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Phosphate Solubilization and Mobilization in Soil Through Microorganisms Under Arid Ecosystems

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1. Introduction

Phosphorous is going to be plant nutrient that will limit the agricultural production in the next millennium**.** It is a major growth-limiting nutrient, and unlike the case of nitrogen, there is no large atmospheric source that can be made biologically available (Ezawa et al., 2002). As regards the role of P, it stimulate root development and growth, gives plant rapid and vigorous start leading to better tillering, essential for many metabolic processes in plant life and for seed formation and organization of cells, encourages earlier maturity, In most soils, its content is about 0.05% of which only 0.1% is plant available (Achal et al., 2007). The total phosphorous content in arid soils in India ranges from 560 to 900 kg ha^{-1}, the available phosphorous is quite low i.e. 15-25 kg ha^{-1} (Dhir, 1977). The soils being poor in organic matter (1.5- 4.2 mg kg^{-1}), most of these phosphorous is present in inorganic form as calcium and aluminium phosphatase. About 20-25% of total phosphorous in arid soils of India is organic in nature and 68% organic phosphorous in the soil is present as phytin (Yadav & Tarafdar, 2007), which are not directly available to plants. Therefore application of phosphatic fertilizers to the soil is essential to maintain adequate amount of soluble P in the soil solution for optimum plant growth as well as to maintain soils sustainability. Efficiency of P fertilizer throughout the world is around 10-25% (Lindsay, 1979), and concentration of bioavailable P in the soil is very low reaching the level of 1.0 mg kg^{-1} soil (Goldstein, 1994). Phosphorous is taken up from the soil in the form of soluble orthophosphate ions; $H_2PO_4^{-1}$, HPO_4^{-2} and PO_4^{-3} and generally the availability of these ions to the plants is in the order of $H_2PO_4^{-1}$> HPO_4^{-3}>PO_4^{-3}. The type of the orthophosphate ion present in the soil is depending on soil reaction. At the relatively low pH of 4 to 5, orthophosphate usually exist as $H_2PO_4^{-1}$ ions. On increasing pH, first HPO_4^{-2} ions are formed which convert to PO_4^{-3} as the soil reaction become alkaline. Large amount of P applied as fertilizer enters in to the immobile pools through precipitation reaction with highly reactive Al^{3+} and Fe^{3+} in acidic soil and Ca^{2+} in calcareous or normal soils (Gyaneshwar et al., 2002; Hao et al., 2002). Although total P pool is high, only a part is available to plants. So, the release and mobilization of insoluble and fixed forms of P is an important aspect of increasing soil P availability. Soil

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microorganisms play an important role in mobilizing P mainly by bringing about pH changes in soil microenvironment and producing chelating substances.

2. Forms of phosphorous in soil

Mainly two forms of phosphorous namely organic and inorganic forms occur in soils and both are important to plants as source of phosphorous. The relative amounts of phosphorous in organic and inorganic forms vary gently from soil to soil.

2.1 Organic phosphorous

Organic phosphorous: Generally organic phosphorous represents about 50% of the total P in soils (varies between 4 and 90% in most soils). Most of the organic P compounds are esters of orthophosphoric acid and have been identified primarily as (1) Inositol phosphates, (2) phospholipids and (3) nuclic acids.

1. Inositol phosphate: It represents a series of phosphate esters ranging from monophosphates up to hexaphosphates. Phytic acid, which has an empirical formula $(CH)_6$ $(H_2PO_4)_6$, had six orthophosphate (H_2P) groups attached to each carbon atom in the benzene ring. Phytin (a Ca-Mg salt of phytic acid), is the most abundant of the known organophosphorous compounds in soils. The total proportion of inositol phosphates in soil is 10-50 per cent.
2. Phospholipids: Phospholipids, phosphorous containing fatty compounds, are insoluble in water but are readily utilized and synthesized by soil microorganisms. Some of the most common phospholipids are derivatives of glycerol. The rate of release of phospholipids from organic sources in soil is rapid. Phospholipids constitute 1-5% of total organic P in soils.
3. Nucleic acids: Nucleic acids occurs in all living cells and are produced during the decomposition of residues by soil microorganisms. Two distinct forms of nucleic acids, ribonucleic acid (RNA) and deoxyribonuclic acid (DNA) are release into the soil in greater quantities than inositol phosphates, and they are broken down more quickly. Nucleic acid constitutes 0.2 to 2.5% of total organic P in soil.

