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Influence of direct and residual phosphorus fertilization on growth and yield of potato in a soybean-potato cropping system

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Abstract

Soybean-potato cropping system with proper nutrient management can be an alternative to rice-wheat cropping system. A field experiment was conducted to study the effect of phosphorus (P) with or without biofertilizers (phosphorus solubilising bacteria and arbuscular mycorrhizae) on soybean-potato cropping system. The trial was planned in split plot design with residual P effects from soybean as main treatments and direct P effects as sub plot treatments during winter seasons of 2008-09 and 2009-10. Application of phosphorus along with biofertilizers to soybean had positive residual effect on the growth (vine length and leaf area index) of succeeding potato. At recommended dose, tuber yield (19.1 t ha^{-1}) from residual effect of RP + biofertilizers was at par with DAP treatments (20.1 and 19.0 t ha^{-1} with and without biofertilizers, respectively in 2008-09. Direct application of 100% of recommended dose of phosphorus (25.8 kg P ha^{-1} as Single Super Phosphate) to potato resulted in significantly higher tuber number and tuber yield, enhancing the yield up to 11.7% over control ($p \leq 0.05$). Biofertilizer application recorded an increase of up to 2.7% in starch content over no biofertilizer application. Improved P use indices in biofertilizers applied plots indicated role of these microorganisms in P solubilisation. P nutrition management with biofertilizers in a cropping season can reduce chemical P input requirement and improve overall sustainability of the system.

Keywords: Arbuscular mycorrhizae, Phosphorus solubilizing bacteria, Residual effect, Rock phosophate, Soybean-potato.
Abbreviations: AE_ Agronomic efficiency, AM_ Arbuscular mycorrhiza, CFU_ Colony Forming Units, DAP_ Diammonium phosphate, DOP_ Days of planting, EC_ Electrical conductivity, LAI_ Leaf area index, RP_ Rock phosphate, P_ Phosphorus PFP_ Partial factor productivity, PSB_ Phosphorus solubilizing bacteria, RDP_ Recommended dose of P, RE_ Recovery efficiency.

Introduction

Long term experiments in rice-wheat cropping system reported stagnating yields with declining total factor productivity. The task of increasing food grain production is confronted with problems of higher nutrient mining, imbalanced soil fertilization, decreasing soil fertility and exploitation of ground water. In this scenario, focus on cropping system rather than individual crop will be more pertinent as crop production might benefit from suitable management practices (De Jong et al., 2001; Robert et al., 2003; Susanna et al., 2007; Lobell et al., 2008). However, at farmer's level, potential productivity and economic benefits act as guiding principles while opting for a particular cropping system. A cropping system with tuber crops and legume oilseeds may answer few of these questions in addition to achieving food and nutritional security. Soybean is an ideal choice for crop sequences as it is a short duration (85–130 days) crop and is comparatively tolerant to abiotic stresses. Cropping systems involving soybean have been confined to only soybean-wheat and soybean-mustard in small pockets (Dercon et al., 2012). Potato has attributes like adaptability, early maturity, quality of produce and tolerance to biotic and abiotic factors. These attributes make it ideal for inclusion in wide range of cropping systems in different agro-climatic conditions. Studies have shown that potato based cropping systems are usually more profitable than cereal based cropping systems (Pandey et al., 2008). Soybean-potato cropping system is one such newly emerging system whose nutrient management practices needs to be worked out to reduce the gap between the potential and actual yields. Among the nutrient management, phosphorus (P) management is crucial as its deficiency results in substantial reduction in dry matter content and consequently the yield for both soybean and potato. Involvement of P in symbiotic nitrogen fixation makes it rather irreplaceable element for soybean (Israel, 1993). In potato, adequate supply of phosphorus is critical for tuber initiation, optimum tuber numbers and yield. Phosphorus deficient potato crops have lower specific gravity and poor yield (Mac Kay et al., 1988). Potato crop yielding 25-30 t ha^{-1} removes about 20-25 kg P ha^{-1} (Gayathri et al., 2009). However, fertilizer P recovery remains low and can range from less than 10% up to 30% depending on soil, crop and management factors (Withers et al., 2005). Rock phosphate (RP) is abundantly available in insoluble form (tri-calcium phosphate). Altering the insoluble form into soluble form in a relatively faster rate remains a big challenge (Chien, 2004). Besides physical and chemical modifications, biological modifications (Arcand and Schneider 2006; Blum et al., 2002; Hagerberg et al., 2003) were tried for faster release of P from RP. Ground RP can be made more efficiently available using microbes like phosphorus solubilizing bacteria (PSB) and arbuscular mycorrhizae (AM). These will be a cheaper P source and eco-friendly input than commonly used fertilizer sources like single super phosphate (SSP) and diammonium phosphate (DAP). Response of soybean and potato to direct application of biofertilizers as soil application has already been documented (Sud and Jatav 2007; Munda et al., 2013). It has been reported that PSB interacts with AM and release some phosphate ions in discrete soil microhabitats in slow rates over a time (El-Azouni, 2008). Phosphate solubilizing bacteria (PSB) have been shown to enhance the solubilization of insoluble P compounds through the release of organic acids and phosphatase enzymes (Sahu and Jana, 2000). The solubility and release rates of these naturally occurring rocks are generally too slow to be available in required amounts in a single cropping season. In addition to these, crop utilizes only a small percent of P in the season or year of application of P. This gives an impetus to study the residual P or carry over effect in the succeeding crop, which has significant effect on agronomic efficiency of fertilizer use and economic returns (Bolland and Gilkes 1995; Barrow et al., 1998). PSB application along with SSP+RP showed residual effects leading to a higher rhizosphere PSB population, available P in the soil in sugarcane (Sundara et al., 2002). Based on the above observations, the aim of this study was to investigate the phosphorus uptake and performance of potato under direct and residual P nutrition in soybean-potato cropping system.

