ESTABLISHING SOIL PHOSPHORUS CRITICAL LEVEL FOR POTATO (*SOLANUM TUBEROSUM* L.) IN ANDISOL OF LEMBANG, INDONESIA

Gossaye Hailu Debaba, Arief Hartono*, Untung Sudadi, Lilik Tri Indriyati
Department of soil science and land resources, Faculty of Agriculture,
Graduate School of Bogor Agricultural University, Indonesia
Jl. Raya Kampus IPB Darmaga 16680, Indonesia
*Corresponding author: hartono@apps.ipb.ac.id

(Received: August 27, 2018; Accepted: May 10, 2019)

ABSTRACT

A greenhouse experiment on soil diagnosis on phosphorus (P) fertilizer trial was conducted for potato in Andisol of Lembang district at Assessment Institute for Agricultural Technology (BPTP) from February to June 2018 in Indonesia. The treatments consisted of seven level of P fertilizer amount (0, 25, 50, 75, 100, 125, and 150 kg ha^{-1}) with three replications for low and high P soil arranged in completely randomized design. Bulk soil samples were collected from agricultural land and categorized as low and high P soil with respect to the soil's native fertility status. Soil test P was extracted by Olsen method. The result showed that P fertilizer significantly affected tuber yield. Correlation and calibration result of Olsen soil test P with relative tuber yield result indicated that 68.8 mg P kg^{-1} and 191 mg P kg^{-1} was critical level for potato production in Andisol for low and high P soils respectively. Result showed that at values less than these critical level of extractable P, P fertilizer should be applied to increase potato tuber yield. The application of phosphorus fertilizer at different amount increased tuber yields of potato by 21.8-40.1% and 15.3-28.4% for low and high P soil respectively as compared to the control yield. Available soil test phosphorus extracted by Olsen method three weeks after planting significantly responded to P fertilizer rate.

Key words: agricultural land, calibration, correlation, fertilizer rate, Olsen P, tuber yield

INTRODUCTION

Indonesia has 56.5 million ha of agricultural land comprised of various soil types (Syuaib 2016). In some parts of the country low fertilizer efficiency due to coated method of fertilizer application restrain agricultural profitability. Thus, low agricultural profitability especially for subsistence farming community is an indicator of low fertilizer efficiency. Agricultural development strategy of the country to improve crop productivity through increasing utilization of agricultural technology such as improved varieties and chemical fertilizer in conjunction with proper soil management is an essential tool to increase fertilizer use efficiency. In developing countries like Indonesia, phosphorus (P) fertilization efficiencies are highly important due to the lack of funding for fertilization (Hartono et al. 2018). Hence, evaluation of fertility status of the soil based on its nutrient supplying ability can help to improve productivity and increase fertilizer use efficiency and reduce environmental risk (Nafiu et al. 2012). Soil diagnosis is a method of evaluating soil fertility status in order to know the level of nutrient availability for a certain crop in a given soil type (Dahnke et al. 1990). Soil diagnosis to determine nutrient status of soils and calibrated to crop response is a major tool for improving and sustaining productivity through site-specific nutrient management (Agegnehu et al. 2015). However, Soil test P (STP) measures the quantity of P nutrient that is extracted from a soil by a particular extractant (Corey 1987). The measured quantity of extractable STP later correlated and calibrated to percent relative yield by assessing crop response in plots or greenhouse experiment to establish critical limits for a certain crop and soil type which may help to make fertilizer recommendation. The major purpose of diagnosing soils for P is to determine the quantity of supplemental P required to prevent economic loss of crop value because of P deficiency (Fixen et al. 1990). Soil test correlation is the process of determining whether there is relationship between plant uptake of a nutrient or yield and the amount of nutrient extracted by a particular soil diagnosis (Corey 1987), while calibration is a means of establishing a relationship between a given STP value and the yield response from adding nutrient to the soil as fertilizer (Admasu 2016, Dahnke et al. 1990).

