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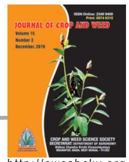

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Phosphate solubilizing micro-organisms enhances phosphatase enzyme activity, phosphorus use efficiency and productivity of castor

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ABSTRACT

A field study was executed to understand the impact of phosphate solubilizing micro-organisms on the performance of castor crop. The pooled data results showed that application of 20 kg P_2O_5 ha^{-1}+ seed treatment with phosphate solubilizing bacteria (PSB) (T_5) and 20 kg P_2O_5 ha^{-1}+bean treatment with bio-phos (T_1) have produced 35.7 and 26.0% higher bean yield over control (T_2). The application of PSB showed positive effect on improving the soil phosphatase enzyme activity and castor bean yield. Efficacy of PSB was found higher at lower P than at medium or high P fertilizer dose. The higher water use efficiency and P use indices like phosphorus use efficiency, agronomic efficiency and apparent recovery efficiency of applied P and net returns (Rs. 32,120 ha^{-1}) and B:C ratio (2.13) were also associated with the application of 20 kg P_2O_5 ha^{-1}+bean treatment with PSB (T_5).

Keywords: Castor, phosphate solubilizing micro-organisms, phosphatase enzyme

Castor (*Ricinus communis* L.) is an important non-edible commercial oilseed crop cultivated in wide ranging edapho-climatic conditions across the globe. Castor oil is a valuable output and has many industrial uses due to the presence of high ricinoleic acid (Cheema *et al.,* 2013). Furthermore, various parts of this plant are widely used in Agriculture, medical and ornamental fields (Ramanjaneyulu *et al.,* 2017). In the recent times, it is attracting the attention of policy makers and scientists for production of biodiesel to minimize the consumption of fossil fuels (Nahar, 2015) as castor oil has less ash (0.02%) and sulfur (<0.04%) (Kareem *et al.,* 2012). Besides, it's very low cloud and pour points (Bauddh *et al.,* 2015) make the castor oil suitable for biofuel purpose in extreme cold weather too. Better cetane number of castor oil is an additional advantage for its usage in diesel engines (Keera *et al.,* 2018). Nevertheless, it's plantation reduce the amount of greenhouse gas (GHG) in the atmosphere as castor plants act as sinks for carbon dioxide by capturing nearly 10 tons per hectare (Chen *et al.,* 2014).

Phosphorus (P) is the second most important macro nutrient required for crop growth and development. It plays a significant role in proper root growth, strengthening of stalks and stems, formation of flowers and beans, crop maturity, improving quality, promoting nitrogen fixation in legumes and economic yield. Besides, it controls key enzyme dependent reactions and regulates metabolic pathways (Theodorou and Plaxton, 1993). Of the total P applied to the crops, only 10-50% is utilized by the current crop (Khasawneh *et al.,* 1979; Lo' Pez-Bucio *et al.,* 2000; Sharma *et al.,* 2013) and rest become unavailable and fixed in the form of $[Ca_3(PO_4)_2]$, $Fe_3(PO_4)_2$, $AlPO_4$, $[Mg_3(PO_4)_2]$ and $Mn_3(PO_4)_2$ due to adsorption and precipitation (Dean, 1949; Kanwar and Grewal, 1990; Holford, 1997; Alam and Ladha, 2004). This problem is acute in Inceptisols, Entisols, Alfisols and Vertisols in arid and semi-arid zones across the globe. Further, P availability depends on various soil physical, chemical and biological factors. The P fertilizers are frequently applied to crops regardless of its availability and fixation leading to low recovery. On the contrary, India is importing 90% of the phosphate requirements to meet the P fertilizer demand in Agriculture leading to loss of foreign exchange. Due to these economic considerations and scarcity of the P fertilizers (Kalayu, 2019), the studies relating to the efficient use of fertilizers and improving the availability of native P have drawn the attention of soil scientists and agronomists. Phosphate-solubilizing microorganisms (PSMs) or P based bio-inoculants play a greater role in supplying insoluble phosphate to the