Results

Growth parameters of potato crop

Both direct and residual P had significant impact on the vine length of potato at all stages of crop growth (Table 1). At 45 and 75 days of planting (DOP), the main plot treatments of 100% recommended dose of P (RDP) either through DAP or RP along with biofertilizers were found to be at par and significantly higher than all other main plot treatments having no biofertilizers. Direct application of 50% RDP recorded longest vine length (17.9 and 21.1cm in 2008 and 2009, respectively) at 45 DOP, which was significantly higher than control and at par with 100% RDP. However, application of 100% RDP at 75 DOP and dehaulming recorded longest vine length, which was significantly higher than control and 50% RDP. At dehaulming, vine length was recorded 25.2 and 28 cm in 2008 and 2009, respectively. Positive interaction effects were found between the treatments to preceding soybean and treatments to potato at dehaulming during 2008-09.
LAI determines the total dry matter accumulation and yield of crops. At all stages of crop growth, application of 100% RDP through DAP + biofertilizers to preceding soybean recorded highest LAI in both years except at 45 DOP stage in 2008-09 (Table 2). Among the treatments applied to potato, 100% RDP recorded significantly higher LAI than rest of the treatments at all stages of crop growth. Similar trend was recorded during both the years.

Yield and yield attributes

The minimum yields were obtained from the controls (both direct and residual effect). Among the various treatments to preceding soybean crop, application of 100 % RDP through DAP in combination with biofertilizers recorded maximum tuber number per plant (29), tuber yield per plant (1.06 kg) and tuber yield (20.1 t ha^{-1}) during 2008-09 and same trend was observed in following year (Table 3). RP treatments also recorded higher yields when biofertilizers were applied. Irrespective of levels and sources of P, biofertilizer treated plots resulted in better yield compared to plots without any biofertilizers. Phosphorus applied at 100 % RDP directly to potato crop registered significantly higher yield and yield attributes than the rest. Like tuber yield, starch content and starch yield are important parameters, which determine the value of potato crop. In the present study, treatments receiving biofertilizers registered positive response though it was statistically non-significant among the treatments to preceding soybean (Table 4). Supplying 100% RDP through DAP in combination with biofertilizers recorded maximum starch content (23%) and starch yield (463 kg ha^{-1}). Direct application of 100% RDP registered significantly higher starch content (21.82%) and starch yield (395 kg ha^{-1}) than the rest in 2008-09. Similar trend was observed in 2009-10.

Nutrient uptake

Total nutrient uptake by potato was influenced by the treatments to preceding soybean and direct application of P to potato. Nutrient uptake, particularly phosphorus was significantly higher in residual 100% RDP through DAP + biofertilizers (74.22 kg N, 10.11 kg P and 103.76 kg K ha^{-1}) than rest of the treatments in first year of experimentation (Table 5). P sources i.e. DAP and RP at 100% RDP recorded no difference in uptake pattern in second year of study. Among the treatments to succeeding potato, 50 and 100% RDP recorded significantly higher uptake of nutrients over control. Irrespective of P source, nutrient uptake was higher in biofertilizers treated plots. Positive interaction effect was recorded between treatments to preceding soybean and treatments to potato in both the years of experimentation.

Effects on phosphorus solubilizing bacteria population in soil

Treatments receiving biofertilizers in the preceding soybean crop recorded higher PSB population, highest being recorded with 100% RDP through DAP along with biofertilizers (151.84 CFU x 10^4 g^{-1}) (Fig. 1). At harvest, PSB population reduced drastically to negligible values in all plots.

Phosphorus use indices of potato

In first year, 100% DAP and biofertilizers recorded maximum PFP (393.59 kg tuber kg P^{-1}) which was at par with 50% RP with biofertilizers (384.95). In the second year, residual effect 50% RP in combination with biofertilizers recorded highest PFP (418.03 kg tuber kg P^{-1}) which was at par with 100% DAP with biofertilizers. All

Table 1. Vine length (cm) of potato at various stages of crop growth as influenced by levels of phosphorus and biofertilizers.

Treatment	2008-09			2009-10		
	45 DOP	75 DOP	At dehaulming	45 DOP	75 DOP	At dehaulming
To preceding soybean						
T1	15.9^{F}	16.6^{G}	19.6^{E}	18.8^{D}	23.4^{D}	23.2^{F}
T2	17.1^{D}	19.1^{F}	22.1^{D}	20.5^{ABC}	23.9^{D}	24.6^{EF}
T3	16.3^{EF}	19.2^{F}	22.2^{D}	20.2^{BCD}	25.1^{CD}	25^{DE}
T4	17.5^{BC}	21.7^{C}	26.6^{A}	20.8^{ABC}	25.0^{CD}	27.01^{BC}
T5	16.4^{EF}	20.4^{D}	25.6^{B}	19.7^{CD}	24.7^{D}	26.5^{CD}
T6	17.3^{BC}	21.7^{C}	24.8^{C}	20.5^{ABC}	25.4^{BCD}	28.41^{B}
T7	17.4^{BC}	20.0^{E}	25.0^{BC}	20.8^{ABC}	25.2^{CD}	26.5^{CD}
T8	18.9^{A}	23.1^{B}	25.0^{BC}	21.7^{A}	27.7^{A}	28.01^{BC}
T9	17.6^{B}	21.8^{C}	26.6^{A}	21.2^{AB}	26.9^{ABC}	28.3^{B}
T10	18.8^{A}	24.3^{A}	26.0^{AB}	21.6^{AB}	27.6^{AB}	30.9^{A}
SEm$\pm$	0.17	0.18	0.25	0.39	0.42	0.62
LSD ($p \leq 0.05$)	0.51	0.55	0.74	1.15	1.24	1.84
To potato						
S1	16.2^{B}	20.3^{C}	23.3^{C}	19.6^{B}	24.5^{B}	25.8^{B}
S2	17.9^{A}	20.7^{B}	24.4^{B}	21.1^{A}	26.0^{A}	26.7^{B}
S3	17.8^{A}	21.4^{A}	25.2^{A}	21.0^{A}	26.3^{A}	28.0^{A}
SEm$\pm$	0.13	0.11	0.16	0.15	0.31	0.27
LSD ($p \leq 0.05$)	0.38	0.32	0.47	0.44	0.88	0.77
T X S (1)						
(SEm$\pm$)	0.42	0.35	1.22	0.48	1.45	1.6
LSD ($p \leq 0.05$)	NS	NS	3.48	NS	NS	NS
T X S (2)						
(SEm$\pm$)	2.28	1.98	1.27	2.98	1.57	1.55
LSD ($p \leq 0.05$)	NS	NS	3.62	NS	NS	NS

PSB: Phosphate solubilizing bacteria; AM: Arbuscular mycorrhizae; RP: Rock phosphate; DAP: Diammonium phosphate; DOP: Days of planting, 1: SEm & LSD of two sub-plot means at the same main-plot treatment .2: SEm & LSD of two main-plot means at the same or different subplot treatment. Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by LSD test.

