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RESEARCH ARTICLE

Determination of the P critical limit for French bean in the acidic soil of Mizoram

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Abstract

An experiment was conducted through pot culture from soils collected across the upland and lowlands of Kolasib district, Mizoram, to study French bean cv. Zorin bean response to different doses of phosphorus (P) application to determine the P critical limit. The critical limit of a nutrient and a suitable extractant is necessary for site-specific nutrient management. The collected soils across the region were acidic with a mean pH value of 4.64 ± 0.11, SOC content 8.13 ± 0.93 g kg-1 and soil texture ranging from loam to sandy clay loam. Phosphorus (P) was applied @ 0, 50 and 100 kg ha-1, while nitrogen (N) and potassium (K) were applied @ 50:50 kg ha-1. Available P in soils and concentration in the plants increase significantly with an increased in the level of P application. Dry matter yield and plant uptake were also found to increase with P application @ 50 kg P ha-1. Bray's percent yield (BPY, r=0.79**) and Bray's percent uptake (BPU, r=0.72**) showed the highest significant positive correlation with Melich-1 extractant. The P critical limit in soil was 15 mg kg-1 for Olsen, 8 mg kg-1 for Bray−1, and 10 mg kg-1 for Mehlich-1, respectively. The P critical limit in the French bean (Zorin bean) plant was observed to be 0.16%.

Keywords: Degraded soil, Stunted growth, P deficiency, Zorin bean, Extractant.

Introduction

Phosphorus (P) is an important major essential nutrient next to nitrogen (N), which is necessary for plant growth, development and productivity. It plays a critical role in biochemical processes like photosynthesis, energy storage, cell division, cell enlargement, respiration and nitrogen fixation. Phosphorus is essential for the metabolism of energy, the production of nucleic acids and membranes, and the fixation of atmospheric N in leguminous crops. The availability in soils for plant uptake is restricted by a number of soil conditions, despite its significance in crop nutrition.

Phosphorus is tightly bound in soils because it precipitates with calcium ions in calcareous and high pH soils and is adsorbed by oxides of iron (Fe) and aluminium (Al) in acidic soils (Hinsinger 2001). Studies in Mizoram acidic soils across different land use revealed that moderately labile P pools (Fe and Al oxides adsorbed P) dominated the total P pool due to intense soil weathering in sub–tropical humid soils (Lungmuaana and Lalparmawii 2023). Fertilizer P application is an important practice for increasing soil available P and ensuring adequate crop production in an agricultural ecosystem with an initial low P status (Lungmuana et al. 2023). Since P deficiency is the primary factor limiting crop development in acidic soils, P fertilisers must be used in order to promote optimal plant growth and development and the production of fibre and foods. Phosphorus deficiencies cause delayed maturation, stunted growth, poor root growth, decreased yield and productivity, and lower–quality crops (Mishra 2012). When planted on P-deficient soil, French bean develops poorly and its deficiency in soils and plant tissue leads to low productivity in beans (Rahman et al. 2007; Athokpam et al. 2018). Phosphorus stimulates the development of lateral, fibrous, and healthy roots early in the root system, which is critical for the production of nodules and the fixation of atmospheric N.

The relationship of plant nutrient content in various stages of growth and different yield parameters is important for determining the critical nutrient requirement for optimum growth (Trishanku et al. 2021). The critical limit or critical soil test value is the one that distinguishes between a set of soils that respond significantly to fertilisers and those that don't. Cate and Nelson's (1965) graphical method to identify a soil test critical nutrient level is widely employed by plotting relative yield percent against the values of soil

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test data. Crop yield does not significantly increase with additional P application if the available P concentration in soil has reached a certain critical value (Bai et al. 2013; Deng et al. 2017). Proper P nutrition is required for crops as the soils of Mizoram are deficient in P (Lungmuana and Lalparmawii, 2023). Therefore, determination of the critical limit for a particular nutrient is necessary for site-specific nutrient management. The P critical limit will be used in the interpretation of French bean (Zorin bean) P requirement for better crop yield (Prasad et al., 2017). A plant's critical limit is the point at or below which the plant either exhibits deficiencies or produces lower crop yields than ideal yields (Prasad et al. 2017). Thus, determining the critical limit of a particular nutrient and a suitable extractant is necessary for a site-specific approach of nutrient management. The main objectives of this study were to determine the critical limit of P in soils and plants and a suitable extractant of available P for French bean in the acidic soil of Mizoram.