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plants. Biophos (*Chaetomium globosum*), a naturally occurring P mobilizing fungal organism (Tarafdar and Gharu, 2006) and phosphate solubilizing bacteria (PSB) (Pal, 1998; Zaida *et al*., 2003, Chung *et al.,* 2005; Vikram and Hamzehzarghani, 2008) when applied through bean treatment before sowing or in sowing furrows by mixing with sand, improves the availability of native unavailable phosphorus. Further, PSB can reduce the antagonistic effect of calcium on soil P availability (Adnan *et al.,* 2017). They also decrease soil pH through production of gluconic and mineral acids (Chen *et al.,* 2006), produces alkaline phosphatase enzymes (Rodriguez and Fraga, 1999), phytohormones (Xiao *et al.,* 2017), siderophores (Sugihara *et al.,* 2010) which promotes P solubilization thus accessibility to the plants. Exploitation of these bio-inoculants can reduce the frequent addition of P fertilizers to the Agricultural lands leading to significant reduction in cost of cultivation and damage to the environment (Rajan *et al.,* 1996).

Phosphorous is a very important nutrient to enhance castor production (Mathukia and Modhwadia, 1993; Mathukia *et al.,* 2014). The castor growers are compelled to use P based complex fertilizers even for top dressing too due to non-availability of straight fertilizers and also lack of awareness. This is resulting in excessive application of P fertilizers leading to huge cost on inputs, labour and escalation of production cost. Further, it has also led to accumulation and fixation in soil resulting in medium to high P status. P fertilizers are costlier than other primary nutrient fertilizers, hence, it is very important to enhance its use efficiency (Renjith *et al.,* 2020). Ramanjaneyulu *et al.* (2021) recommended application of only 20 kg P_2O_5 ha^{-1} besides bean treatment with bio-phos for castor grown on medium P Alfisols, however, 60 kg P_2O_5 ha^{-1} along with bean treatment with bio-phos in low P soils (Suresh *et al.,* 2015) was found optimum. However, in view of lack of availability of biophos in all castor growing zones, it is essential to find out the local strains that are alternative to it. Hence, a field investigation was carried out to find out the comparative effect of PSB and biophos on phosphatase enzyme activity without adversely affecting the yield and economics of castor grown on Alfisols.

MATERIALS AND METHODS

A field experiment was conducted during *kharif* season (July to January) of 2014-15, 2015-16 and 2016-17 at Regional Agricultural Research Station, Professor Jayashankar Telangana State Agricultural University, Palem, Telangana state, India. Agro-climatologically, it comes under Southern Telangana Zone. The soil type was typic haplustalf with a pH ranging from 6.0 to 6.5, low in organic carbon (0.2 to 0.3%), low in nitrogen (220.5 kg ha^{-1}), medium in available phosphorus (24.7 kg ha^{-1}) and high in available potash (345.3 kg ha^{-1}). The study was executed with nine treatments *viz*., T_1: 20 kg P_2O_5 ha^{-1} + bean treatment with bio-phos (3.0 kg ha^{-1}); T_2: Control (No phosphorus and no PSB/bio-phos), T_3: Bean treatment with PSB alone (0.5 kg ha^{-1}), T_4: 20 kg P_2O_5 ha^{-1}, T_5: 20 kg $P_2O_5ha^{-1}$+ T_3, T_6: 40 kg P_2O_5 ha^{-1}, T_7: 40 kg $P_2O_5ha^{-1}$+ T_3, T_8: 60 kg $P_2O_5ha^{-1}$; T_9: 60 kg $P_2O_5ha^{-1}$+T_3. The trial was laid out in a Randomized Block Design replicated thrice. The T_1 treatment was included in the present trial based on the recommendations of All India Co-ordinated Research Project on castor (DOR, 2013-14), India.

An amount of 419.4 mm rainfall in 33 rainy days, 330.1 mm in 23 days and 482.4 mm in 27 days was received against the normal rainfall of 538.6 mm, 609.26 mm and 542.36 mm leaving a deficit of 22.1%, 45.8% and 11.1% during the crop growing season (July to January) in 2014-15, 2015-16 and 2016-17, respectively.