Table 2. Leaf area index of potato at various stages of crop growth as influenced by levels and sources of phosphorus and biofertilizers.

Treatment	2008-09			2009-10		
	45 DOP	75 DOP	At dehaulming	45 DOP	75 DOP	At dehaulming
To preceding soybean						
T1	1.39^{B}	2.84^{B}	3.29^{E}	1.36^{F}	2.83^{D}	3.21^{E}
T2	1.40^{B}	2.84^{B}	3.31^{DE}	1.41^{E}	2.85^{CD}	3.25^{E}
T3	1.40^{B}	2.84^{B}	3.30^{CDE}	1.42^{DE}	2.85^{CD}	3.33^{D}
T4	1.44^{A}	2.88^{AB}	3.34^{BCDE}	1.45^{CD}	2.88^{ABC}	3.38^{BCD}
T5	1.44^{A}	2.85^{B}	3.33^{CDE}	1.46^{BC}	2.86^{CD}	3.35^{CD}
T6	1.48^{A}	2.88^{AB}	3.35^{ABCDE}	1.48^{ABC}	2.89^{ABC}	3.4^{ABC}
T7	1.45^{A}	2.86^{AB}	3.39^{ABC}	1.47^{ABC}	2.87^{BC}	3.4^{ABC}
T8	1.47^{A}	2.90^{A}	3.36^{ABCD}	1.48^{AB}	2.91^{AB}	3.41^{ABC}
T9	1.46^{A}	2.90^{A}	3.4^{AB}	1.48^{ABC}	2.91^{AB}	3.44^{AB}
T10	1.47^{A}	2.90^{A}	3.41^{A}	1.49^{A}	2.92^{A}	3.46^{A}
SEm$\pm$	0.01	0.01	0.01	0.01	0.01	0.01
LSD ($p \leq 0.05$)	0.04	0.03	0.03	0.04	0.03	0.04
To potato						
S1	1.42^{B}	2.84^{A}	3.31^{C}	1.43^{C}	2.85^{C}	3.33^{B}
S2	1.44^{B}	2.87^{B}	3.34^{B}	1.45^{B}	2.88^{B}	3.36^{B}
S3	1.46^{A}	2.89^{C}	3.38^{A}	1.47^{A}	2.91^{A}	3.40^{B}
SEm$\pm$	0.003	0.001	0.010	0.003	0.001	0.010
LSD ($p \leq 0.05$)	0.010	0.003	0.020	0.010	0.003	0.020
T X S (1)						
(SEm$\pm$)	0.01	0.01	0.02	0.01	0.02	0.02
LSD ($p \leq 0.05$)	NS	NS	0.04	NS	NS	NS
T X S (2)						
(SEm$\pm$)	0.08	0.08	0.13	0.08	0.10	0.12
LSD ($p \leq 0.05$)	NS	NS	NS	NS	NS	NS

PSB: Phosphate solubilizing bacteria; AM: Arbuscular mycorrhizae; RP: Rock phosphate; DAP: Diammonium phosphate; DOP: Days of planting, 1: SEm & LSD of two sub-plot means at the same main-plot treatment .
2: SEm & LSD of two main-plot means at the same or different subplot treatment. Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by LSD test.

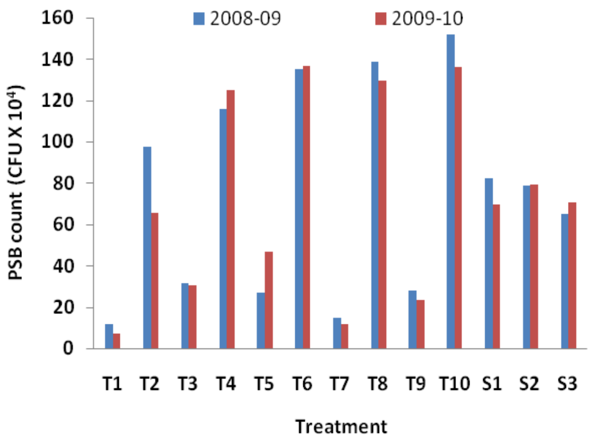

Fig 1. PSB count (CFU X 10^4) before planting of potato.

treatments with biofertilizers recorded significantly higher PFP than treatments without biofertilizers at same level and source of P. Among the treatments to potato, 50% RDP as SSP (651.03 kg tuber kg P^{-1}) recorded significantly higher PFP than 100% RDP (340.83 kg tuber kg P^{-1}). Similar trends were observed in case of AE and RE of applied P (Fig 2). Significant correlation was observed between P use indices and tuber yield in both the years (Table 6). Pearson correlation value for AE with tuber yield was 0.65 in 2008-09 and 0.75 in 2009-10, whereas between RE and tuber yield, it was 0.61 in 2008-09 and 0.64 in 2009-10.

Discussion

Growth parameters of potato crop

Among the treatments to the preceding soybean, application of rock phosphate or diammonium phosphate at RDP in combination with biofertilizers recorded better vine lengths compared to treatments without biofertilizers. This is due to the beneficial residual effect of PSB in soils. Addition of organic acids by PSB leads to release of native P present in the soil resulting in sufficient P in soil solution around root zone (Bolan et al., 1994). Gaur (1990) had also ascribed the beneficial effect of phosphate solubilizing microorganisms to the release of P from inorganic fractions and reduction in P fixation capacity of the soil. Several studies have shown that phosphate solubilizing bacteria interact with AM by releasing phosphate ions in the soil, which causes a synergistic interaction that allows for better exploitation of poorly soluble P sources (Azcon-Aguilar et al., 1986; Piccini and Azcon, 1987). The plant through mycorrhizal attachments could more efficiently take up phosphate solubilised by the bacteria. It allows nutrient translocation from soil to plants (Jeffries and Barea, 1994). Positive effects on succeeding potato crop indicate prolonged existence of bacterial and fungal strains in soybean-potato cropping system. It was also observed that application of 50% and 100% RDP registered vine length at par with each other but at latter stages application of 100% RDP recorded better vine length. This implies that at advanced stages of crop growth, potato plant becomes more dependent on applied nutrients. Biofertilizers, especially AM has pronounced influence on leaf expansion which may have attributed to higher leaf area index of potato. McArthur and Knowles (1992) reported that a higher leaf area for AM plants could be ascribed to improved growth due to the symbiosis and, hence, a greater amount of photo-assimilates