2.2 Inorganic phosphorous

Most inorganic phosphorous compounds in soil fall into one of the two groups: (1) those in which calcium is the most dominant controlling cation (calcium phosphate) and (2) those in which iron and aluminium are the controlling cations (iron and aluminium phosphate).

1. Calcium phosphates: The original natural source of phosphorous is the mineral apatite, a calcium phosphate that is nearly insoluble. Apatite minerals may be found in even the more weathered soils, especially in their lower horizons. This fact is an indication of the extreme insolubility and consequent unavailability of the phosphorous contained therein. The simpler compounds of calcium such as mono and dicalcium phosphates are readily available for plant growth. These compounds are present in extremely small quantities only because they easily revert to the more insoluble forms.
2. Iron and aluminum phosphate: In this group the compounds involved are probably hydroxy phosphates such as (a) strengite- iron phosphate and (b) variscite-aluminum

phosphate. Strengite and variscite are too insoluble to contribute much to plant nutrition. The most common P minerals found in soils are presented in Table 1 in order of decreasing solubility.

Minerals	Chemical formula
Acid soils	
Strengite	$FePO_4.2H_2O$
Variscite	$AlPO_4.2H_2O$
Neutral and calcareous soils	
B-tricalcium phosphate	$Ca_3(PO_4)_2$
Dicalcium phosphate	$CaHPO_4$
Dicalcium phosphate dihydrate	$CaHPO_4.\ 2H_2O$
Fluorapatite	$Ca_5(PO_4)_3\ F$
Hydroxyapatite	$Ca_5(PO_4)_3\ OH$
Octacalcium phosphate	$Ca_4H(PO_4)_3.2\text{-}5\ H_2O$

Table 1. Common phosphorous (P) minerals found in acid, neutral and calcareous soils.

3. Phosphate solubilizing microorganisms

Evidence of the involvement of microorganisms in solubilization of inorganic phosphates was reported as early as 1903 (Kucey et al., 1989; Khan et al., 2007). Since then, extensive studies on the solubilization of mineral phosphates by microorganisms have been reiewed (Goldstein, 1986; Kucey et al., 1989; Tarafdar et al., 2003; Achal et al., 2007; Aseri et al., 2009). Phosphate solubilizing microorganisms (PSMs) are ubiquitous, and their numbers vary from soil to soil. Population of PSMs and organic matter content of some selected arid soils of Rajasthan, India was reported by (Venkateswarul et al., 1984) and presented in Table 2.

S.No.	Site	Soil classification	Organic matter (%)	P-solubilizing microorganisms ($\times 10^3\ g^{-1}$ soil)
1.	Barmer	Torripsamments	0.16	42.0
2.	Chandan	Calciorthids	0.11	16.0
3.	Churu*	Torripsamments	0.05	5.0
4.	Churu**	Torripsamments	0.10	0.37
5.	Degai	Calci-camborthids	0.74	1300
6.	Gowrisar	Torripsamments	0.11	123.0
7.	Jetpura	Calci-camborthids	0.63	220.0
8.	Jodhpur	Camborthids	0.31	240.0
9.	Masitwali	Torrifluvents	0.25	330.0
10.	Moulasar	Torripsamments	0.33	120.0
11.	Ramgarh*	Torripsamments	0.12	7.0
12.	Ramgarh**	Torripsamments	0.02	0.20

*Stabilized dunes; ** Unstabilized dunes

Table 2. Population of phosphorous solubilizing microorganisms and organic matter content of some selected arid soils of Rajasthan, India (Venkateswarul et al., 1984).