The popular castor cultivar PCH-111, a double bloom, fusarium wilt resistant and high yielding hybrid was used in the experimentation. First, the castor beans were treated with a fungicide carbendazim (3.0 g kg^{-1}) uniformly across the nine treatments. Thereafter, jaggery solution (250 ml ha^{-1} bean) followed by biophos (3.0 kg ha^{-1}) were applied on beans and both were mixed gently without rupturing the bean coat, in case of T_1 treatment. Similarly, in case of T_3, T_5, T_7 and T_9 treatments, the bio-phos was replaced with PSB (0.5 kg ha^{-1}). Finally, the beans were shade dried for half an hour before sowing.

The castor beans (5 kg ha^{-1}) were sown at a spacing of 90 cm x 60cm on 12-7-2014, 16-7-2015 and 13-7-2016, on a well pulverized soil. An amount of 40 kg N and 30 kg K_2O ha^{-1} through urea and muriate of potash were applied as basal. Further, another 40 kg N ha^{-1} through urea was applied in three equal splits at monthly interval upto 90 DAS. In general, 40 kg P_2O_5 ha^{-1} is recommended for hybrid castor under rainfed conditions. However, in this trial, the treatment wise phosphorus dose (20 or 40 or 60 kg ha^{-1}) was applied through single super phosphate (SSP) as basal. A pre-emergence herbicide Pendimethalin @ 1.0 kg a.i ha^{-1} was sprayed on the second day after sowing followed by intercultivation twice with cattle drawn blade and one intra row hand weeding. The castor semi looper (*Achaea janata*), tobacco caterpiller (*Spodoptera litura*) and shoot and capsule borer (*Dichocrosis punctiferalis*) were managed by erecting bird perches and also spraying Novoluron 10% EC @ 1 ml lit^{-1} during all the years of study. Though the crop was grown rainfed, three lifesaving irrigations each at 50 mm depth were given during October and November 2014 and only one life saving irrigation during last week of October 2015 to overcome moisture stress during post monsoon period.

A gross plot size of 5.4 m x 6.0m (6 rows x10 plants) was maintained in all the treatments. However, only 3.6m x 4.8m area (4 rows x 8 plants) was considered for the purpose of data recording on ancillary characters by selecting five representative plants with consistent growth. Three pickings were done at an interval of 25 days during November, December and January every year and bean yield from all three harvesting was totalled to obtain at final bean yield. The phosphorus use efficiency (PUE) was computed by dividing the castor bean yield with the amount of P applied.

The nitrogen, phosphorus and potash concentrations in plant were determined duly following the standard methods advocated by Piper (1966). Further, the treatment wise soil sample from the plant's root zone was analyzed to obtain information on alkaline phosphatase enzyme activity. It determines release of p-nitrophenol colorimetrically when the soil is incubated with buffered sodium p-nitrophenyl phosphate solution and toluene at 37°C for one hour. The released p-nitrophenol is stained and measured spectro photometrically at 400 nm (Tabatabai and Bremner, 1969). The pre sowing soil samples were analyzed for pH, EC and available K (Jackson, 1973), available N (Subbaiah and Asija, 1956) and P (Olsen *et al.,* 1954).

The water use efficiency (WUE), Phosphorus use efficiency (PUE), Agronomic efficiency of applied P (AEP) and Apparent recovery efficiency of applied P (AREP) were computed by the formulae given below

WUE (kg ha^{-1} mm^{-1}): Y/(ER+W)

PUE (kg kg^{-1}): Y/FP

AEP (kg kg^{-1}): (YP – Y0)/FP

AREP (kg kg^{-1}): (UP – U0)/FP

Where,

ER: Effective rainfall (mm)

W: Irrigation water applied (mm)

FP: Fertilizer phosphorus applied (kg ha^{-1})

Y: Bean yield (kg ha^{-1})

YP: Bean yield in P fertilizer applied treatment

UO: Bean yield in control treatment

UP: Phosphorus uptake in P fertilizer applied treatment

UO: Phosphorus uptake in control treatment

The data on various parameters was analyzed using randomized block design (RBD). The significance was determined using f-test and the least significant differences were considered at the 5% probability level to determine the significance of the difference among treatments (Panse and Sukhatme, 1985). Further, year x treatment was found significant for bean yield and P uptake only.