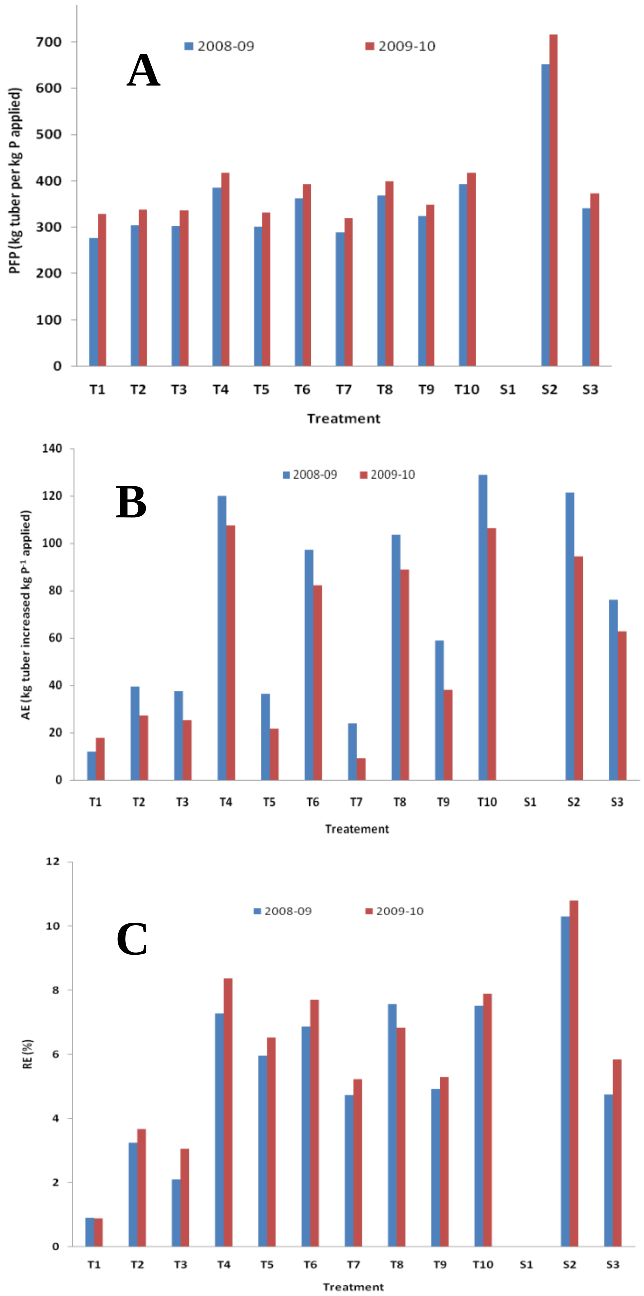

Fig 2. P use indices of potato as influenced by sources and levels of phosphorus and biofertilizers, 2A: PFP, 2B: AE, 2C: RE.

for shoot development. AM influence on leaf expansion was mostly responsible for the greater total leaf area index.

Yield and yield attributes

The favourable influence of inorganic and biofertilisers on chemical, physical and biological properties of soil would have resulted in such maximum tuber yields of potato. Higher tuber yield due to P fertilization could be due to higher cell division and elongation that ultimately lead to more photosynthesis and translocation of photosynthates to the tuber by the plants as evident by higher growth characters due to P application. Both DAP and RP treated plots recorded higher yields with biofertilizers application.

Table 3. Yield attributes and yield of potato as influenced by treatments.

Treatment	2008-09			2009-10		
	Tuber number plant^{-1}	Tuber yield per plant (kg)	Tuber yield (t ha^{-1})	Tuber number plant^{-1}	Tuber yield per plant (kg)	Tuber yield (t ha^{-1})
To preceding soybean						
T1	24.5	0.83	15.5^{D}	22.3^{E}	0.75^{B}	17.5^{C}
T2	26.2	0.85	15.5^{D}	22.9^{DE}	0.78^{B}	17.7^{C}
T3	26.3	0.89	15.6^{D}	23.3^{CDE}	0.80^{B}	17.7^{C}
T4	27.2	0.91	18.5^{B}	25.2^{ABCD}	0.94^{A}	20.6^{AB}
T5	25.8	0.88	16.3^{CD}	24.2^{BCDE}	0.86^{AB}	18.8^{BC}
T6	28.4	0.97	16.6^{C}	26.2^{AB}	0.95^{A}	20.9^{A}
T7	27.9	0.97	16.1^{CD}	25.8^{AB}	0.97^{A}	20.6^{AB}
T8	27.6	1.04	19.1^{AB}	26.6^{AB}	0.93^{A}	20.3^{AB}
T9	28.0	1.03	19.0^{AB}	25.7^{ABC}	0.94^{A}	20.7^{AB}
T10	29.0	1.06	20.1^{A}	27.4^{A}	0.97^{A}	21.4^{A}
SEm$\pm$	0.58	0.02	0.44	0.6	0.02	0.41
LSD ($p \leq 0.05$)	NS	NS	1.32	1.8	0.05	1.23
To potato						
S1	25.5^{C}	0.91^{B}	16.2	23.7^{B}	0.84^{B}	18.9^{B}
S2	27.3^{B}	0.94^{B}	17.4	25.2^{AB}	0.89^{B}	19.7^{A}
S3	28.5^{A}	0.98^{A}	18.1	26.3^{A}	0.94^{A}	20.6^{A}
SEm+	0.43	0.01	0.16	0.3	0.01	0.18
LSD ($p \leq 0.05$)	1.22	0.04	0.44	0.8	0.02	0.52
T X S (1)						
(SEm+)	1.35	0.05	0.73	2.14	0.02	0.58
LSD ($p \leq 0.05$)	NS	NS	1.48	NS	NS	NS
T X S (2)						
(SEm+)	7.40	0.26	0.76	2.11	0.14	0.62
LSD ($p \leq 0.05$)	NS	NS	1.56	NS	NS	NS

PSB: Phosphate solubilizing bacteria; AM: Arbuscular mycorrhizae; RP: Rock phosphate; DAP: Diammonium phosphate; DOP: Days of planting. 1: SEm & LSD of two sub-plot means at the same main-plot treatment.
2: SEm & LSD of two main-plot means at the same or different subplot treatment. Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by LSD test.