In general among the whole microbial population in soil P solubilizing bacteria constitute 1-50% and P solubilizing fungi 0.1 to 0.5% of the total respective population (Chen et al., 2006). Phosphate solubilizing bacteria generally out-number P solubilizing fungi by 2-150 folds (Banik & Dey, 1982; Kucey, 1983; Kucey et al., 1989; Alam et al., 2002). Most of the PSMs solubilize Ca-P complexes and only a few can able to solubilize Fe-P and Al-P (Kucey et al., 1989).Hence, these PSMs could be effective in calcareous soils in which Ca-P complexes are present, but not in other soils such as Alfisols in which phosphates are complexed with Fe and Al ions. Most P-solubilizing bacteria (Baya et al., 1981; Venkateswarul et al., 1984) and fungi (Venkateswarul et al., 1984; Tarafdar et al., 2003; Tarafdar & Gharu 2005; Achal et al., 2007; Yadav & Tarafdar 2007; Aseri et al., 2009; Yadav & Tarafdar 2010; Yadav & Tarafdar 2011) were isolated from the rhizosphere of various plant and are known to be metabolically more active than those isolated from sources other than rhizosphere. The phosphate solubilizing ability in bacteria was lost upon repeated sub culturing but no such loss has been observed in the case of phosphate solubilizing fungi. (Sperber, 1958; Kucey, 1983). In general, fungal isolates exhibit greater P- solubilizing ability than bacteria in both liquid and solid culture (Banik & Dey 1982; Venkateswarlu et al., 1984; Kapoor et al., 1989).

4. Mechanisms of phosphate solubilization

The potential mechanism for phosphate solubilization might be acidification either by protone extrusion associated with ammonium assimilation (De Freitas et al., 1997; Reyes et al., 1999) or by organic acids production and proton extrusion (Cunningham & Kuiack, 1992; Dutton & Evans, 1996; Nahas, 1996; Jones, 1998). Acid phosphatases and phytases secreated by these microorganisms also have an important role in phosphate solubilization (Richardson et al., 2000; Tarafdar et al., 2003; Aseri et al., 2009). Some phosphatase and phytase producing fungi from arid soils of Rajasthan, India were isolated by Tarafdar et al. (2003) and Aseri et al. (2009). Their phosphatase (acid & alkaline) and phytase secreting efficiency at different time intervals were presented in Table 3& 4 and Table 5.

S.No.	Fungal Species	Acid phosphatases activity (EU $\times 10^6$) g^{-1} dry fungal mat							
		Days after inoculation							
		7		14		21		28	
		I	E	I	E	I	E	I	E
1.	*Aspergillus candidus*	11.7	7.9	32.3	12.4	68.7	28.3	29.8	8.7
2.	*Aspergillus fumigatus**	26.3	10.4	52.7	58.8	69.2	24.9	21.6	10.4
3.	*Aspergillus niger*	13.6	8.7	39.8	29.3	65.6	19.3	14.7	12.3
4.	*Aspergillus parasiticus*	19.3	7.9	56.3	43.8	79.6	25.7	50.3	24.3
5.	*Aspergillus rugulosus*	14.9	11.4	16.3	13.5	27.9	11.1	14.3	7.9
6.	*Aspergillus terreus*	34.6	20.7	57.3	37.2	72.3	25.7	26.9	13.6
7.	*Penicillium rubrum*	10.4	4.3	21.3	12.9	43.6	18.9	13.4	6.9
8.	*Penicillium simplicissimum*	20.4	12.3	39.6	18.7	59.8	21.3	21.3	10.5
9.	*Pseudeurotium zonatum*	16.3	8.9	31.6	17.4	53.8	24.3	22.4	6.7
10.	*Trichoderma harzianum*	22.9	16.8	39.6	21.7	97.3	42.7	26.3	17.4
11.	*Trichoderma viride*	21.7	17.3	38.3	20.6	89.3	40.6	21.7	16.3
	LSD($p<0.05$)	1.2	0.6	2.1	1.0	3.9	2.1	0.8	0.4

*Adopted from Tarafdar et al. (2003), I=Intracellular, E= Extracellular

Table 3. Secretion of acid phosphatase by fungi at different time intervals (Aseri et al., 2009).