RESULTS AND DISCUSSION

Changes in ancillary traits of castor due to P application

As furnished in Table 1, the plant population did not vary significantly due to P application in different treatments evaluated. Though the castor plants grew taller due to supply of 40 kg P_2O_5 or 20 kg P_2O_5ha^{-1}+ bean treatment with PSB, but, they were on par with lower or higher P doses with or without integration of either PSB or bio-phos. Similarly, the P fertilizer applied in combination with or without PSB or bio-phos did not exert any significant influence on no. of branches, nodes, no. of racemes and effective racemes plant^{-1}, total and effective raceme length. The 100 bean weight was statistically similar among all the tested treatments. On the contrary to the present results, Ponmurugan and Gopi (2006) reported enhanced plant growth due to phosphate solubilizing micro-organisms following solubilization of insoluble phosphates.

Changes in bean yield of castor due to P application

The castor bean yield was comparatively less during 2015-16 as compared to that of 2014-15 and 2016-17. It was mainly due to receipt of less rainfall by 45.8% in second year against 22.1% in first year and 11.1% in third year of experimentation (Table 1).

During *kharif* 2014-15, basal application of 20 kg P_2O_5 ha^{-1} besides bean treatment with PSB (T_5) registered significantly higher bean yield of castor (2576 kg ha^{-1}) as compared to that of control without P application (T_2: 1898 kg ha^{-1}), 40 kg P_2O_5 + PSB (T_7: 1937 kg ha^{-1}), 60 kg P_2O_5 + PSB (T_9: 1886 kg ha^{-1}). However, it was found to be on par with application of 20 kg P_2O_5 ha^{-1}+ bean treatment with bio-phos (T_1: 2394 kg ha^{-1}), 20 kg P_2O_5 ha^{-1} (T_4: 2350 kg ha^{-1}), 40 kg P_2O_5 ha^{-1} (T_6: 2306 kg ha^{-1}) and 60 kg P_2O_5 ha^{-1} (T_8: 2353 kg ha^{-1}). Production of significantly longer racemes is the main attributing factor for significantly higher bean yield of castor in T_5, T_1, T_4 and T_6. Supply of 20 kg P_2O_5 ha^{-1}+bean treatment with PSB (T_5) and 20 kg P_2O_5 ha^{-1}+bean treatment with bio-phos (T_1) have produced 35.7 and 26.1% higher bean yield over no P addition (control). During *kharif* 2015-16, though higher castor bean yield (1134 kg ha^{-1}) was realised due to application of 20 kg P_2O_5 ha^{-1} alone, all treatments performed equally good. This phenomenon could be attributed to non-significant effect of P application on growth and yield parameters under severe deficit rainfall conditions (Table 1). During *kharif* 2016-17, significantly higher castor bean yield (1643 kg ha^{-1}) could be achieved owing to application of 40 kg P_2O_5 ha^{-1}+bean treatment with PSB (T_7) than rest of the treatments barring 40 kg P_2O_5 ha^{-1}alone (T_6: 1643 kg ha^{-1}), 20 kg P_2O_5 ha^{-1}+bean treatment with PSB (T_5: 1505