Andisol is one of the 12 soil orders in Soil Taxonomy and defined taxonomically by the presence of andic soil properties (Soil Survey Staff 1998) formed from volcanic ejecta and has high P retention and Al saturation are limiting factors for plant growth (Yatno et al. 2008). Volcanic ash soils are among the most fertile soils in the world (Shoji et al. 2002), but in volcanic ash soil P is strongly sorbed by non-crystalline aluminum and iron materials. Phosphate retention by allophanic soils can reduce P availability for plant uptake (Stevenson et al. 1999). In turn, the applied P fertilizer readily react with weathering products of monocrystalline aluminum and iron materials, resulting formation of insoluble metal-phosphorus compounds (Shoji et al. 2002). However, the high retention of phosphate on Andisol causes the majority of P cannot be used by plants (Sembiring et al. 2017). Andisol covers appreciable area in Lembang district, West Java, Indonesia. Hence, inadequate P concentration in soil influences plant growth and development in the study area. It is estimated that 30–40% of global agricultural soils are limited by P availability and it is second only to nitrogen in limiting agricultural productivity (Vance et al. 2003). Thus, P is one of essential plant nutrients (Tisdale et al. 1985, Tan 2011) available in soil and plants can absorb in the form of primary orthophosphate ($H_2PO_4^-$) mostly at low soil pH and secondary orthophosphate (HPO_4^{2-}) at high soil pH. However, after application of mineral P fertilizers to soils the major portion of P (80-90%) cannot be absorbed by plants due to adsorption by soil particles (Fe, Al, Ca) (Daoui et al. 2014).

In the study area farmers grow intensively agricultural crops including potato. However, farmers apply chemical fertilizer while P fertilizer application is not based on soil diagnosis for potato is commonly practiced. It does not consider the spatial and temporal soil fertility variations and farmers apply the same P fertilizer amount to their fields regardless of fertility difference. As a result, profitability of potato production is restrained by low phosphorus fertilizer efficiency. Potato requires high P nutrient for optimum growth and yield, thus, when grown on P deficient soils, considerable yield losses are apparent (Dechassa et al. 2003). In addition method of P fertilizer application that is not based on soil diagnosis increases production cost and environmental risk. Currently there is no information on P requirements of potatoes in the study area while interpretations do available for other types of soils and crop but these may not applicable for potato in Andisol because (Fixen et al. 1990) calibrations are specific for each crop type, soil type, soil pH, climate, plant species, and crop variety. Hence, soil P diagnoses are useful to identify soils deficient in P and provide a guide to determine P requirement as to the magnitude of the crop's response to applied P. Once critical nutrient level established and crop requirement are worked out, farmers and producers could use this relatively simple tool to increase fertilizer profitability (Admasu 2016). In turn, it allows for the growers to have efficient utilization of P fertilizer. The basic aim of soil testing is to assess nutrient status, thereby identifying current and potential need for fertilization (Dahnke et al. 1990). Sound soil test based and site specific nutrient management therefore reliable and accurate method to identify the nutrient rates required to attain a desired level of plant growth and yield (Admasu 2017). Therefore, the objective of this study was soil diagnosis phosphorus calibration to establish phosphorus critical level for potato (*Solanum Tuberosum* L.) in Andisol of Lembang, Indonesia by Cate and Nelson (Cate and Nelson 1965) graphical method in order to determine a relationship between soil test and response to added P nutrient.

MATERIALS AND METHODS

Experimental site. P response trial for potato was conducted in greenhouse from February – June 2018 at Assessment Institute for Agricultural Technology (BPTP) in Lembang. Lembang is in West Java province, geographically located between 6º45'- 6º50' south latitude and 107º30'-107º40' East longitude. Potato is grown by farmers for local markets with other agricultural crops in Lembang district. Altitude of the study area is 1235 m above sea level and receives average annual rain fall 3047 mm.

Thirty soil samples (0-15 cm depth) were collected before the onset of the trial from the upper 0-15 cm because P from fertilizers stays in this layer due to strong sorption and precipitation. Soil samples were air-dried, sieved <2 mm and stored in sealed plastic bags at ambient laboratory temperature prior to analyses. Soil samples were analyzed for pH using in a ratio of 10 g of soil to 25 ml of water (1:2.5). Soil particle size distribution was analyzed by the hydrometer method (Bouyoucos 1962) using sodium hexametaphosphate (Calgon) as a dispersing agent. Soil textural class names were determined following the textural triangle of USDA system (Rowell 1994). Available P was determined by Olsen method (Olsen et al. 1954). Organic carbon content was determined using the Walkley and Black method (Walkley and Black 1934), total nitrogen using Kjeldhal digestion, distillation and titration method as described by Blake (Blake 1965), exchangeable cations and cation exchange capacity (CEC) using ammonium acetate method (Chapman 1965).