S.No.	Fungal Species	Alkaline phosphatases activity (EU × 10^6) g^{-1} dry fungal mat							
		Days after inoculation							
		7		14		21		28	
		I	E	I	E	I	E	I	E
1.	*Aspergillus candidus*	17.3	10.6	32.6	12.7	13.7	5.8	4.8	3.1
2.	*Aspergillus fumigatus**	14.3	5.2	15.5	9.7	9.7	5.7	4.2	2.4
3.	*Aspergillus niger*	5.4	3.2	8.9	5.4	6.6	3.4	4.9	2.6
4.	*Aspergillus parasiticus*	21.6	12.9	38.2	14.3	12.3	6.2	6.9	2.8
5.	*Aspergillus rugulosus*	5.6	3.7	9.1	5.6	6.9	3.2	4.6	2.9
6.	*Aspergillus terreus*	20.6	11.9	30.6	14.6	10.0	6.1	6.8	3.2
7.	*Penicillium rubrum*	4.6	2.8	7.2	4.9	6.1	3.4	3.9	1.2
8.	*Penicillium simplicissimum*	17.9	12.3	29.7	13.9	18.6	8.2	7.2	4.6
9.	*Pseudeurotium zonatum*	18.9	12.8	36.7	9.8	11.3	4.9	6.9	2.1
10.	*Trichoderma harzianum*	28.6	18.3	45.7	18.4	16.2	7.3	8.9	3.6
11.	*Trichoderma viride*	21.9	16.3	42.8	12.8	14.9	7.8	7.6	4.9
	LSD($p<0.05$)	0.5	0.8	1.1	1.3	1.0	0.2	0.3	0.2

*Adopted from Tarafdar et al. (2003), I=Intracellular, E= Extracellular

Table 4. Secretion of alkaline phosphatase by fungi at different time intervals (Aseri et al., 2009).

S.No.	Fungal Species	Phytase activity (EU ×10^6) g^{-1} dry fungal mat							
		Days after inoculation							
		7		14		21		28	
		I	E	I	E	I	E	I	E
1.	*Aspergillus candidus*	0.16	10.1	0.11	6.2	0.04	3.6	0.02	0.9
2.	*Aspergillus fumigatus**	NE	NE	NE	NE	NE	NE	NE	NE
3.	*Aspergillus niger*	0.16	6.2	0.12	5.2	0.08	4.1	0.04	1.2
4.	*Aspergillus parasiticus*	0.20	10.4	0.12	7.1	0.08	4.2	0.03	1.0
5.	*Aspergillus rugulosus*	0.11	6.1	0.09	3.2	0.02	2.1	0.01	0.3
6.	*Aspergillus terreus*	0.19	10.2	0.10	6.9	0.06	4.1	0.01	0.9
7.	*Penicillium rubrum*	0.12	7.2	0.09	4.1	0.06	3.2	0.02	0.8
8.	*Penicillium simplicissimum*	0.14	6.9	0.09	4.0	0.04	2.1	0.02	0.3
9.	*Pseudeurotium zonatum*	0.19	7.0	0.06	3.9	0.02	1.9	0.01	0.4
10.	*Trichoderma harzianum*	0.16	12.8	0.12	8.9	0.08	4.3	0.06	1.2
11.	*Trichoderma viride*	0.15	11.9	0.12	7.6	0.06	3.9	0.01	1.4
	LSD($p<0.05$)	0.02	0.4	0.01	0.3	0.01	0.1	0.001	0.1

*Adopted from Tarafdar et al. (2003); NE-Not estimated, I=Intracellular, E= Extracellular

Table 5. Secretion of phytase by fungi at different time intervals (Aseri et al., 2009).

Phosphorous solubilization is carried out by a large number of saprophytic bacteria and fungi acting on sparingly soluble soil phosphates, mainly by chelating-mediated mechanism (Bajpai & Sundara Rao, 1971; Moghimi et al., 1978; Whitelaw 2000). Inorganic P is solubilized by the action of organic and inorganic acids secreted by PSMs in which hydroxyl and carboxyl groups of acids chelate cations (Ca, Al and Fe) and decrease the pH in basic soils (Kpomblekou & Tabatabai, 1994). The PSMs also dissolved the P through production acids such as (acetate, lactate, oxalate,tartatate,succinate, citrate, gluconate, ketogluconate and glycolate (Banik &Dey, 1982; Goldstein,1986; Cunningham & Kuiack, 1992; Goldstein, 1995; Gyaneshwar et al., 1998; Kim et al., 1997,1998; Deubel et al., 2000) and lowering the pH of the rhiosphere. The pH of the rhizosphere is lowered through biotical production of proton/ bicarbonate release (anion/ cation balance) and gaseous (O_2/CO_2) exchanges. Release of root exudates such as organic ligands can also alter the concentration of P in the soil solution (Hinsinger, 2001).The organic acids produed by PSMs solubilize insoluble phosphates by lowering the pH, chelation of cations and competing with phosphate for adsorption sites in the soil (Nahas, 1996). Inorganic acids such as hydrocholoric acid can also solubilize phosphate but they are less effective compared to organic acids at the same pH (Kim et al., 1997). In certain cases phosphate solubilization is induced by phosphate starvation (Gyaneshwar et al., 1999). Organic phosphates is catalysed through hydrolysis of C-O-P ester bond by phosphatase and phytase released by PSMs (Tarafdar & Rao, 1996; Tarafdar et al., 2001; Yadav & Tarafdar, 2007; Yadav & Tarafdar, 2010; Yadav & Tarafdar, 2011). The efficiency of different phosphatase and phytase secreating fungi isolated from arid soils of Rajasthan, India to hydrolyse different organic P compounds were reported (Tarafdar et al., 2003; Aseri et al., 2009) and presented in Table 6.