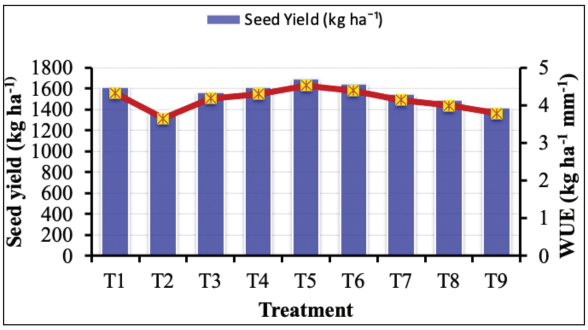

Fig. 1a: Changes in WUE due to P application

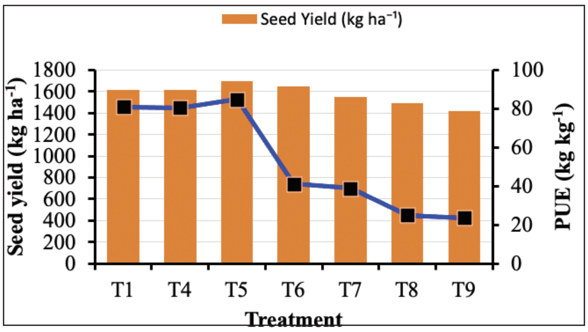

Fig. 1b: Changes in PUE due to P application

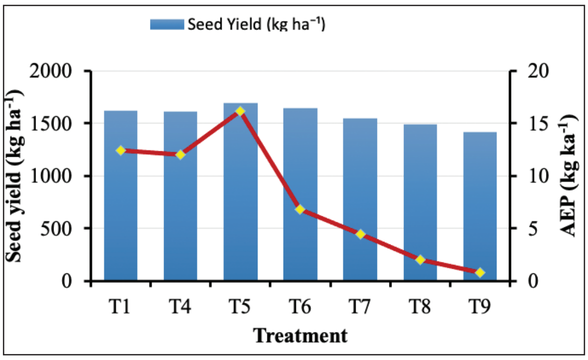

Fig. 1c: Changes in AEP due to P application

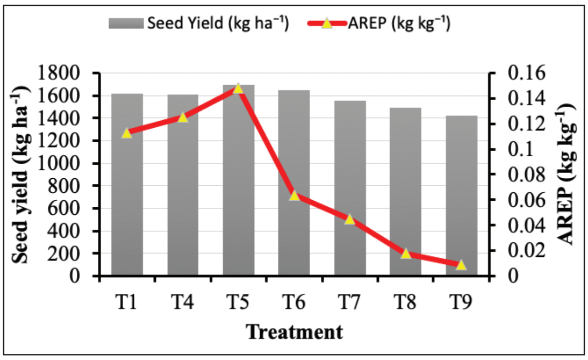

Fig. 1d: Changes in AREP due to P application

Fig. 1: Changes in WUE and P use indices due to P fertilizer and PSMs (Pooled data of 2013-14 to 2016-17)

kg ha^{-1}) and 20 kg P_2O_5 ha^{-1}+bean treatment with bio-phos (T_1: 1565 kg ha^{-1}). Further, pooled statistical analysis of three years data indicated that castor bean yield showed linear improvement with the P application from control (T2: 1371 kg ha^{-1}) upto application of 20 kg P_2O_5 ha^{-1}+bean treatment with PSB (T5: 1696 kg ha^{-1}) after which it showed inverse relationship. The improvement in bean yield obtained in T_5 treatment ranged from 3.1 to 23.7%, the highest being over control. The yield reduction at higher dose of P application (60 kg P_2O_5 ha^{-1}) was greater (13.52 and 19.44%) than at medium P dose (40 kg P_2O_5 ha^{-1}: 3.10 and 9.35%) and lower dose of P applied (20 kg P_2O_5 ha^{-1}: 5.21%) and bean treatment with PSB (8.16%) and bio-phos (4.76%) in comparison with that of T_5 treatment. The efficacy of PSB seems to be high at low or medium P doses than high P dose as evident through yield details furnished in Table 1. The reasons for better performance of P fertilizer applied in integration with PSB or bio-phos can be explained as detailed below.

A kind of synergistic association exists between PSMs and crops due to which PSMs provides soluble phosphates to the plants and in return crop plants dispense nutrients to microbes through root exudates thus promotes microbial growth. Further, they promote plant growth through release of phytohormones such as auxins, gibberellins, cytokinines, or polyamides (Santana *et al.,* 2016; Yousefi *et al.,* 2011) thus improving the crop yield. They also foster plant growth indirectly by improving the accessibility to other trace elements such as siderophore (Wani *et al.,* 2007). Several researchers reported enhanced growth and quality and also 10-20% yield improvement across various crops (Singh and Kapoor, 1999; Son *et al.,* 2006; Bano and Fatima, 2009; Walpola and Yoon, 2012) due to use of PSMs as biofertilizers. Further, PSB application could reduce the P fertilizer requirement by 50% without substantial reduction in yield (Jilani *et al.,* 2007; Yazdani *et al.,* 2009). Thus, PSMs can be promoted as plausible alternatives for inorganic phosphate fertilizers to meet the P demands and sustaining Agriculture. So, inoculation with PSMs hold a great promise for sustaining crop production through optimization of P fertilization.