Greenhouse experimental setup. The soil analysis was carried out at Department of Soil Science, Faculty of Agriculture, Bogor Agricultural University. 11 kg field soil was filled to 14 litter pots and the pots were arranged in complete randomized design with seven levels of P (0, 25, 50, 75, 100, 125 and 150 kg P ha^{-1}) each have three replications. The mean soil P analytical results of the study site soil were interpreted as low and high using Olsen available P in the range < 10 , 10 – 25, 26-45, >46 mg kg^{-1} categorized in very low, low, medium and high STP respectively. The plant materials used for the experiment were sprouted tubers of median potato variety obtained from local farmers. This variety was selected due to local agro climatic condition adaptability and its availability in the area. The soil media used for growing potato was prepared from low P soil (21 pots) and high P soil (21 pots) filled with 11 kg of experimental site field soil with a total of 42 pots. The sprout was planted on April. The sources of nitrogen (N), P and potassium (K) were urea (46% N), triple super phosphate (TSP 45% P_2O_5), and KCl (60% K_2O) respectively. The P and KCl (135 kg ha^{-1}) fertilizers were applied at planting while the recommended N fertilizer (100 kg ha^{-1}) was applied in two dozes, half at planting and half after 45 days of planting. The amount of N and K fertilizers applied based on local farmers practice and also farmers in the study area apply 100 kg ha^{-1} of P fertilizer for potato. One sprouted tubers of size between 85-100g weights of tubers were planted at 10 cm depth after watering the media well. Every two days interval after watering the pots, the pot soil was mixed to the depth of 5 cm in order to make sure that the P fertilizer distribute uniformly at the top soils of pot without damaging the planted sprout until three weeks. Three weeks after planting soil samples were taken from all pots (5 cm depth) in order to give enough time to dissolve P fertilizer in the pot to analyze soil test P by Olsen extraction method (Olsen et al. 1954). Olsen extractant used because of the soil initial pH was 6.2 such that acid extractant the results correlate better with plant response in soil with pH less than 6.0. Holford (1980) found that acid extractants extracts large amounts of non-labile P in soils with pH greater than 6.0 results over estimation of available P in soil. In addition Maghanga et al. (2012) suggested that the Olsen extractant is useful for both acid and calcareous soils. In calcareous soils, increased P solubility is as a result of decreased Ca concentration by high CO_3^{2-} to form $CaCO_3$. In acid or neutral soils, the solubility of the Al and Fe phosphates increases as OH^- concentration decreases. The type of fertilizers application used in this study was band method around the planted sprout. All of the other cultural practices used throughout the growing season were similar to those that were practiced by regular farmers. Agronomic parameter collected was total tuber yield after crop maturity.

Determination of critical P concentration (Pc). To correlate relative yield versus soil test P values and determine critical P concentration, the available P was extracted from the soil samples taken three weeks after planting from each pot using Olsen method and three replications for each treatment. The Cate-Nelson graphical method (Cate and Nelson 1965) used to determine the critical P value using relative yields and soil test P values obtained from P fertilizer trials conducted in greenhouse, to assess the relationship between tuber yield response to nutrient rates and soil test P values, relative potato tuber yields in percent were computed for both high and low P soil separately by the formula below:

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

Where yield stands for tuber yield obtained from all treatment with their respective replication, and maximum yield stands for the maximum yield obtained among replications.

The scatter diagram of relative yield (Y-axis) versus soil test value (X-axis) was plotted and the range in values on the Y-axis was 0 to 100%. A pair of intersecting perpendicular lines was drawn to divide the data into four quadrants. The vertical line defines the responsive and non-responsive ranges. The observations in the upper left quadrants overestimate the P fertilizer requirement while the observations in the lower right quadrant underestimate the fertilizer requirement. The intersecting line was moved about horizontally and vertically on the graph, always with the two lines parallel to the two axes on the graph, until the number of points in the two positive quadrants was at a maximum (or conversely, the number of points in the two negative quadrants was at a minimum). It was divided according to the probability (high or low) that potato respond to fertilization. Then, the soil- test value where the vertical line crosses the x-axis is selected as the soil critical level of extractable P concentration for potato. Thus, the vertical line separates the point between nutrient deficiencies to sufficiency range.

Statistical Analysis. The effect of P treatments on potato yield and three weeks after planting soil test P was evaluated by analyses of variance (ANOVA), using the statistical analysis system version 9.1 (SAS 2004) software. Means for the main effects were compared using the means statement 5% significance level in order to separate the treatment means. Tukey's test at 5% levels of significance was used to separate the treatment means.