Materials and Methods

Site description

Soil collection was done randomly across the lowland and upland in Kolasib district of Mizoram (Table 1), at an elevation ranging from 27 to 944 m msl with GPS coordinates (Degrees and decimal minutes: DMM) from 24 01.631 N, 92 40.345 E to 24 24.038 N, 92 48.107 E. The average maximum annual temperature ranged between 30 and 34°C and the minimum was 8–10°C. The locations received an average rainfall of about 2500 mm per annum.

Soil sampling and analytical methods

The collected soils were shade air dried in a room and grounded using a pestle and mortar made from wood, subject to passed through 2 mm sieve. All the initial soil physicochemical properties (Table 1; Soil pH, texture, SOC, available N, P and K) were analysed with standard analysis as reported in Lungmuana and Lalparmawii (2023). The initial soils were also extracted as triplicate with different available P extractants to determine the suitable P extractant to correlate with Bray's percent uptake and yield. The available P was determined by using different extractants such as Bray–1 and Bray–2 (Bray and Kurtz 1945), Olsen P (Olsen et al. 1954), Mehlich^{-1} (Mehlich 1953), $CaCl_2$ (Houba et al. 1990), H_2O (van der Paauw 1971) and Morgan's (Morgan 1937), respectively.

A pot culture experiment for one season was conducted in a shade net at ICAR RC NEH region, Kolasib, Mizoram, to determine the P critical limit of soil and plant for French bean cv. Zorin bean. Three kg of soil as a triplicate was filled in the pots and arranged in a completely randomized design (CRD). Phosphorus was applied at 0, 50 and 100 kg ha^{-1} through diammonium phosphate (DAP) as a basal application along with 25:50 N and K kg ha^{-1} in the form of MOP in each pot. Another 25 kg ha^{-1} N was applied after 30 days from sowing and the remaining N requirement from DAP was calculated and given through urea. Five seeds of Zorin bean were sown in each pot and further thinned to three plants after 7 days of germination. The moisture level was maintained in all the experimental pots by providing equal irrigating water as and when required. The crops were harvested at 60 days after sowing and important growth parameters such as no of branches, no of leaves, plant height and leaf area were recorded. The harvested plant samples were washed with water carefully to remove dirt and oven dried at 65°C for 48 hours to record the dry matter yield. After harvest, plant P concentration and uptake by the plants were also recorded.

Critical limit determination

The P critical limit of soil and plant was determined using the graphical method of Cate and Nelson (1965) by plotting the relative yield against the level of available P in the soil, where soil *p-values* were plotted on the x-axis and the relative yield values on the y-axis. The scatter points were divided into two populations by positioning the vertical and horizontal aiming to maximize the number of scatter points in the positive quadrants and minimize the number in the negative quadrants. It was finally divided according to the probability (high or low) that French beans will respond to fertilizer application. The P soil test value where the vertical line crosses the x-axis was selected as the soil critical level of available extractable P concentration for French bean.

Bray's percent yield and Bray's percent uptake of French bean were calculated as:

$$\text{Bray's percent yield (BPY)} = \frac{\text{Yield without fertilizer}}{\text{Maximum yield in fertilizer pots}} \times 100$$

$$\text{Bray's percent uptake (BPU)} = \frac{\text{Uptake without fertilizer}}{\text{Maximum uptake in fertilizer pots}} \times 100$$

Results and discussion

Soil physico-chemical properties

The initial properties of the experimental soils are presented in Table 1. All the soil samples used in the experiment are acidic, i.e., soil pH varying from 4.06 to 5.54 with an average value of 4.64. The soil texture varied from clay loam, silt loam, loam, and sandy clay loam. The SOC status ranged from 3.52 to 15.54 g kg^{-1} while the available N content of the soil was low, ranging from 59.36 to 132.16 kg ha^{-1}. The soil P values ranged from 1.98 to 7.78 kg ha^{-1} (highest in TL) while the available K varied from 36.75 to 319 kg ha^{-1} (highest in KU–4).

Effect of P on plant characteristics

Different plant characteristics are significantly influenced by different levels of P (Table 2). The number of branches of the control pot varied from 5.33 to 30.67 (highest in TL)

Table 1: Initial physical and chemical characteristics of the experimental soils.