Changes in economic returns due to P application

The economic returns followed the trend set by the bean yield of castor. The economic analysis of pooled data of three years (Table 1) revealed that higher net returns (Rs. 32,120 ha^{-1}) and B:C ratio (2.13) were obtained with the application of 20 kg P_2O_5 ha^{-1} + bean treatment with PSB (T5). It was closely followed by

Table 1: Changes in ancillary characters, yield and economics of castor due to P fertilizer and PSMs (Pooled data of *kharif* 2014-15 to 2016-17)

Treatments	Plant population ha^{-1}	Plant height (cm)	No. of branches $plant^{-1}$	No. of nodes $plant^{-1}$	No. of racemes $plant^{-1}$	No. of eff. racemes $plant^{-1}$	Total raceme length (cm)	Eff. raceme length (cm)	100 bean weight (g)	Bean yield (kg ha^{-1})				Net returns (Rs ha^{-1})	B:C ratio
										2014	2015	2016	Pooled		
T1	15706	56.9	3.7	10.9	4.5	2.7	42.1	35.9	30.4	2394	900	1565	1619	29292	2.02
T2	16255	55.6	3.8	10.8	4.2	2.6	42.1	36.5	30.9	1898	887	1329	1371	21154	1.76
T3	15878	56.6	3.4	10.9	4.3	2.7	37.4	34.2	30.8	2421	785	1498	1568	27989	1.99
T4	16564	53.6	3.4	10.7	4.8	3.5	41.1	34.1	30.3	2350	1134	1352	1612	29224	2.05
T5	16701	58.2	3.8	11.0	4.8	3.5	44.4	35.6	30.5	2576	1006	1506	1696	32120	2.13
T6	16084	59.6	3.5	11.0	4.7	3.3	42.8	36.6	30.6	2306	1048	1581	1645	30024	2.05
T7	17044	54.6	3.7	10.9	4.5	3.4	42.1	37.4	29.9	1937	1071	1643	1551	26503	1.93
T8	16564	54.2	3.5	10.6	4.5	3.3	39.2	32.6	30.3	2353	840	1288	1494	24180	1.82
T9	16838	57.0	3.4	11.0	4.8	3.0	43.3	37.0	31.9	1886	1072	1303	1420	21701	1.76
SEm(±)	**494**	**2.6**	**0.2**	**0.3**	**0.2**	**0.2**	**1.8**	**1.3**	**0.4**	**121**	**146**	**41**	**61**		
LSD (0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**365**	**NS**	**125**	**185**		

T_1: 20 kg P_2O_5 ha^{-1} + bean treatment with bio-phos (3.0 kg ha^{-1}); T_2: Control (No phosphorus and no PSB/bio-phos), T3: Bean treatment with PSB alone (0.5 kg ha^{-1}), T_4: 20 kg P_2O_5 ha^{-1}, T_5: 20 kg P_2O_5 ha^{-1}+ T_3, T_6: 40 kg P_2O_5 ha^{-1}, T_7: 40 kg P_2O_5 ha^{-1}+ T_3, T_8: 60 kg P_2O_5 ha^{-1}; T_9: 60 kg P_2O_5 ha^{-} +T3.