RESULTS AND DISCUSSION

Initial soil physical and chemical properties. The soil medium prepared for growing potato was Andisol with pH 6.20, 0.72 g cm^{-3} bulk density, EC 0.50 ds m^{-1} and other soil physical and chemical properties analyzed (Table 1) based on respective methods. The mean textural class of the study site was categorized under silt loam. The mean soil pH was under the range of slightly acidic class (4.3-6.7). The lowest soil pH was recorded from low P soil but at high P soil the soil pH recorded higher than low P soil. This is because on high P soil farmers apply high amounts of organic materials in addition to chemical fertilizer that may raise the soil pH, because organic materials raise soil pH either by mineralization of organic anions to CO_2 and water thereby removing H^+ or the alkaline nature of organic materials (Helyar 1976). The mean value of organic carbon (5.02%) and total nitrogen (0.47%) were under the range of medium (2.59 – 5.17%) and very high (>0.25%) status respectively according to ratings developed by Tekalign (1991). Extractable P content extracted by Olsen method for low P soil a mean of 23.4 mg kg^{-1} and high P soil 118 mg kg^{-1}. This indicates a high variation in P content among low and high P soil. This is because on high P soils farmers were applied high amount of organic material for crop production complementary to chemical P fertilizer, while in low P soil farmers were not used organic matter.

Table 1. Summary of soil physical and chemical properties of trial site

Selected soil properties	Average	±SE	Range
pH (10:25 H_2O)	5.57	0.12	4.30-6.70
Total N (%)	0.47	0.01	0.29 - 0.55
Olsen-extractable P(mg kg^{-1}) for high P soil	118	5.26	115-121
Olsen-extractable P (mg kg^{-1}) for low P soil	23.4	1.64	22.1-25.0
Organic carbon (%)	5.02	0.07	4.20-5.60
Exchangeable K (cmolc kg^{-1})	0.58	0.04	0.13-1.08
Exchangeable Ca (cmolc kg^{-1})	3.53	0.47	0.90-10.14
Exchangeable Mg (cmolc kg^{-1})	0.52	0.08	0.19-1.42
Exchangeable Na (cmolc kg^{-1})	0.05	0.001	0.04-0.07
CEC (cmolc$_{(+)}$ kg^{-1})	27.8	0.35	26.1-31.0
Soil texture			
- Sand (%)	42.4		36.2-50.2
- Silt (%)	52.6		43.2-54.6
- Clay (%)	5.07		3.21-6.74
- Texture	Silt loam		

Note: CEC, Cation Exchange Capacity; SE, Standard Error

Yield responses to P fertilizer. The analysis of variance of the experiment result indicated that there were significant ($P < 0.05$) responses of tuber yield to P fertilizer rates. The highest mean tuber yield (15,336 kg ha^{-1}) was recorded from 75 kg P ha^{-1} with mean relative yield response of about 91% on low P soil (Fig. 1), while on high P soil the highest mean tuber yield (16,211 kg ha^{-1}) was recorded from 50 kg P ha^{-1} with mean relative yield response of about 92% (Fig. 2). The application of P fertilizer at different rates increased tuber yields of potato by 21.9-40.1% and 15.3-28.4% for low and high P soil respectively as compared to the control yield (Table 2).

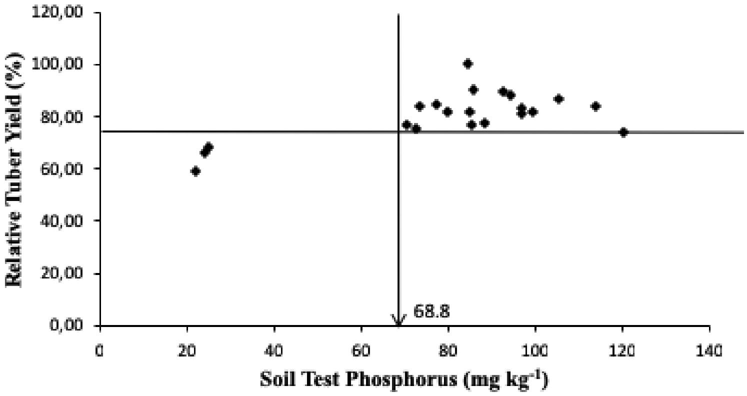

Fig. 1. Effect of available soil test phosphorous value analyzed three weeks after planting to P fertilizer rate for low P soil as determined by Cate-Nelson graphical method. The arrow indicates the phosphorus critical level for potato on low P Andisol.
Note: Soil Test Phosphorus (STP in mg kg^{-1}) available phosphorus extracted by Olsen method 3 weeks after planting with respect to each treatment (each pot soil).