Sl.No.	*Location*	*Code*	*GPS coordination*	*pH*	*SOC(gkg-1)*	*N (kg ha-1)*	*P (kg ha-1)*	*K (kg ha-1)*	*Clay(%)*	*Silt (%)*	*Sand(%)*	*Class*
1	Kawnpui Upland 4	KU-4	N24003.300′ E092040.495′ 869m	4.52	11.43	133.84	3.73	290.25	12.40	20.00	67.60	SL
2	Tuichhuahen Upland	TU	N24012.035′ E092037.670′ 165m	4.30	5.86	109.76	2.46	39.00	22.40	6.00	71.60	SCL
3	Bualpui Upland 5	BU-5	N24005.457′ E092040.913′ 944m	4.48	3.52	59.36	1.98	36.75	22.40	10.00	67.60	SCL
4	Chemphai Upland	CU	N24020.166′ E092044.414′ 85m	4.53	7.33	77.28	3.57	77.25	22.40	26.00	51.60	SCL
5	Saiphai Upland	SU	N24024.038′ E092048.107′ 101m	5.05	4.98	91.84	3.33	319.50	22.40	16.00	61.60	SCL
6	Buhchangphai Upland	BU	N24019.364′ E092038.909′ 61m	4.28	3.52	79.52	2.62	84.00	18.40	10.00	71.60	SL
7	Phaipheng Lowland	PL	N24020.424′ E092041.364′ 42m	5.54	7.04	63.84	2.46	77.25	10.40	18.00	71.60	SL
8	Kawnpui Upland 3	KU-3	N2401.631′ E092040.345 697m	5.15	15.24	132.16	6.59	175.50	14.40	22.00	63.60	SL
9	Thingdawl Upland 2	TU-2	N24008.763′ E092041.777 766m	4.22	15.54	120.96	4.13	66.75	10.40	18.00	71.60	SL
10	Thingdawl Upland 1	TU-1	N24009.362′ E092041.567′ 763m	4.35	9.67	105.28	6.75	76.50	20.40	26.00	53.60	SCL
11	Buhchangphai Lowland	BL	N24019.919′ E092039.134′ 27m	4.50	5.86	94.64	3.25	45.75	24.40	28.00	47.60	L
12	North Chawnpui Lowland	NCL	N24022.249′ E092046.694 33m	4.06	9.97	107.52	3.73	114.75	10.40	14.00	75.60	SL
13	Saiphai Lowland	SL	N24023.545′ E092048.094′ 30m	5.16	9.09	95.20	4.68	183.00	16.40	26.00	57.60	SL
14	Chemphai Lowland	CL	N24020.507′ E092045.060′ 32m	4.74	8.21	104.72	6.11	51.00	34.40	36.00	29.60	CL
15	Meidum Lowland	ML	N24010.753′ E092034.908′ 35m	4.54	6.74	110.88	4.29	52.50	16.40	28.00	55.60	SL
16	Tuichhuahen Lowland	TL	N24014.610′ E092038.568′ 56m	4.82	6.16	84.56	7.78	68.25	12.40	18.00	69.60	SL
	Mean			4.64	8.13	98.21	4.22	109.87	18.15	20.12	61.72	
	Standard error (±)			0.11	0.93	5.12	4.57	21.05	1.62	1.87	2.87	

Note: SOC= Soil organic carbon; SL=Sandy loam; SCL=Sandy clay loam; L=Loam; CL=Clay loam.

Table 3: Effect of phosphorus application on dry matter yield, P concentration and its uptake by French bean.