Table 2: Changes in soil phosphatase enzyme activity and P uptake by plant due to P fertilizer and PSMs (*kharif* 2014-15 to 2016-17)

Treatments	Soil alkaline phosphatase (mg g dry wt $soil^{-1}$ hr^{-1})				P uptake by beans (kg ha^{-1})				P uptake by stalks (kg ha^{-1})				Total P uptake (kg ha^{-1})			
	2014	**2015**	**2016**	**Pooled**	**2014**	**2015**	**2016**	**Pooled**	**2014**	**2015**	**2016**	**Pooled**	**2014**	**2015**	**2016**	**Pooled**
T1	446.8	164.9	189.7	267.1	8.65	2.88	5.30	5.61	9.31	3.90	5.57	6.27	17.95	6.78	10.87	11.88
T2	306.8	148.3	183.0	212.7	6.47	2.84	4.39	4.56	7.18	3.41	4.73	5.06	13.65	6.24	9.11	9.63
T3	433.7	181.1	196.0	270.3	8.74	2.49	5.05	5.42	8.78	2.98	5.71	5.79	17.52	5.47	10.76	11.22
T4	289.9	108.2	175.3	191.1	8.69	3.88	4.80	5.79	8.96	4.66	5.35	6.33	17.64	8.54	10.16	12.12
T5	435.1	201.5	201.9	279.5	9.70	3.32	5.30	6.10	10.21	3.98	5.52	6.48	19.91	7.30	10.82	12.59
T6	431.4	166.4	184.6	260.8	8.54	3.50	5.52	5.85	8.97	4.20	5.96	6.33	17.51	7.69	11.48	12.18
T7	387.7	195.6	201.6	261.6	7.18	3.59	5.78	5.52	7.33	4.31	6.21	5.92	14.52	7.90	11.98	11.44
T8	422.0	139.9	177.5	246.5	8.47	2.64	4.34	5.15	8.69	3.26	4.86	5.59	17.16	5.89	9.19	10.74
T9	392.5	186.7	189.0	256.1	6.41	3.53	4.35	4.76	7.46	4.13	4.77	5.40	13.87	7.66	9.12	10.16
SEm(±)	**10.4**	**12.38**	**4.3**	**5.5**	**0.43**	**0.57**	**0.15**	**0.25**	**0.55**	**0.69**	**0.17**	**0.33**	**0.95**	**1.26**	**0.30**	**0.57**
LSD (0.05)	**31.3**	**36.78**	**NS**	**16.2**	**1.30**	**NS**	**0.44**	**0.75**	**1.66**	**NS**	**0.52**	**NS**	**2.86**	**NS**	**0.90**	**1.71**
Initial	378.9	116.8	192.0	229.1												

T_1: 20 kg P_2O_5 ha^{-1} + bean treatment with bio-phos (3.0 kg ha^{-1}); T_2: Control (No phosphorus and no PSB/bio-phos), T3: Bean treatment with PSB alone (0.5 kg ha^{-1}) , T_4: 20 kg P_2O_5 ha^{-1}, T_5: 20 kg P_2O_5 ha^{-1}+ T_3, T_6: 40 kg P_2O_5 ha^{-1}, T_7: 40 kg P_2O_5 ha^{-1}+ T_3, T_8: 60 kg P_2O_5 ha^{-1}; T_9: 60 kg P_2O_5 ha^{-1}+T3.

supply of 40 kg P_2O_5 ha^{-1} (Rs. 30,024 ha^{-1}; 2.05), 20 kg P_2O_5 ha^{-1}+bean treatment with bio-phos (T_1: Rs. 29,292 ha^{-1}; 2.02) and 20 kg P_2O_5 ha^{-1} alone (T_4: Rs. 29,224 ha^{-1}; 2.05). The performance of castor crop was poor in terms of economic returns (Rs. 21,154 ha^{-1}, 1.76), when received neither phosphorus chemical fertilizer nor PSB bean treatment owing to low bean yield. Combined use of half the dose of P fertilizer (20 kg P_2O_5 ha^{-1}) with phosphate solubilizing bacteria (PSB) could reduce the P dose by 50% besides enhancing the net returns by Rs. 2096 ha^{-1} over recommended dose of P (40 kg P_2O_5 ha^{-1}) and Rs. 2828 ha^{-1} over 20 kg P_2O_5 ha^{-1} + bio-phos.