Critical P concentration (Pc). The correlation between relative tuber yield response and soil P measured with Olsen method is indicated that the critical level of extractable P concentration for potato using data of soil available P and corresponding relative tuber yield for all treatments, extracted by Olsen extraction method was 68.8 mg P kg^{-1} (Fig. 1) and 191 mg kg^{-1} (Fig. 2) for low and high P soils respectively determined by Cate-Nelson graphical method (Cate and Nelson 1965).

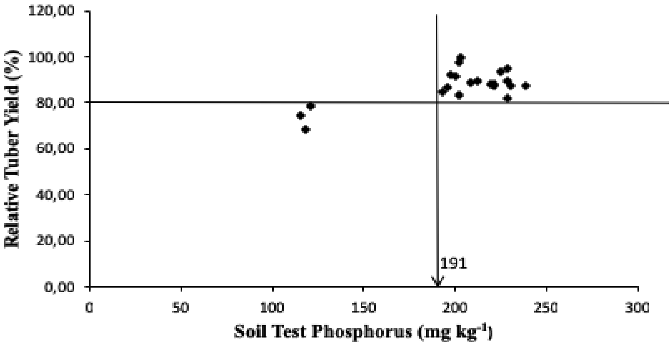

Fig. 2. Effect of available soil test phosphorous value analyzed three weeks after planting to P fertilizer rate for high P soil as determined by Cate-Nelson graphical method. The arrow indicates the phosphorus critical level for potato on high P Andisol.
Note: Soil Test Phosphorus (STP in mg kg^{-1}), available phosphorus extracted by Olsen method 3 weeks after planting with respect to each treatment (from each pot soil).

The increase in soil P response to P fertilizer applied was linear up to 75 kg P ha^{-1}, but the increase in yield was not significantly different beyond 75 kg P ha^{-1}; on low P soil, on the other hand the increase was linear up to 50 kg P ha^{-1}, but the increase in yield was not significantly different beyond 25 kg P ha^{-1} on high P soil (Table 2), a slight decline in yield was even observed at the greatest P rate. This suggests that the magnitude of potato response to P might be limited by supply of other nutrients, particularly N, because nitrogen deficiency causes a marked reduction in uptake of P, K, Ca, Mg, Mn, Cu, and Zn (Mengel et al. 2001). In addition (Fixen et al. 1990) suggested that the extractable soil P level is only one of several factors influencing plant response to P fertilizer. At soil test phosphorus values of less than 68.8 mg kg^{-1} and 191 mg kg^{-1} critical levels of extractable P on low and high P soils respectively, P fertilizer should be applied to increase potato tuber yield at values of greater than or equal to 68.8 mg kg^{-1} on low P soil the crop achieved about 75% of its maximal yield (Fig. 1) and at values of greater than or equal to 191 mg kg^{-1} on high P soil the crop achieved about 80% of its maximal yield (Fig. 2). 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 concentration at this level.

Results showed some yield responses from P fertilizer application had soil test levels above the critical level. Hence, to protect potential potato tuber yield loss, at least a maintenance application of 25 kg ha^{-1} P for both low and high P soil may be required depending on yield goal and profitability. Conversely, P fertilizer application is not likely to increase tuber yield of potato at soil P concentration above the critical level. Agegnehu et al. (2015) suggested that to increase P beyond this level, the cost of additional P fertilizer to produce extra yield would likely be greater than the value of additional yield. Thus, farmer’s economic return may also reduce. Therefore, in soils with available P status below 68.8 mg kg^{-1} on low P soil and 191 mg kg^{-1} on high P soil, potato tuber yield could show a significant response to application of P fertilizers. Observations showed that plant heights were taller in pots treated with P fertilizer than untreated ones on low P soil. Susila et al. (2010) in line with the result of this study reported that critical Olsen Phosphorus values of 117 mg kg^{-1} and 267 mg kg^{-1} for low P and high P soil respectively for Yard Long Bean on Ultisols in Nanggung-Bogor district, Indonesia. The correlation analysis (Fig. 1 and Fig. 2) indicated that there is significance correlation between soil test P and potato tuber yield. Application of P fertilizer could be recommended to raise soil P to the critical value and maintain it there. The analysis of variance also indicated that soil with low initial P concentration, response of crop to fertilizer application was also higher than high P soil (Table 2). This implies that potato grown on soil with initially high P concentration can get more available P nutrient for growth and development than low initial P soil.