		Efficiency µg P release * min^{-1}	
S.No.	Fungal species	Phytin	Glycerophosphate
1.	*Aspergillus candidus*	2.72	4.72
2.	*Aspergillus niger*	1.72	2.46
3.	*Aspergillus parasiticus*	3.21	5.12
4.	*Aspergillus rugulosus*	0.98	1.82
5.	*Aspergillus terreus*	3.09	4.98
6.	*Penicillium rubrum*	2.16	2.90
7.	*Penicillium simplicissimum*	2.21	2.99
8.	*Pseudeurotium zonatum*	2.59	3.62
9.	*Trichoderma harzianum*	3.54	5.89
10	*Trichoderma viride*	3.32	5.46
	LSD($p<0.05$)	0.64	0.71

*Initial P added 500ppm either as phytic acid or as Na- glycerophosphate

Table 6. Efficiency of fungal mat of different fungi to hydrolyze different organic P compounds (Aseri et al., 2009).

5. Solubilization of calcium phosphate (Ca-P)

Soil phosphates mainly the apatites and metabolites of phosphatic fertilizers are fixed in the form of calcium phosphates in alkaline conditions under arid and semi arid region. Many of

the calcium phosphates, including rock phosphate ores (fluoroapatite, francolite), are insoluble in soil with respect to the release of inorganic P (Pi) at rates necessary to support agronomic levels of plant growth (Goldstein, 2000). Phosphate solubilizing microorganisms could increase the P nutrition of plants through increased solubility of Ca-phosphates (Sujatha et al., 2004; Vassilev et al., 2006) and their solubility increases with a decrease of soil pH. Phosphate solubilization is the result of combined effect of pH decrease and organic acids production (Fankem et al., 2006). Microorganisms through secretion of different types of organic acids (Deubel et al.,2000; Deubel & Merbach, 2005) and rhizospheric pH lowering mechanisms (He & Zhu, 1988; Hinsinger,2001) dissociate the bound forms of phosphate like $Ca_3(PO_4)_2$. Nevertheless, buffering capacity of the medium reduce the effectiveness of PSMs in releasing P from tricalcium phosphates (Stephen & Jisha, 2009). Acidification of the microbial cell surroundings releases P from apatite by proton substitution / excretion of H^+ (accompanying greater absorption of cations than anions) or release of Ca_2^+ (Illmer & Schinner 1995; Villegas & Fortin 2002). While, the reverse occurs when uptake of anions exceeds that of cations, with excretion of OH^- / HCO_3^- exceeding that of H^+ (Tang & Rengel, 2003). Carboxylic anions produced by PSMs, have high affinity to calcium, solubilize more phosphorus than acidification alone (Staunton & Leprince, 1996). Complexing of cations is an important mechanism in P solubilization if the organic acid structure favors complexation (Fox et al., 1990). It is controlled by nutritional, physiological and growth conditions of the microbial culture (Reyes et al., 2007), but it is mostly due to the lowering of pH alone by organic acids (Moghimi & Tate, 1978) or production of microbial metabolites (Abd- Alla, 1994). Organic anions and associated protons are effective in solubilizing precipitated forms of soil P, chelating metal ions that may be associated with complexed forms of P or may facilitate the release of adsorbed P through ligand exchange reactions (Jones, 1998). Calcium phosphate (Ca-P) release results from the combined effects of pH decrease and carboxylic acids synthesis, but proton release cannot be the single mechanism (Deubel et al., 2000).