Effect of P chemical fertilizer and PSM on soil alkaline phosphatase enzyme activity

The phosphatase enzymes are known for improving the solubility and mobility of occluded phosphates thus improving availability and uptake of phosphorus. Phosphatases cleave the phosphate ester bonds and hydrolyze the insoluble poly and organic phosphates. In the current study, significantly higher soil alkaline phosphatase enzyme activity was found in the treatment where seed treatment with PSB was done along with supply of 20 kg P_2O_5 ha^{-1} (279.5 mg g dry wt soil^{-1} hr^{-1}) as furnished in Table 2 It was at par with that of bean treatment with PSB alone (T_3: 270.3) and 20 kg P_2O_5 ha^{-1} + biophos (T_1: 267.1). The overall analysis further showed that addition of PSB improved enzymatic activity with addition of different P fertilizer levels, however, the magnitude of increase was higher at lower dose than at medium and high doses. Furthermore, the phosphatase activity improved with the addition of P fertilizer with or without bean treatment with bio-inoculant, except at 20 kg P_2O_5 ha^{-1} (Table 2). According to Singh *et al.* (2000), *phosphate solubilizing micro-organisms* release acid phosphatases to solubilize and mobilize complex forms of rhizospheric phosphates thus enhances accessibility to soil P by host plant. Infact, PSMs produces phosphatases like phytase which mineralizes and hydrolyze the soil organic P thus release inorganic phosphorus for assimilation by plants (Tarafdar *et al.,* 2003; Aseri *et al.,* 2009; Selvi *et al.,* 2017).

Changes in P uptake

The P uptake by beans, stalks and total plants of castor varied significantly due to P fertilizer and bio-inoculants except during the second year of study (Table 2). Based on the results of 2014-15 and also pooled data, the castor crop responded significantly upto application of low P dose (20 kg P_2O_5 ha^{-1}) + seed treatment with PSB, after which it showed declining trend with regard to P uptake. However, during 2016-17, the response was significant up to supply of recommended dose of P (40 kg P_2O_5 ha^{-1}) + seed treatment with PSB. This might be due to receipt of near normal rainfall (only 11.1% deficit) and also higher alkaline phosphatase enzyme activity (Table 2). The greater performance of these treatments could be due to better uptake and assimilation of P by plants following solubilization, mobilization and availability of phosphorus by the action of phosphate solubilizing bacteria (Pradhan and Sukla, 2005). Earlier reports by Pandey *et al.* (2006) also confirmed that PSMs enhanced the P uptake due to enhanced growth and yield.

Water use efficiency and phosphorus use indices

The WUE followed the similar pattern as that of castor bean yield. It was significantly higher when castor plants received basal dose of 20 kg P_2O_5 ha^{-1} besides bean treatment with PSB (4.53 kg ha^{-1} mm^{-1}) (Fig. 1a) which could be attributed to significantly greater amount of bean yield. The phosphorus use indices were significantly influenced by P fertilizer and bio-inoculants. PUE which indicates castor bean yield obtained for every kilogram of P fertilizer applied was significantly greater owing to use of 20 kg P_2O_5 ha^{-1} with (T_5: 84.8) or without PSB (T_4: 80.6) and with bio-phos treatment (T1: 81.0) than rest of medium and high dose of P applied including or excluding PSB (Fig. 1b). AEP which denotes increase in yield due to P application over control for kilogram P fertilizer applied (Fig.1c) and AREP (Figure 1d) which represents increase in P uptake over control for every kg P fertilizer applied also followed the similar trend of PUE. All the three P use indices had an inverse relationship with P dose applied, with lowest values at highest P dose.

The three years field study suggested that bean treatment with PSB besides reduced soil application of P by 20 kg P_2O_5 ha^{-1} can be suggested for castor due to realisation of significantly higher bean yield (1696 kg ha^{-1}), alkaline phosphatase enzyme activity, better P use and economic viability. Between two inoculants tested, PSB due to its superior performance, cost effectiveness and easy availability, was found a better substitute over biophos. Considering the large area under castor in the country and the world, exploitation of phosphate solubilizing micro-organisms (PSMs) save huge investments on P fertilizers. They also provide an agronomically, environmentally and economically sustainable and sound solution to address the P fertilizer scarcity and its efficient utilization by the plants.

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