Sl.No,	Location	*P (soil)*				*Dry matter yield (g pot-1)*				*P concentration (%)*				*P uptake (mg pot-1)*				*BPU*	*BPY*
		P0	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*		
1	KU-4	5.05	11.22	16.03	10.77	5.63	15.77	4.22	8.54	0.11	0.12	0.16	0.13	6.36	19.36	7.14	10.95	32.75	39.07
2	TU	4.18	15.11	10.79	10.03	0.81	1.31	2.61	1.58	0.13	0.17	0.16	0.15	1.06	2.20	4.20	2.49	25.11	30.91
3	BU-5	3.92	8.84	7.46	6.74	3.26	3.44	1.45	2.72	0.12	0.13	0.16	0.14	4.34	4.95	2.34	3.88	73.77	90.64
4	CU	4.23	9.58	22.43	12.08	3.14	5.12	6.12	4.79	0.15	0.22	0.17	0.18	4.89	11.14	10.23	8.75	39.39	48.49
5	SU	4.81	8.68	17.49	10.33	2.11	2.59	3.25	2.65	0.08	0.09	0.08	0.08	1.74	2.25	2.71	2.23	67.06	66.02
6	BU	5.85	10.32	13.89	10.02	1.82	2.91	2.44	2.39	0.07	0.08	0.08	0.08	1.20	2.39	1.94	1.84	52.98	65.45
7	PL	3.36	4.95	8.41	5.57	8.30	11.20	5.42	8.31	0.17	0.23	0.14	0.18	14.23	25.74	7.43	15.80	55.01	75.15
8	KU-3	5.42	7.54	7.41	6.79	1.88	3.94	5.15	3.66	0.12	0.12	0.16	0.13	2.30	4.96	8.06	5.11	31.76	35.50
9	TU-2	6.61	8.52	8.86	8.00	0.70	2.11	1.92	1.58	0.13	0.19	0.15	0.16	0.89	4.18	2.79	2.62	22.92	34.32
10	TU-1	8.78	13.57	24.13	15.49	0.49	1.90	3.26	1.88	0.15	0.15	0.16	0.15	0.73	2.91	5.29	2.98	13.83	15.29
11	BL	4.81	7.38	11.46	7.88	4.07	8.35	6.16	6.19	0.14	0.18	0.18	0.17	5.81	15.72	10.96	10.83	39.54	50.30
12	NCL	6.48	12.25	18.17	12.30	1.42	3.04	4.41	2.96	0.10	0.12	0.14	0.12	1.44	3.54	6.10	3.69	23.69	32.46
13	SL	6.38	7.38	17.91	10.56	4.79	5.33	8.35	6.16	0.10	0.14	0.20	0.15	4.63	7.15	16.01	9.26	28.70	58.49
14	CL	6.64	7.80	6.14	6.86	7.65	8.32	5.43	7.13	0.13	0.14	0.17	0.15	9.96	11.86	9.02	10.28	77.77	91.40
15	ML	5.11	5.93	14.10	8.38	5.20	6.48	8.32	6.67	0.13	0.14	0.13	0.13	6.98	9.40	10.82	9.07	65.98	62.78
16	TL	8.02	9.74	16.46	11.41	7.17	7.30	4.89	6.45	0.20	0.21	0.24	0.22	13.95	15.51	11.54	13.67	88.64	98.28
	Mean	5.27	8.75	13.01	9.01	3.44	5.24	4.32	4.33	0.12	0.14	0.15	0.13	4.74	8.43	6.86	6.68	43.47	52.62
F value	Location	241.55**			2.78**	9.78**			5.16**	71.24**			13.94**	17.43**			7.31**	8.54**	14.4**
	Dose	42.96**				ns				31.64**				3.13*					
	L*D	ns				2.35*				3.41**				2.37**					

WNote: *=significant at 5%; **=significant at 1%; ns=not significant; BPU=Bray's percent uptake; BPY=Bray's percent yield.