Table 2. Yield response to phosphorus fertilizer at low and high P soil

	Soil P status	
Amount of P fertilizer ($kg\ ha^{-1}$)	**Low P**	**High P**
	Tuber yield ($kg\ ha^{-1}$) Mean ±SE	
0	10,946 ± 470a	12,622 ± 493a
25	13,338 ± 455ab	14,550 ± 176ab
50	13,497 ± 436ab	16,211 ± 459b
75	15,336 ± 882b	15,775 ± 497b
100	14,646 ± 452b	15,502 ± 374b
125	13,914 ± 91.8b	15,312 ±344b
150	13,801 ± 658b	14,769 ±356b
F value	6.49	8.68

Within each column, means with different letters are significantly different at $p < 0.05$; SE, Standard Error

When the soil test value is below the critical value additional information is needed on the quantity of P required to raise the soil P to the required level. Havlin et al. (2005) suggested that when the soil test is below the critical level it may be desirable to apply P at rates that increase soil test above the critical level. This is known as buildup or sufficiency program. Generally, Havlin et al. (2005) suggested applications of 5 to 15 kg P ha^{-1} are required to increase soil test P level to 1 mg kg^{-1}, depending on soil properties influencing P-fixation capacity. When soil test is at or slightly above the critical level, it can be maintained by P fertilizer rates that replace P removal and loss by crop removal, erosion, and fixation. In this regard Dahnke et al. (1990) suggested that knowledge of the soils ability to supply nutrients, the amount of nutrients required for crop growth, and the influences of applied nutrients on crop growth is all needed to improve fertilizer recommendations. Over all this research clearly indicated that the positive significance influence of P fertilizer application on potato tuber yield on Andisol of study area. In addition, soil test P calibration trial can provide information about the soil P status in order to improve P fertilizer efficiency.

Soil test p after three weeks of planting. Extractable P concentration extracted after three weeks of planting by using Olsen extraction method were also significantly differed ($P < 0.05$) among P fertilizer amount applied (Fig. 3 and 4). The main effect of P fertilizer resulted in mean soil test P values of 23.8 to 113 mg kg^{-1} and 118 to 229 mg kg^{-1} for low and high P soils respectively. The highest mean soil P concentration 113 mg kg^{-1} (Fig. 3) and 229 mg kg^{-1} (Fig. 4) was recorded from 150 kg P fertilizer ha^{-1} for low P and high P soils respectively. Soil test P responded to P fertilizer rate analyzed after three weeks of planting higher at low P soil (Fig. 3) than high P soil (Fig. 4). This is because the initial P status of low P soil lower than high P soil. Thus, yield response to P fertilizer was also higher on low P soil than high P soil.

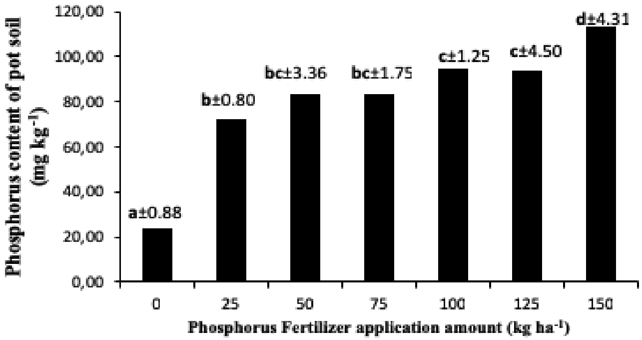

Fig. 3. Low P soil three weeks after P fertilizer application mean soil test P using Olsen extraction methods with response to P fertilizer rates. Graphs represented by different letters are significantly different at $P < 0.05$; bars with standard error.