6. Solubilization of Iron phosphate / aluminum phosphate (Fe-P / Al-P)

Solubilization of Fe and Al occurs via proton release by PSMs by decreasing the negative charge of adsorbing surfaces to facilitate the sorption of negatively charged P ions. Proton release can also decrease P sorption upon acidification which increases $H_2PO_4^-$ in relation to HPO_4^{2-} having higher affinity to reactive soil surfaces (Whitelaw, 2000). Carboxylic acids mainly solubilized Al-P and Fe-P (Khan et al., 2007; Henri et al., 2008) through direct dissolution of mineral phosphate as a result of anion exchange of PO_4^{3-} by acid anion, or by chelation of both Fe and Al ions associated with phosphate (Omar, 1998). It is through root colonizing pseudomonads with high-affinity iron uptake system based on the release of Fe^{3+} chelating molecules i.e. siderophores (Altomare et al., 1999). Moreover, carboxylic anions replace phosphate from sorption complexes by ligand exchange (Otani et al., 1996; Whitelaw, 2000) and chelate both Fe and Al ions associated with phosphate, releasing phosphate available for plant uptake after transformation. Ability of organic acids to chelate metal cations is greatly influenced by its molecular structure, particularly by the number of carboxyl and hydroxyl groups. Type and position of the ligand in addition to acid strength determine its effectiveness in the solubilization process (Kpomblekou & Tabatabai, 1994).

7. Mineralization of organic phosphate

Mineralization of soil organic P plays an imperative role in phosphorus cycling of a farming system. Organic P may constitute 4-90 % of the total soil P. Almost half of the microorganisms in soil and plant roots possess P mineralization potential under the action of phosphatases (Tarafdar et al., 1988). Mineralization of organic to inorganic phosphate involves processes catalyzed by phosphatase enzymes, which are specifically involved in this conversion. Acid and alkaline phosphatases use organic phosphate as a substrate to convert it into inorganic form (Beech et al., 2001). Principal mechanism for mineralization of soil organic P is the production of acid phosphatases (Hilda & Fraga, 2000). Release of organic anions, and production of siderophores and acid phosphatase by plant roots / microbes (Yadav & Tarafdar, 2001) or alkaline phosphatase (Tarafdar & Claasen, 1988) enzymes hydrolyze the soil organic P or split P from organic residues. Many PSMs produce these enzymes (Tarafdar et al., 1988; Tarafdar et al., 2003; Aseri et al., 2009). In addition, some fungi produce phytase, an enzyme which releases soluble inorganic (PO_4^{3-}) phosphate from organic P compound (inositol hexaphosphate) (Tarafdar & Gharu, 2005; Yadav & Tarafdar 2007; Yadav & Tarafdar 2011). Some heterotrophic micro-organisms are also capable of solubilizing phosphates combined with calcium or magnesium (Atlas & Bartha, 1998). These soluble forms can now be readily taken up by plants, algae, cyanobacteria, and autotrophic bacteria and assimilated into organic cellular components such as DNA, RNA, and ATP. Phosphatase enzymes are present in all organisms but only bacteria, fungi, and some algae are able to secrete them outside of their cells. As exoenzymes, they participate in the dissolution and mineralization of organic phosphate compounds in the environment (Jones, 2002).

8. Response of phosphate solubilizing microorganisms under arid ecosystems

The role of phosphate solubilizing microorganisms in native P solubilization and increasing crop yield under arid ecosystem of India has been studies (Tarafdar et al., 1992; Tarafdar et al., 1995; Tarafdar & Rao, 1996; Tarafdar & Graru, 2005; Yadav & Tarafdar, 2007; Yadav & Tarafdar, 2010; Yadav & Tarafdar, 2011). The work on P solubilization in soil using plant growth test have been carried out under green house conditions (Tarafdar et al., 1992; Tarafdar et al., 1995; Tarafdar & Rao, 1996; Tarafdar & Graru, 2005; Yadav &Tarafdar, 2010), although the results of field studies are also available (Tarafdar & Graru, 2005; Yadav & Tarafdar, 2007; Yadav & Tarafdar, 2010; Yadav & Tarafdar, 2011). The effectiveness of inoculation with phosphate solubilizing microorganisms has been found to vary with the soil physico-chemical properties and the test crop.