Table 2: Effect of phosphorus application on plants characteristics

Sl.No.	Location	*No. of branches*				*No. of leaves*				*Leaf area (cm2)*				*Plant height (cm)*			
		P0	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*	*P0*	*P50*	*P100*	*Mean*
1	KU-4	10.67	24.33	26.67	20.56	40.00	76.00	45.33	53.78	647.29	907.51	167.89	574.23	163.67	213.00	112.00	162.89
2	TU	7.33	10.00	15.00	10.78	23.33	22.00	36.33	27.22	38.30	83.78	248.99	123.69	68.97	94.33	165.93	109.74
3	BU-5	9.33	14.67	9.33	11.11	19.33	33.67	22.33	25.11	373.73	552.54	209.76	378.68	154.07	172.00	129.37	151.81
4	CU	14.67	17.00	19.00	16.89	37.00	42.33	54.33	44.55	244.64	224.97	339.00	269.54	125.23	122.47	174.00	140.57
5	SU	15.33	17.33	11.00	14.55	37.67	30.33	30.67	32.89	601.66	134.74	149.73	295.38	187.33	145.13	108.57	147.01
6	BU	9.33	15.00	13.00	12.44	23.00	40.67	32.67	32.11	55.89	209.69	239.38	168.32	103.83	110.83	114.33	109.66
7	PL	24.67	31.67	18.33	24.89	65.67	88.67	50.33	68.22	861.71	1455.83	452.07	923.20	261.33	207.00	189.43	219.25
8	KU-3	8.33	17.67	13.67	13.22	26.33	44.67	49.33	40.11	90.54	304.85	498.68	298.02	130.80	154.67	218.77	168.08
9	TU-2	8.67	14.00	14.67	12.45	15.00	39.67	13.33	22.67	19.52	199.37	67.96	95.62	106.67	136.70	127.90	123.76
10	TU-1	5.33	11.33	16.00	10.89	13.33	31.00	47.00	30.44	59.91	159.01	322.82	180.58	64.30	126.53	147.00	112.61
11	BL	18.67	22.33	18.67	19.89	46.00	50.33	38.67	45.00	410.05	629.76	282.83	440.88	141.87	131.67	149.07	140.87
12	NCL	12.33	15.67	17.33	15.11	28.67	31.67	35.67	32.00	139.11	218.04	255.34	204.16	102.17	161.67	165.00	142.95
13	SL	17.00	13.67	21.00	17.22	36.67	36.00	46.33	39.67	352.62	375.11	627.15	451.63	154.07	135.00	192.33	160.47
14	CL	22.00	18.33	16.33	18.89	65.33	47.00	41.67	51.33	842.58	481.15	395.01	572.91	208.33	163.17	141.33	170.94
15	ML	16.67	18.33	22.00	19.00	42.33	46.67	60.00	49.67	373.41	374.07	680.54	476.01	155.70	152.10	158.03	155.28
16	TL	30.67	21.00	18.00	23.22	77.33	56.67	40.33	58.11	1788.22	611.42	199.83	866.49	317.87	141.33	146.67	201.96
	Mean	13.59	16.61	15.88	15.36	35.12	42.20	37.90	38.41	405.83	407.17	302.18	371.73	143.89	139.27	143.51	142.23
F value	Location	16.49**			9.52**	26.81**			17.26**	18.74**			7.34**	3.91**			ns
	Dose	12.4**				6.45*				12.95**				ns			
	L*D	4.93**				7.87**				8.57**				2.54*			

Note: *=significant at 5%; **=significant at 1%; ns=not significant.

Table 4: Phosphorus extraction by different extractants

S. No	*Location*	*Bray-1*	*Bray-2*	*Olsen*	*Mehlich-1*	*CaCl2*	*H2O*	*Morgan's*
		mg kg-1						
1	KU-4	4.76	5.78	8.23	2.48	0.65	3.49	11.90
2	TU	3.41	6.61	5.11	5.16	0.54	2.66	36.44
3	BU-5	3.68	9.49	9.68	6.45	0.16	1.22	40.52
4	CU	3.82	16.34	12.58	9.57	1.37	4.14	44.51
5	SU	4.09	9.44	6.83	4.54	1.13	5.75	20.36
6	BU	2.93	8.01	6.67	3.85	0.16	0.86	33.78
7	PL	3.41	14.01	9.25	9.41	2.10	6.29	17.55
8	KU-3	6.88	8.28	9.14	7.32	0.48	3.44	52.05
9	TU-2	5.67	10.08	14.14	6.51	0.27	0.65	41.46
10	TU-1	8.25	15.99	9.84	6.04	0.32	1.61	40.33
11	BL	3.66	2.26	6.88	3.30	1.02	2.58	28.92
12	NCL	4.76	5.16	7.85	4.19	0.43	1.67	25.11
13	SL	5.78	12.85	9.14	5.10	0.32	1.61	26.01
14	CL	6.21	9.84	8.17	5.20	0.32	3.28	39.25
15	ML	4.46	5.03	8.87	4.42	0.89	1.72	24.35
16	TL	8.36	9.73	15.65	12.82	0.16	1.45	28.86
	Mean	5.01	9.31	9.25	6.02	0.64	2.65	31.96
	F Value	37.49**	661.17**	411.20**	76.15**	44.61**	24.06**	13.95**

Note: *=significant at 5%; **=significant at 1%; ns=not significant.