This indicated that combined inoculation of biofertilizers not only helped in making the P available from RP, it may also have helped the solubilisation and mobilization of native soil P or P fixed form DAP and made it more available to plants (Supplementary Table 1 and 2). We also found highest CFU count (151.84 CFU x 10^4 g^{-1}) with 100% RDP through DAP along with biofertilizers. All yield attributes and yields were found to be better in biofertilizers applied treatments when compared to similar fertilizer application with no biofertilizers. This signifies that there is possibility of higher production even with residual biofertilizers effect. Further, RP+ biofertilizer recorded yields at par when compared to DAP treated plots indicating the efficacy of biofertilizers. Dua et al. (2008) reported that application of P increased the number and yield of seed size tubers. Similarly, response to P fertilization was significant with respect to total tuber yield and biomass yield up to application of 80 kg P ha^{-1} (Kumar et al., 2007).

Starch content

Results indicate direct relation of phosphorus to starch content of tuber. High P content in potato starch is prerequisite for high quality (Noda et al., 2006). P nutrition has been reported to increase reducing sugars content at harvest and after storage (Kolbe et al., 1995).

Effects on nutrient uptake

Phosphorus uptake trend in the present investigation corroborates previous findings. Phosphorus recovery was reported to be higher by over 14% in combined application of PSB and P than that of P alone (Sud and Jatav, 2007). Insoluble P compounds were solubilised through the release of organic acids and phosphatase enzymes from PSB (Sahu and Jana, 2000). Nitrogen uptake was higher in biofertilizer applied treatments. A positive effect of biofertilizers application on N and K uptake has been reported by Jat and Ahlawat (2006) and Dutta and Purohit (2009) in chickpea and by Tran et al. (2006) in soybean. Increased availability of P by PSB facilitates better N and K utilisation (Sundara et al., 2002).

Phosphorus use indices of potato

Phosphorus use indices indicated improvement in the efficiency of applied P and substantial residual effect of P fertilizers when used in conjunction with biofertilizers. The plant with the help of mychorrhizae more efficiently takes up phosphate solubilised by the bacteria (Jeffries and Barea, 1994). This further corroborate to the findings of Jilani et al. (2007) and Yazdani et al. (2009). They emphasized the fact that biofertilizers have the potential to replace up to 50% of the applied fertilizer. Additional advantage with lower dose of chemical fertilizer when combined with biofertilizers indicates sustainability of system.

Materials and methods

Site description

Field experiments were conducted during 2008-09 and 2009-10 at the research farm of the Indian Agricultural Research Institute, New Delhi (28°35' N, 77°12' E and 228.6 m above mean sea level). The soil was Inceptisol having sandy loam with EC 0.44 dS m^{-1}.

The mean annual rainfall of Delhi is 652 mm and more than 80% of it occurs during the south-west monsoon season (July-September). The mean annual evaporation is 850 mm (Supplementary Fig. 1 and 2). Before sowing of soybean, the soils of experimental field had 252 kg ha^{-1} alkaline permanganate oxidizable N (Subbiah and Asija, 1956), 17.5 kg ha^{-1} available P (Olsen et al., 1954), 170 kg^{-1} N ammonium acetate exchangeable K (Stanford and English, 1949) with soil pH 7.2 (1: 2.5 soil and water ratio) in 2008. In 2009, the experimental soil had 242 kg ha^{-1} alkaline permanganate oxidizable N, 17.5 kg ha^{-1} available P, 186 kg^{-1} N ammonium acetate exchangeable K with soil pH 7.4.

Plant materials

Soybean variety 'DS 9814' was sown in summer season (July to October) as preceding crop. Medium duration (100-110 days) potato (Var. 'Kufri Badshah') was sown using a seed rate of 3000 kg ha^{-1} in 45 cm rows in the first fortnight of November during both the years of experimentation.

Experimental design

The main plot (residual effect) treatments consisted of 2 sources of phosphorus viz., diammonium phosphate [DAP(18-46-0, N-P_2O_5-K_2O)] and rock phosphate [RP(0-18-0, N-P_2O_5-K_2O)]; 2 levels viz., 50% (16.12 kg P ha^{-1}) and 100% (32.25 kg P ha^{-1}) of recommended dose of phosphorus (RDP) and combined inoculation of biofertilizers [PSB (*Pseudomonas striata*) and AM (*Glomus fasciculatum*)] (Table 7). The PSB and AM used in the experiment were collected from the Division of Microbiology, Indian Agricultural Research Institute, New Delhi, India. The PSB was applied at 500mL ha^{-1} with a density of 10^8 CFU mL^{-1}. The AM was applied at 11.25 kg ha^{-1} of a formulation with 1000 g^{-1} spore count. After the harvest of soybean, the undisturbed plots were divided and three levels of P were applied to potato 0, 50% (12.9 kg P ha^{-1}) and 100% (25.8 kg P ha^{-1}) in the form of single super phosphate. Thus, there were 30 treatment combinations with treatment to soybean as main plots and treatments to potato as sub-plots, replicated thrice. The plot size was 14.0m X 3.6m for main plot and 4.0m X 3.0m for sub plot. The crop was raised as per the recommended package of practices except for the treatments. Details of the treatments have been presented in Table 7.

Biometric observations (vine length and leaf area index)

For recording biometric observations (vine length and LAI), five representative plants of potato from each treatment were selected randomly at 45, 75 days of planting and at dehaulming. All the leaves were removed from the selected plants and their area was measured using leaf area meter (1/2-MDL-1000 LICOR Ltd., USA).

Tuber yield and yield attributes

Five representative plants were carefully dug without disturbing the tubers and their total number was counted. The tubers collected from five representative plants were weighed and expressed as tuber yield per plant (kg). After dehaulming, the harvesting was done by digging out the potato tubers from net plot area in every treatment and tuber yield was recorded as tonnes ha^{-1}.

Table 4. Starch content and starch yield of potato tubers as influenced by treatments.