Under green house conditions Tarafdar et al. (1992, 1995) and Tarafdar & Rao (1996) studied the effect of different phosphatase- producing fungi on growth and nutrition of mungbean, clusterbean, wheat and chickpea. They reported a significant increase in phosphatase, nitrogenase and dehydrogenase activity after inoculation with different phosphate solubilizing fungi (Table 7 & 8). Inoculation with phosphatase producing fungi significantly increased dry matter production and grain yield (Table 9).

Treatments	Acid phosphatase†	Alkaline phosphatase†	Dehydrogenase‡	Nitrogenase ∫
Un-inoculated control	7.5	8.6	2.4	0.4
Aspergillus niger	8.1*	9.0*	3.3**	1.0***
Aspergillus fumigatus	8.0*	9.9***	3.1*	1.3***
Aspergillus rugulosus	4.8**	10.8***	5.3***	1.4***
Aspergillus terreus	8.9***	9.4**	5.9***	0.7*

†=n Kat $100g^{-1}$soil;‡ =p Kat g^{-1} soil; ∫= μ mole C_2H_4 h^{-1} $plant^{-1}$;
*p<5% ; ** p<1%; *** p<0.1%

Table 7. Effect of inoculation with phosphatase-producing fungi on rhizosphere enzyme activities in clusterbean (Tarafdar et al., 1995).

Treatments	Dehydrogenase†			Acid phosphatase‡			Alkaline phosphatase‡		
	NR[W]	Chickpea	Wheat	NR	Chickpea	Wheat	NR	Chickpea	Wheat
Control	10.6	11.9	12.4	25.0	66.1	38.1	71.1	72.1	71.1
Aspergillus niger	10.4	16.3[c]	15.6[c]	25.0	78.6	49.1[c]	69.1	75.1[a]	85.6[c]
Aspergillus fumigatus	10.1	14.5[c]	14.3[a]	24.5	91.6[c]	51.1[c]	72.6	72.6	87.6[c]
Aspergillus rugulosus	11.7	16.3[c]	15.0[b]	29.0[a]	78.6[b]	46.1[b]	80.6[a]	81.6[c]	88.6[c]
Aspergillus terreus	11.2	15.8[c]	14.0[a]	25.5	85.6[c]	45.1[a]	86.1[c]	86.6[c]	87.1[c]

†= μg TPF kg^{-1} per 24 h;‡= μg pNP g^{-1} h^{-1}; [W] = soil without plant (a=p<5%; b= p<1%; c =p<0.1%)

Table 8. Dehydrogenase and phosphatase activities as influenced by inoculum with *Aspergillus* in rhizosphere and non-rhizosphere soils. (Tarafdar and Rao, 1996).

Treatments	Yield (g $plant^{-1}$)					
	Clusterbean		Chickpea		Wheat	
	Dry matter	Grain	Dry matter	Grain	Dry matter	Grain
Control	20.8	5.4	2.1	2.0	4.7	1.6
Aspergillus niger	24.1*	6.3*	2.2	2.9*	8.0***	2.1*
Aspergillus fumigatus	26.5***	6.9**	3.2*	3.6***	8.7***	2.3**
Aspergillus rugulosus	27.2***	7.1***	4.0***	3.7***	7.8***	2.7***
Aspergillus terreus	24.4**	6.3*	3.2*	3.6***	6.7***	2.5***

*p<5% ; ** p<1%; *** p<0.1%

Table 9. Effect of inoculation with phosphatase-producing fungi on dry matter production and grain yield of clusterbean, chickpea and wheat (Tarafdar et al., 1995; Tarafdar and Rao, 1996).

They also observed significant improvement in the uptake of major and micronutrients (Table 10 & 11).

Treatments	N†	P†	K†	Ca‡	Mn‡	Na‡
Uninoculated control	19.0	1.8	3.8	86	216	125
Aspergillus niger	26.1**	2.1*	4.2	111**	244*	129
Aspergillus fumigatus	29.7***	2.2*	4.7*	101*	320***	137
Aspergillus rugulosus	31.5***	2.2*	4.2	108**	288***	106
Aspergillus terreus	24.9*	2.1*	4.2	114***	241*	96*

† = mg g-1;‡=mg kg-1; *p<5% ; ** p<1%; *** p<0.1%

Table 10. Effect of inoculation with phosphatase-producing fungi on mineral uptake by clusterbean (Tarafdar et al., 1995).