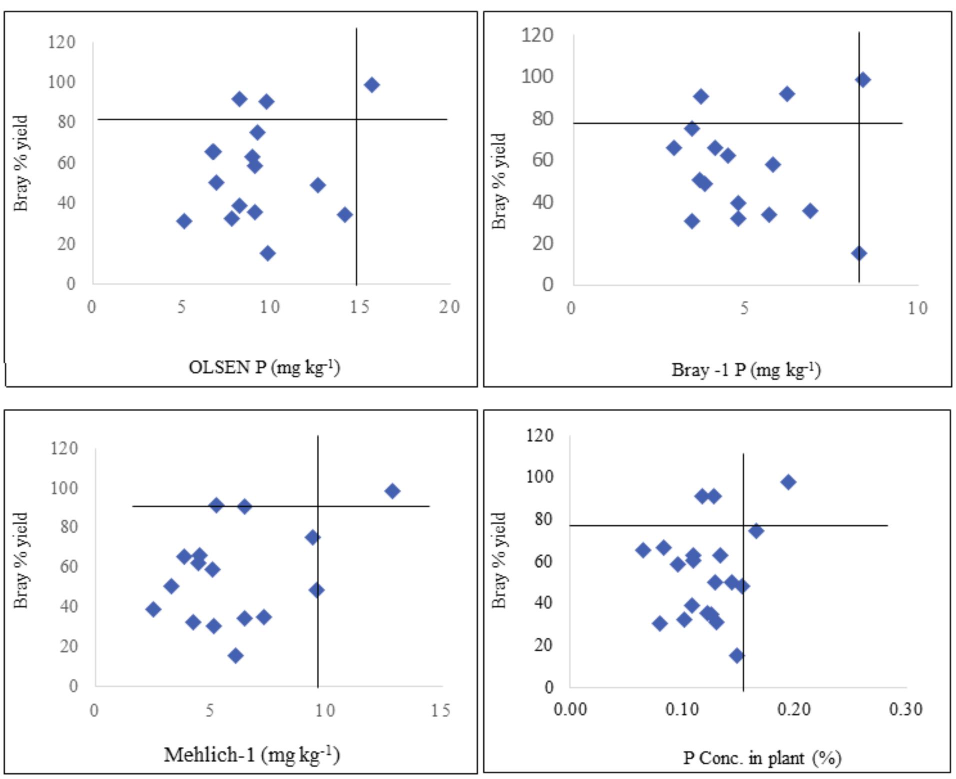

Figure 1: Scatter diagram showing the critical limit of P.

as compared with 10.00 to 31.67 (highest in PL) in 50 kg P ha-1 and 9.33 to 26.67 (highest in KU-4) in 100 kg P ha-1. The number of leaves of the control pot varied from 13.33 to 77.33 (highest in TL) compared with 22.00 to 88.67 (highest in PL) in 50 kg P ha-1 and 13.33 to 60.00 in 100 kg P ha-1 (highest in ML). The overall highest number of branches and number of leaves was observed in 50 kg P ha-1, both for PL, indicating that P application of 50 kg P ha-1 was sufficient to increase the number of branches and leaves. Leaf area for the control pot varied from 19.52 to 1788.22 cm2 (highest in TL) compared with 83.78 to 1455 cm2 (highest in PL) in 50 kg P ha-1 and 67.96 to 627.15 cm2 (highest in SL) in 100 kg P ha-1. The decrease in leaf area is less than that of the control may be due to the P level being higher than the optimum requirement, interfering with other nutrient elements, which can result in decrease growth of the bean (Meseret and Amin 2014). Phosphorus fertilizer application in the experiment has no significant effect on plant height. Plant height for the control pot varied from 64.30 cm to 317.87 cm (highest in ML) compared with 94.33 cm to 213.00 cm2 (highest in KU–4) in 50 kg P ha-1 and 112.00 to 218.77 cm (highest in KU–3) in 100 kg P ha-1.

Effect of P on dry matter yield, P content and uptake

The present study revealed that the dry matter yield of French bean cv. Zorin bean was affected by different levels of P concentrations (Table 3). Dry matter yield of the control pot varied from 0.49 to 8.30 g pot^{-1} (highest in PL) as compared with 1.31 to 15.77 g pot^{-1} in 50 kg P ha^{-1} (highest in KU–4) and 1.45 to 8.35 g pot^{-1} in 100 kg P ha^{-1} (highest in SL), respectively. There was a significant difference in dry matter yield among the different soil samples and no significant with different levels of P. The highest dry matter production was observed with the application of 50 kg P ha^{-1}. The mean percentage increase in applying 50 kg P ha^{-1} from the control pot was 24.70% while from the 100 kg P ha^{-1} treated pot was 20.44% indicating that 50 kg P ha^{-1} was more efficient. The increased in dry matter may be due to the increase in the number of branches and leaves, leaf area and plant height (Athokpam et al. 2018).