Treatment	2008-09		2009-10	
	Starch Content (%)	Starch Yield (kg ha^{-1})	Starch Content (%)	Starch Yield (kg ha^{-1})
To preceding soybean				
T1	20.40	319.01^{DE}	21.36	374^{D}
T2	20.42	319.01^{DE}	21.75	386^{CD}
T3	20.51	315^{E}	21.40	382^{CD}
T4	20.62	386.01^{BC}	21.60	443^{B}
T5	21.24	345^{DE}	21.68	409^{C}
T6	21.36	353.01^{CD}	21.92	458^{AB}
T7	21.42	346^{DE}	22.17	473^{A}
T8	21.81	416^{B}	21.43	442^{B}
T9	22.41	418^{B}	22.73	470^{AB}
T10	23.02	463^{A}	22.81	487^{A}
SEm$\pm$	0.59	13.2	0.36	10.83
LSD ($p \leq 0.05$)	NS	40.8	NS	38.61
Treatments to potato				
S1	20.75^{B}	337^{B}	21.37^{B}	405^{C}
S2	21.35^{A}	372^{A}	21.90^{B}	432^{B}
S3	21.82^{A}	395^{A}	22.39^{A}	461^{A}
SEm$\pm$	0.16	5.61	0.16	5.42
LSD ($p \leq 0.05$)	0.45	14.82	0.46	15.24
T X S (1)				
(SEm$\pm$)	0.50	13.19	0.55	18.25
LSD ($p \leq 0.05$)	1.36	NS	1.58	NS
T X S (2)				
(SEm$\pm$)	0.65	19.90	0.69	20.57
LSD ($p \leq 0.05$)	2.16	NS	1.97	NS

PSB: Phosphate solubilizing bacteria; AM: Arbuscular mycorrhizae; RP: Rock phosphate; DAP: Diammonium phosphate; DOP: Days of planting 1: SEm & LSD of two sub-plot means at the same main-plot treatment.
2: SEm & LSD of two main-plot means at the same or different subplot treatment Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by LSD test.

Table 5. Total nutrient uptake (kg/ha) of potato as influenced by treatments.

Treatment	2008-09			2009-10		
	N	P	K	N	P	K
To preceding soybean						
T1	50.23^{D}	5.66^{H}	64.25^{D}	52.69^{E}	5.86^{C}	68.39^{D}
T2	59.5^{BC}	7.3^{FG}	75.19^{CD}	60.91^{CDE}	7.22^{B}	72.83^{CD}
T3	55.62^{CD}	6.91^{G}	69.72^{D}	57.42^{DE}	6.98^{B}	72.45^{CD}
T4	66.05^{B}	8.65^{C}	87.16^{BC}	69.45^{ABC}	8.88^{A}	77.5^{BCD}
T5	56.64^{CD}	7.66^{EF}	70.12^{D}	59.72^{DE}	7.75^{B}	65.3^{D}
T6	65.71^{B}	9.59^{B}	89.82^{B}	76.15^{A}	9.5^{A}	90.5^{AB}
T7	65.84^{B}	8.33^{CD}	75.5^{CD}	65.07^{BCD}	7.9^{B}	88.43^{AB}
T8	61.89^{BC}	9.24^{B}	75.05^{CD}	61.95^{CDE}	8.93^{A}	89.73^{AB}
T9	56.35^{CD}	7.98^{DE}	75.44^{CD}	58.37^{DE}	7.67^{B}	83.62^{BC}
T10	74.22^{A}	10.11^{A}	103.76^{A}	71.5^{AB}	9.69^{A}	99.72^{A}
SEm$\pm$	2.70	0.15	4.29	3.18	0.31	4.29
LSD ($p \leq 0.05$)	8.03	0.45	12.74	9.44	0.92	12.75
Treatments to potato						
S1	57.71^{B}	7.63^{B}	75.26^{B}	59.33^{B}	7.36^{B}	76.87^{B}
S2	62.26^{A}	8.33^{A}	78.97^{A}	64.86^{A}	8.26^{A}	82.47^{A}
S3	63.64^{A}	8.48^{A}	81.57^{A}	65.77^{A}	8.49^{A}	85.50^{A}
SEm$\pm$	1.16	0.07	0.97	1.68	0.15	1.60
LSD ($p \leq 0.05$)	3.30	0.19	2.78	4.79	0.42	4.57
T X S (1)						
(SEm$\pm$)	5.17	0.29	4.35	7.49	0.66	7.15
LSD ($p \leq 0.05$)	14.77	0.59	12.43	21.42	1.88	20.45
T X S (2)						
(SEm$\pm$)	5.01	0.28	5.57	6.89	0.62	7.25
LSD ($p \leq 0.05$)	14.32	0.81	15.91	19.70	1.77	20.72

PSB: Phosphate solubilizing bacteria; AM: Arbuscular mycorrhizae; RP: Rock phosphate; DAP: Diammonium phosphate; DOP: Days of planting. 1: SEm & LSD of two sub-plot means at the same main-plot treatment . 2: SEm & LSD of two main-plot means at the same or different subplot treatment. Note: In each column the mean values followed by common letters are not significantly different ($p \leq 0.05$) between treatments by LSD test.

Table 6. Pearson Correlation Coefficients between tuber yield and P use indices.

P use indices	Tuber yield 2008-09	Tuber yield 2009-10
PFP	0.37**	0.27**
AE	0.75**	0.65**
RE	0.61**	0.64**

**$p \leq 0.01$

Table 7. Allocation of treatments to soybean and potato.

To preceding soybean (main plot)		To succeeding potato (sub plot)	
T1	Control	S1	0% P
T2	PSB+AM	S2	50% P
T3	50% P as RP	S3	100% P
T4	50% P as RP + PSB+AM		
T5	50% P as DAP		
T6	50% P as DAP + PSB+AM		
T7	100% P as RP		
T8	100% P as RP + PSB+AM		
T9	100% P as DAP		
T10	100% P as DAP+ PSB+AM		

Starch content and starch yield in potato tuber

A representative fresh sample was used for starch content analysis by Anthrone method (Thimmiah, 1999) using spectrophotometer at 630 nm and expressed in %.

Plant and soil sampling

The representative plant samples were oven dried at 65°C for 48 hours and the same was used for chemical analysis by following standard procedures. Rhizospheric soil samples (0–30 cm depth) were collected by an auger from five spots at random before sowing and after the harvest of crops for studying the nutrient availability and PSB status in the soil.