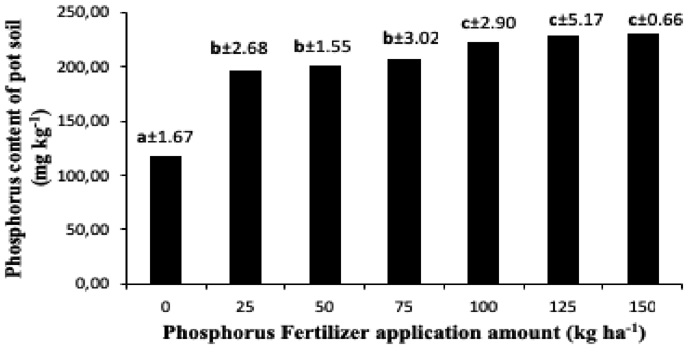

Fig. 4. High P soil three weeks after P fertilizer application mean soil test P using Olsen extraction method with response to P fertilizer rates. Graphs represented by different letters are significantly different at $P < 0.05$; bars with standard error.

CONCLUSION

According to the results it was concluded that potato tuber yield responded to P fertilizer rate significantly different as compared with yield obtained without P fertilizer on Andisol of the study area. The results of this experiment clearly revealed the importance of soil test-based P fertilizer application for improving yield of potato and P fertilizer efficiency on Andisol of Lembang in turn it can help to increase farmer's agricultural profitability. Using the Cate and Nelson graphical method the critical level of soil extractable P concentration for potato production was 68.8 mg kg^{-1} and 191 mg kg^{-1} by Olsen extraction method for low and high P soils respectively. There was strong relationship between soil test and response to P fertilizer. Extractable P concentration extracted after three weeks of planting by using Olsen extraction method was also significantly differed among P fertilizer rates. This result will provide important information for soil fertility specialists and farmers in the study area on the practical use of soil test-based for P fertilizer recommendation program. Researchers can use this study for future intensification in other areas as a basis for developing soil test system for fertilizer recommendation.

Soil test crop response fertilizer recommendation could be economically and environmentally promising in Lembang. Furthermore, further soil test calibration field trial should conduct to determine how well this greenhouse test can be perform in the field to get more accurate information about final calibration and interpretation data in order to determine fertilizer requirement. In addition similar experiments on potato to determine critical limit for other nutrients also needed to improve productivity on Andisol of study area.

ACKNOWLEDGEMENT

The authors are grateful to the Directorate General of Higher Education, Ministry of Education and Culture of Indonesia (DIKTI) for funding this research.

REFERENCES CITED

Admasu, L. 2017. Soils test phosphorous calibration for Tef [*Eragrostis Tef (Zucc) Trotter*] production on Nitisols of Central Ethiopian Highlands. American-Eurasian J. Agric and Environ. Sci. 17 (4): 320–331.

Admasu, L. 2016. Response of phosphorous fertilizer and its recommendation for food barley (*Hordium Vulgare L.*) production on Nitisols of central Ethiopian highlands. Afri. J. Agri. Res. 12 (7): 467–476.

Agegnehu G., P. Nelson, M. Bird, and C. Van Beek. 2015. Phosphorus response and fertilizer recommendations for wheat grown on Nitisols in the Central Ethiopian Highlands. Com. Soil Sci. and Plant Anal. 46: 2411-2424.

Bouyoucos, G.J., 1962. Hydrometer method improved for making particle size analysis of soils. J. Am. Soc. Agron. 54:464-465.

Blake C.A. 1965. Methods of Soil Analysis. Part I, American Society of Agronomy. Madison, Wisconsin, USA. 1572 p.

Cate R.B., and L.A. Nelson. 1965. A Rapid Method for Correlation of Soil Test Analysis with Plant Response Data. Int. Soil Testing Series (Tech. Bull No. 1) N.C. State Uni. agric. Exp. Stn. Raleish, USA.

Chapman, D. D. 1965. Determination of exchangeable Ca, Mg, K, Na, Mn and effective cation exchange capacity in soil, pp 902-904. In C.A. Black (ed.). Methods of soil analysis. Madison.

Corey, R.B. 1987. Soil test procedures: correlation, pp 15-22. In J.R. Brown (ed.). Soil testing: sampling, correlation, calibration, and interpretation. SSSA Spec. Publ. 21. SSSA, Madison.

Dahnke, W. C. and R A. Olsen. 1990. Soil test correlation, calibration, and recommendation, pp 45-68. In R.L. Westerman (ed.). Soil testing and plant analysis, 3rd ed. SSSA Book Series.

Daoui K., R. Mrabet, A. Benbouaza, and E. H. Achbani. 2014. Responsiveness of different potato (*Solanum Tuberosum*) varieties to phosphorus fertilizer. J. Procedia Engi. 83: 344–47.