Phosphorus concentrations in the plants ranged from 0.07% to 0.31% in the control pot as compared with 0.12 to 0.34% in 50 kg P ha^{-1} and 0.08 to 0.35% in 100 kg P ha^{-1}. P content in the plants was found to be influenced by P application. The plants showed highest P concentration at 100 kg P ha^{-1} in comparison to other treatments. The P uptake by the plant ranged from 0.73 to 52.75 mg pot^{-1} in the control pot compared with 2.20 mg pot^{-1} to 36.06 mg pot^{-1} in 50 kg P ha^{-1} and 1.94 to 21.15 mg pot^{-1} in 100 kg P ha^{-1}. The increase in P uptake was significantly influenced by P application, where the highest uptake was observed in 50 kg P ha^{-1}. The overall increase in P uptake was due to higher dry matter accumulation and an increase in P content in the plants due to P application (Athokpam et al. 2018). The improvement in the mean growth parameters was more prominent in the application of P @ 50 kg P ha^{-1} from control than an increment to P @ 100 kg ha^{-1}. Thus, results also suggest that P application of P @ 50 kg ha^{-1} may be sufficient to improve the growth, as most of the soil does not further improve the growth with increasing the P beyond 50 kg P ha^{-1}. The optimum P requirement for French bean growth and productivity is normally around 60 kg P ha^{-1} (Rahman et al. 2007). In general, chemical fertilizers may increase the yield, but it is important to decrease the dose to aim for sustainability. Moreover, P is highly vulnerable to adsorption to Fe and Al, depending on the soil types in the NEH region, which may not be sustainable and economical (Lungmuaana and Lalparmawii 2023). The agronomic P efficiency is generally much higher in low P soils by P application as it requires more P to raise the level compared to high P soils, which is why P application may have a lesser respond to high P soils (Ros et al. 2020).

Extraction of available P and its relationship with BPU and BPY

The amount of available P differed due to different extractants, viz Bray–1, Bray–2, Olsen, Melich-1, $CaCl_2$, H_2O, and Morgan's reagent (Table 4). The maximum value of P (11.90-67.67 mg kg^{-1}) was extracted by Morgan reagent and the minimum value (0.16-3.06 mg kg^{-1}) by $CaCl_2$. The average values of P extracted by different extractants were in the order: Morgan's> Bray–2> Olsen> Bray–1> Melich–1> H_2O> $CaCl_2$. $CaCl_2$ extracts lower amounts of P than H_2O methods due to the formation of Ca-phosphate (Kulhanek et al. 2007). Among the different extractants, Mehlich-1 reagent has the highest positive relationship with BPU (r=0.72**) and BPY (r=0.79**), suggesting that available P determination in French bean soils in acidic soils of this region may be most suitable with Mehlich-1 compared to other extractants.

Critical level of P

The critical level of extracted P and plant concentration P was done with the most common soil P extractants (Fig. 1). The critical limit of P for soils was 15 mg kg-1 for Olsen reagent, 8 mg kg-1 for Bray–1 reagent and 10 mg kg-1 for Mehlich-1 reagent. The critical limit of P in the French bean (Zorin bean) plant was observed to be 0.16%, which was little lower than 0.29 reported by Athokpam et al. (2018), which may be due to the varietal difference (Zorin bean against the contender variety). Another reason may be due to the differences in soil condition (present study area soil pH: 4.06 to 4.54 against 4.4 to 6.3). A value of 0.16% could differentiate the P-deficient plants from the sufficient plants. This results in partitioning the two-dimensional percentage yield versus P content in the 60-day-old French bean plants (control) into two different groups.

Conclusion

From the experiment, it was concluded that available P and dry matter were influence by P application. The critical limits for available P in different extractants for soil across the study region were found to be 15 mg kg^{-1} for Olsen reagent, 8 mg kg^{-1} for Bray–1 reagent and 10 mg kg^{-1} for Mehlich-1 reagent and P concentration in French bean (Zorin bean) plant to be 0.16%. Soils and French bean (Zorin bean) plants with P concentration below this critical level will be considered P-deficient and application of P fertilizer would be required.

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