Phosphate solubilizing bacteria count

The population of PSB was estimated by plate count method (Ravina et al., 1992). Soil samples were serially diluted and spread on Pikovskaya agar media and the plates were incubated for 7 days at 30ºC. Colonies of PSB were detected by clear zones of solubilization.

Determination of nutrient content in soil and their uptake by potato

Available nitrogen (N) in soil was estimated by alkaline $KMnO_4$ method as suggested by Subbiah and Asija (1956). Available P in soil was estimated following the method proposed by Olsen et al. (1954). Available potassium (K) in soil was determined using neutral normal ammonium acetate (NH_4OAC) method and flame photometry as described by Stanford and English (1949). The N concentration in plant was estimated by micro-kjeldahl method (Prasad et al., 2006) and for estimation of P and K, plant samples were digested with di-acid mixture (HNO_3:$HClO_4$ :: 10:4) and then P content in the extracts was determined by stannous chloride method (Watanabe and Olsen, 1965) and K was determined by flame photometer.

Calculation of partial factor productivity (PFP), agronomic efficiency (AE), and recovery efficiency (RE) of applied P

The physiological indices provided useful information on the efficiency with which P fertilizers are utilized with and without biofertilizers. Recovery efficiency was worked out to assess the P uptake efficiency. The PFP, AE and RE of applied P were computed using the following expressions as suggested by Fageria and Baligar (2003) and Dobermann (2005).

PFP = YP / Na ---------------------(1)

AE = (YP – Yc)/ Na --------------(2)

RE = [(UP – Uc)/ Na] x 100-----(3)

where, YP and UP refer to the tuber yield (kgha^{-1}) and total P uptake (kg ha^{-1}), respectively, of the crop in P applied plots; Yc and Uc refer to the tuber yield (kg ha^{-1}) and total P uptake (kg ha^{-1}), respectively, of the crop in absolute control (no P); Na refers to the nutrient (P) applied (kg ha^{-1}).

Statistical analysis

Data were analyzed following analysis of variance (SAS Software packages, SAS EG 4.3) and means of treatments were compared based on LSD test at $p \leq 0.05$.

Conclusions

Application of biofertilizers in addition to DAP or RP to preceding soybean resulted in better growth and yield of succeeding potato crop. It may be inferred from the present investigation that full dose of P either as DAP or RP in combination with biofertilizers applied to preceding soybean proved to be superior in terms of growth and yield parameters to the succeeding potato crop. Combined inoculation of biofertilizers had considerable effect on P uptake by plants even in DAP (water soluble) applied plots indicating higher mobilization and absorption of P. This investigation suggests that improving the quality of tuber by increasing the starch content is possible through proper P nutrition. Phosphorus use indices of the system indicate higher sustainability at lower P levels. Present investigation also demonstrates that potato in the soybean-potato cropping system owns the potential to perform well with comprehensive nutrient management strategy. This research would shed light on exploring soybean-potato cropping systems in Northern belt of India, which is facing problems of declining yields and PFP in continuous rice-wheat cropping system.

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References

Arcand M, Schneider KD (2006) Plant and microbial based mechanisms to improve the agronomic effectiveness of phosphate rock. A review. An Acad Bras Cienc. 78: 791-807.

Azcon-Aguillar C, Gianinazzi-Pearson V, Fardeau JC (1986) Effect of vesicular-arbuscular mycorrhizal fungi and phosphate solubilizing bacteria on growth and nutrition of soybean in a neutral calcareous soil amended with ^{32}P - ^{45}Ca tricalcium phosphate. Plant Soil. 96: 3-15.

Barrow NJ, Bolland MDA, Allen DG (1998) Effect of previous additions of superphosphate on sorption of phosphate. Aust J Soil Res. 36: 359-372.

Bolan NS, Naidu R, Mahimairaja S, Bhaskaran S (1994) Influence of low molecular weight organic acids on the solubilisation of phosphates. Biol Fert Soil. 18: 311-319.

Bolland MDA, Gilkes RJ (1995) Long-term residual value of North Carolina and Queensland rock phosphates compared with triple superphosphate. Fert Res. 41: 151-158.

Blum JD, Klaue A, Nezat CA, Driscoll CT, Johnson CE, Siccama TG, Eagars C, Fahey TJ, Likens GE (2002) Mycorrhizal weathering of apatite as an important calcium source in base-poor forest ecosystems. Nature. 417: 729-731.

Chien SH (2004) Soil testing for phosphate rock application. In: Zapata F, Roy RN (eds) Use of rock phosphates for sustainable agriculture, Use of Fertilizer and Plant Nutrition Bulletin. Food and Agriculture Organization of the United Nations, Rome.

De Jong R, Li KY, Bootsma A, Huffman T, Roloff G, Gameda S (2001) Crop yield variability under climate change and adaptive crop management scenarios. Final report for Climate Change Action Fund Project A080. Eastern Cereal and Oilseed Research Centre (ECORC), Agriculture and Agri-Food Canada.

Dercon G, Kumar S, Garg AK, Manchanda JS, Aulakh, MS, Nguyen ML (2012) Crop production and nutrient use efficiency of conservation agriculture for soybean-wheat rotation in the Indo-Gangetic Plains of Northwestern India. Soil Till Res. 120: 50-60.

Dobermann A (2005) Nitrogen use efficiency-state of the art. In: IFA International Workshop on Enhanced-Efficiency of Fertilizers. International Fertilizer Association, Frankfurt, Germany, 28-30 June 2005. pp 1-18 http://digitalcommons.unl.edu/agronomyfacpub/316

Dua VK, Jaiswal RC, Khurana SC, Kumar D, Nandekar DN, Raghav M, Rawal S, Sasani GV, Trehan SP, Trivedi SK, Jatav MK, Lal SS, Thakur KC, Pandey SK, Naik PS (2008) Manipulation of agronomic practices for tuber-size distribution in potato (*Solanum tuberosum*) seed crop. Indian J Agron. 53 (3): 217-223.

Dutta D, Prohit B (2009) Performance of chickpea (*Cicer arietinum* L.) to application of phosphorus and biofertilizer in laterite soil. Arch Agron Soil Sci. 55: 147–155.

El-Azouni I (2008) Effect of phosphate solubilizing fungi on growth and nutrition uptake of soybean (*Glycine max* L.). Plants J Appl Sci Res. 4(6): 592-598.

