017. The carbon bonus of organic nitrogen enhances nitrogen use efficiency of plants. *Plant, cell & environment*, *40* (1), pp. 25-35.

[17] Fresew Belete, Nigussie Dechassa, Adamu Molla and Tamado Tana. 2018. Efect of nitrogen fertilizer rates on grain yield and nitrogen uptake and use efciency of bread wheat (Triticum aestivum L.) varieties on the Vertisols of central highlands of Ethiopia. Agric and Food Secur 7: 78.

[18] Gomez, K. A. and Gomez, A. A. 1984. Statistical Procedures for Agricultural Research. 2nd ed. John Wiley and Sons, New York, USA. P. 680.

[19] Hadi, F., Arif, M. and Hussain, F. 2012. Response of dual purpose barley to nitrogen rates. *ARPN Journal of Agricultural and Biological Science.* 7 (7), 533–540.

[20] Haftom Gebretsedik, Mitiku Hhaile and Yamoah, CH. 2009. Tillage frequency, soil compaction and N-fertilizer rate effects on yield of tef (Eragrostis tef (Zucc.) Trotter) in central zone of Tigray, northern Ethiopia. *Ethiopia Journal of Science*. 1: 82-94.

[21] Hazelton, P. and Murphy, B. 2007. Interpreting Soil Test Results: What Do All the Numbers Mean? 2nd Edition. CSIRO Publishing.

[22] Jones, J. Benton. 2003. Agronomic Hand Book: Management of crops, soils and their fertility. CRC Press, Washington, USA.

[23] Kefyalew Assefa, Tilahun Firomsa and Tadesse Hunduma. 2017. Phosphorus Critical Level and Optimum Nitrogen Rate Determination on Teff for Sustainable Soil Fertility Management and Economical Teff Production at Lume Area of Oromia Region, Ethiopia. *Journal of Biology, Agriculture and Healthcare,* 7 (19): 14-21.

[24] Kefyalew Assefa Gejea and Tilahun Firomsa Erenso. 2018. Phosphorus Critical Level and Optimum Nitrogen Rate Determination on Bread Wheat for Sustainable Soil Fertility Management and Economical Production at Lume Area of Oromia Region, Ethiopia. *Journal of Biology, Agriculture and Healthcare*, *8* (1): 26-33.

[25] Ketema Niguse and Mulatu Kassaye. 2018. Response of Food Barley (Hordeum vulgare L.) Varieties to Rates of Nitrogen Fertilizer in Limo District, Hadiya Zone, Southern Ethiopia. *Journal of Natural Sciences Research,* 8 (15), 17–31.

[26] Lake Mekonnen and Bezabih W/kiros. 2018. Response of Food Barley (*Hordeum Vulgare* L.) to Various Levels of P Fertilizer. *International Journal of Research in Agriculture and Forestry,* 5 (2), 21-26.

[27] Landon, J. R., 1991. Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Sub Tropics. Longman Scientific and Technical, Essex, New York, USA, 474p.

[28] Lindsay, W. L., Norvell, W. L., 1978. Development of a DTPA soil test for zinc, iron, manganese and copper. *Soil science society of America journal,* 42 (3): 421-428.

[29] Mesfin Kassa and Zemach Sorsa. 2015. Effect of Nitrogen and Phosphorus Fertilizer Rates on Yield and Yield Components of Barley (Hordeum Vugarae L.) Varieties at Damot Gale District, Wolaita Zone, Ethiopia. *American Journal of Agriculture and Forestry*, 3 (6), 271-275.

[30] Mulugeta Eshetu, Shure Sebboka, Tilahun Chibsa, Chala Chimdessa, Negash Bedasso. Optimization of Fertilizer Recommendations for Bread Wheat at Sinana District of Bale Zone, Southeastern Oromia, Ethiopia. International Journal of Science and Qualitative Analysis. Vol. 3, No. 6, 2017, pp. 55-60. doi: 10.11648/j.ijsqa.20170306.11.

[31] Mulugeta Eshetu, Daniel Abegeja, Regassa Gosa, Tesfaye Ketama, Girma Getachew, Tilahun Chibsa. Soil Test Based Crop Response Phosphorus Calibration Study for Bread Wheat Production in Sinana District of Bale Zone, Southeastern Ethiopia. International Journal of Science and Qualitative Analysis. Vol. 8, No. 1, 2022, pp. 1-12. doi: 10.11648/j.ijsqa.20220801.11.

[32] Nelson, L. A. and Anderson, R. L., 1977. Partitioning of soil test—Crop response probability. *Soil testing: Correlating and interpreting the analytical results*, *29*, pp. 19-38.

[33] Okalebo, J. R., K. W. Gathua and P. L. Womer, 2002. Laboratory Methods of Soil and Plant Analyses: A Working Manual, 2nd Ed. TSBF-CIAT and SACRED Africa, Nairobi, Kenya. 128.

[34] Olsen, S. R., Cole, C. V., Watanabe, F. S., and Dean, L. A. 1954. Estimation of available phosphorous in soils by extraction with Sodium Bicarbonate. *USDA Circular,* 939: 1-19.

[35] Rhoades JD. 1982. Solubale salts. In: Page AL, Millere RH and Page DT (eds) Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, pp 167–180. Madison, WI: American Society of Agronomy.

[36] Tekalign Tadesse. 1991. Soil, plant, water, fertilizer, animal manure and compost analysis. Working DocumentNo. 13. International Livestock Research Center for Africa, Addis Ababa.

[37] USDA (United States Department of Agriculture). 1987. Soil Mechanics Level I-Module 3: USDA Textural Classification Study Guide. National Employee Development Staff, Soil Conservation Service, USDA.

[38] USDA (United States Department of Agriculture). 2017. National Agricultural Statistics Services Barley: Area, yield, and production, by State and United States, 2014–2016.

[39] Wakene Tigre, Walelign Worku, Wassie Haile. 2014. Effects of Nitrogen and Phosphorus Fertilizer Levels on Growth and Development of Barley (Hordeum vulgare L.) at Bore District, Southern Oromia, Ethiopia. *American Journal of Life Sciences*, 2 (5), 260-266.

[40] Walkley, A, Black, I. A, 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science, 37: 29-37.

[41] Wogene Solomon and Agena Anjulo. 2017. Response of Bread Wheat Varieties to Different Levels of Nitrogen at Doyogena, Southern Ethiopia. *International Journal of Scientific and Research Publications*, 7 (2), 2250-3153.

[42] Wortmann, C. S., Kaizzi, K. C., Maman, N., Cyamweshi, A., Dicko, M., Garba, M., Milner, M., Senkoro, C., Tarfa, B., Tettah, F. and Kibunja, C., 2019. Diagnosis of crop secondary and micro-nutrient deficiencies in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems*, *113* (2), pp. 127-140.