Dechassa, N., M.K. Schenk, N. Claassen, and B. Steingrobe. 2003. Phosphorus efficiency of cabbage (*Brassica oleraceae L. var. Capitata*), carrot (*Daucus carota L.*), and potato (*Solanum tuberosum L.*). Plant and Soil 250: 215-224.

Fixen P. E. and J. H. Grove. 1990. Testing soils for phosphorus, pp 141-172. In R.L. Westerman (ed). Soil testing and plant analysis, 3rd ed.- SSSA Book Series.

Hartono A., S. Anwar, A.T. Putri, and K. Yokota. 2018. Decreasing phosphorous sorption using fishpond sediment and goat manure in acid upland soil. J. ISSAAS 24 (1): 118-126.

Havlin J. L., J. D. Beaton, S. L. Tisdale, and W. L. Nelson. 2005. Soil Fertility and Fertilizers: an Introduction to Nutrient Management. 7th Edition, Pearson Educational, Inc., Upper Saddle River, New Jersey. 361 p.

Helyar, K. R. 1976. Nitrogen cycling and soil acidification. J. Aust. inst. Agric. Sci. 42: 217-221.

Holford, I.C.R. 1980. Greenhouse evaluation of four phosphorus soils tests in relation to phosphate buffering and labile phosphate in soils, Soil Sc. Soc. Am. J. 44:555-559.

Maghanga K., Justin, K. L. John, S. K. Fred, and K. O. Peter. 2012. Comparison of soil phosphorous extraction by Olsen and double acid methods in acid soils of Western Kenya. East Afri. J. of App. Sci. 2 (1): 1-5.

Mengel, K., and E. Kirby. 2001. Principles of Plant Nutrition. Dordrecht, the Netherlands: Kluwer Academic Publishers. 849 p.

Nafiu A. K., M. O. Abiodun, I. M. Okpara, and V. O. Chude. 2012. Soil fertility evaluation: a potential tool for predicting fertilizer requirement for crops in Nigeria. African J. Agric. Res. 7 (47): 6204-6214.

Olsen, S.R., C.V Cole, and F.S. Watanabe. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA, US Government Printing Office, Washington DC. 19 p.

Rowell, D.L. 1994. Soil Science: Methods and Applications. Addison Wesley Longman Singapore Publishers P. Ltd., England, UK., 350 p.

Sembiring M., D. Elfiati, E. S. Sutarta, and T. Sabrina, 2017. Phosphate solubilization agents in increasing potatoes production on Andisol sinabung Area. Asian J. Plant Sci. 16: 141-148.

Shoji S., and T. Takahashi. 2002. Environmental and agricultural significance of volcanic ash soils. J. Global Environ. Res. 6:113-135.

Soil Survey Staff. 1998. Keys to Soil Taxonomy, 8th ed. USDA Natural Resources Conservation Service, U.S. Govt. Printing Office, Washington DC. 326 p.

SAS. 2004. User's Guide: version 9.1, SAS Institute, Cary, North Carolina, USA.

Stevenson F. J., M. A. Cole. 1999. Cycles of Soils: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients, 2nd ed. John Wiley Publishing; New York City, United States. 448p.

Susila A. D., J.G. Kartika, T. Prasetyo, and P. M. Celiz. 2010. Fertilizer recommendation: correlation and calibration study of soil P test for yard long bean (*Vigna Unguilata* L.) on Ultisols in Nanggung-Bogor. J. Agron. Indonesia 38(3): 225–31.

Syuaib, M. F. 2016. Sustainable agriculture in Indonesia: Facts and challenges to keep growing in harmony with environment. Agricultural Engineering International: CIGR Journal 18 (2): 170–84.

Tan, K.H. 2011. Principles of Soil Chemistry, 4th ed. CRC Press, Georgia USA. 390 p.

Tekalign, T. 1991. Soil, Plant, Water, Fertilizer, Animal Manure and Compost Analysis. Working Document No. 13. International Livestock Research Center for Africa, Addis Ababa, Ethiopia.

Tisdale, S.L., W. L Nelson, and J. D. Beaton. 1985. Soil Fertility and Fertilizers, 4th ed. Macmillan Publishing, New York. 569 p.

Vance, C.P., C. Uhde-Stone, and D.L. Allan. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol. 157: 423–447.

Walkley, A. and I. A. Black. 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37: 29-38.

Yatno E., and S. Zauyah. 2008. Properties and management implications of soils formed from volcanic materials in Lembang area, West Java. Indonesian J. Agri. Sci. 9(2): 44-54.