Fageria NK, Baligar VC (2003) Methodology for evaluation of lowland rice genotypes for nitrogen use efficiency. J Plant Nutr. 26: 1315-1333.

Gaur AC (1990) Physiological functions of phosphate solubilizing micro-organisms. In: Gaur AC (ed) Phosphate solubilizing micro-organisms as biofertilizers, Omega Scientific Publishers, New Delhi.

Gayathri A, Vadivel A, Santhi R, Murugesa BP, Natesan R (2009) Soil test based fertilizer recommendation under integrated plant nutrition system for potato (Solanum tuberosum) in hilly tracts of Nilgiri district. Indian J Agr Res. 43: 52-56.

Hagerberg D, Thelin G, Wallander H (2003) The production of ectomycorrhizal mycelium in forests: Relation between nutrient status and local mineral sources. Plant Soil. 252: 279-290.

Israel DW (1993) Symbiotic dinitrogen fixation and host-plant growth during development of and recovery from phosphorus deficiency. Physiol Plantarum. 88: 294-300.

Jat RS, Ahlawat IPS (2006) Direct and residual effect of vermicompost, biofertilizers and phosphorus on soil nutrient dynamics and productivity of chickpea-fodder maize sequence. J Sustain Agr. 28(1): 41-54.

Jeffries P, Barea JM (1994) Bioeochemical cycling and arbuscular mycorrhizas in the sustainability of plant-soil system. In: Gianinazzi S, Schuepp H (eds) Proceedings of Impact of arbuscular mycorrhizas on sustainable agriculture and natural ecosystems, Basel, Birkhauser Verlag, Switzerland, 1994.

Jilani G, Akram A, Ali RM, Hafeez FY, Shamsi IH, Chaudhry AN, Chaudhry AG (2007) Enhancing crop growth, nutrients availability, economics and beneficial rhizosphere microflora through organic and biofertilizers. Ann Microbiol. 57: 177-18.

Kolbe H, Muller K, Olteanu G, Gorea T (1995) Effects of nitrogen, phosphorus and potassium fertilizer treatments on weight loss and changes in chemical composition of potato tubers stored at 4°C. Potato Res. 38: 97-107.

Kumar P, Pandey SK, Singh BP, Singh SV, Kumar D (2007) Optimizing phosphorus requirement of chipsona varieties for west-central plains of India. Potato J. 34(3-4): 199-202.

Lobell D, Burke M, Tebaldi C, Mastrandrea MD, Falcon WP and Naylor RL (2008) Prioritizing climate change adaptation needs for food security in 2030. Science. 319: 607–610.

MacKay DC, Carefoot JM, Entz T (1988) Detection and correction of mid season P deficiency in irrigated potatoes. Can J Plant Sci. 68: 523- 534.

McArthur DAJ, Knowles NR (1992) Resistance responses of potato to vesicular arbuscular mycorrhizal fungi under varying abiotic phosphorus levels. Plant Physiol. 100: 341-351.

Munda S, Shivakumar BG, Gangaiah B, Rana DS, Manjaiah KM, Lakshman K, Layek J (2013) Response of soybean (*Glycine max*) to phosphorus with or without biofertilizer. Indian J Agron. 58(1): 86-90.

Noda T, Tsuda S, Mori M, Takigawa S, Matsuura-Endo C, Kim SJ, Hashimoto N, Yamauchi H (2006) Determination of the phosphorus content in potato starch using an energy dispersive X-ray fluorescence method. Food Chem. 95: 632-637.

Olsen SR, Cole CL, Watanabe FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular No. 939. Washington, pp 72-75.

Pandey SK, Singh JP, Gopal J (2008) Potato varieties and cropping systems in India. Potato J. 35(3-4): 103-110.

Piccini D, Azcon R (1987) Effect of phosphate-solubilizing bacteria and vesicular-arbuscular mycorrhizal fungi on the utilization of Bayovar rock phosphate by alfalfa plants using a sand vermiculite medium. Plant Soil. 50: 45-50.

Prasad R, Shivay YS, Kumar D, Sharma SN (2006) Learning of doing exercises in soil fertility. A Practical Manual for Soil Fertility, Division of Agronomy, Indian Agricultural Research Institute, New Delhi, India.

Ravina MD, Acea MJ, Carballas T (1992) Seasonal fluctuations in microbial populations and available nutrients in forest soil. Biol Fert Soil. 16: 198-204.

Robert KD, Joe S, Sandra G (2003) Life on the edge: vulnerability and adaptation of African ecosystems to global climate change. Mitigation and Adaptation Strategies for Global Change. 8: 93–113.

Stanford S, English L (1949) Use of flame photometer in rapid soil tests for K and Ca. Agron J. 41: 446-447.

Subbiah BV, Asija GL (1956) A rapid procedure for the estimation of available N in soils. Current Sci. 25: 259-260.

Sud KC, Jatav MK (2007) Response of potato to phosphorus and phosphorus solubilizing bacteria in brown hill soils of Shimla. Potato J. 34: 1-2.

Sundara B, Natarajan V, Hari K (2002) Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugarcane and sugar yields. Field Crop Res. 77: 43-49.

Susanna R, Barry S, Wayne C, Suzanne B (2007) Vulnerability and adaptation to climate risk in Ontario agriculture. Mitigation and Adaptation Strategies for Global Change. 12: 609–637.

Thimmaiah SK (1999) Standard methods of biochemical analysis. Kalyani Publishers, New Delhi, India.

Tran TNS, Cao ND, Truong TMG (2006) Effect of bradyrhizobia and phosphate solubilizing bacteria application on soybean in rotational system in the Mekong Delta. Omonrice 14: 48–57.

Watanabe FS, Olsen SR (1965) Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soils. Soil Sci Soc Am Proc. 29: 677-678.

Withers PJA, Nash DM, Laboski CAM (2005) Environmental management of phosphorus fetilizers. In: Sims JT, Sharpley AN (eds) Phopshorus: Agriculture and the Environment. Monograph no. 46 (Chapter 25), American Society of Agronomy, Madison.

Yazdani M, Bahmanyar MA, Pirdashti H, Esmaili MA (2009) Effect of phosphate solubilization microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) on yield and yield components of Corn (*Zea mays* L.). World Acad Sci Eng Tech. 49: 90-92.