Treatments	Concentration (mg kg^{-1})			
	Fe	Mn	Cu	Zn
Uninoculated control	3.4	5.0	8.0	6.2
Aspergillus niger	4.9***	5.0	7.2*	8.1*
Aspergillus fumigatus	5.9***	5.5	7.5	8.2*
Aspergillus rugulosus	4.4***	4.9	9.9*	8.7***
Aspergillus terreus	5.1***	5.2	9.8*	8.0*

*p<5%; ** p<1%; *** p<0.1%

Table 11. Effect of inoculation with phosphatase-producing fungi on uptake of some trace elements by clusterbean (Tarafdar et al.,1995).

Further, Yadav et al. (2009) conducted an experiment with *Chaetomium globosum* and organic matter on P mobilization and yield of clusterbean under arid ecosystem. They observed increase in acid phosphatase (15%), alkaline phosphatase (12%) and phytase by 71% more due to inoculation of *C. globosum* with organic matter compared to application of only organic matter. They also reported the seed yield of clusterbean increased by 7.4% with *C. globosum* in the presence of high level of organic matter. In general 6%, 23% and 10% more N, P and K accumulation in plant was recorded due to inoculation of *C. globosum.*

Under field conditions (Tarafdar & Gharu, 2005; Yadav & Tarafdar, 2007, 2010 & 2011) reported significant increased in yield and P content of pearl millet and clusterbean in arid ecosystem after inoculation with different P solubilizing fungi. In pearl millet an increase in dry matter production by 29-39% and P concentration in shoot by 14-19%, in root by 5-7% and seed by 34 to 35% was reported with irrespective inoculation of seed with *Chaetomium globosum, Emericella rugulosa* and *Penicillium purpurogenum.* The experiment conducted by Yadav and Tarafdar (2010) reported that grain yield of clusterbean was increased by 26% and straw yield by 42%, plant P content by 12% and seed P content by 10% due to inoculation of *Emericella rugulosa*. The comparison of results from different experiments is difficult because of the variation in the rainfall of the cropping season, soil properties and phosphate solubilizing microorganisms. Generally, the positive response of the phosphate solubilizing microorganisms have been observed high organic matter content and low P availability under arid ecosystem of Rajasthan, India.

9. Conclusion

The arid ecosystem extended over the earth from the tropical to the sub-alpine zones and mean sea level to above 3000 m. In Indian arid zone average rainfall varies from as low as 100 to 400 mm with different drought intensities. Annual crop can hardly be cultivated under moderate to severe drought conditions. With increase in both human and population in Indian arid zone, the demand for grain, fodder and fuel wood is increasing. But the agricultural production is low owing to the poor soil fertility and occurrence of frequent droughts. So, the enhancement of soil fertility thus assumes a great significance for sustained agriculture production in drought prone areas. Given the socio-economic conditions of the farmers, the extensive use of chemical fertilizers to augment the crop production is a risky proposition. Besides, use of only chemical fertilizers may result in degradation of soil productivity/health as has happened in other ecosystems. The use of P solubilizing microorganisms as a P biofertilizer under arid ecosystem may improve the soil fertility and increase the crop production to fulfill the requirement. Further, the efficiency of these microorganisms to meet P requirement of crops will depend greatly on their impact under practical farming conditions.

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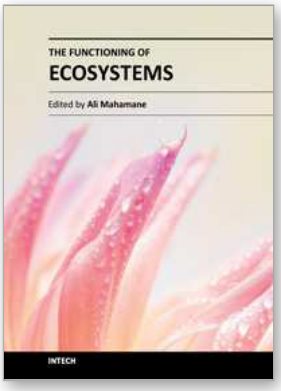

The Functioning of Ecosystems

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The ecosystems present a great diversity worldwide and use various functionalities according to ecologic regions. In this new context of variability and climatic changes, these ecosystems undergo notable modifications amplified by domestic uses of which it was subjected to. Indeed the ecosystems render diverse services to humanity from their composition and structure but the tolerable levels are unknown. The preservation of these ecosystemic services needs a clear understanding of their complexity. The role of the research is not only to characterise the ecosystems but also to clearly define the tolerable usage levels. Their characterisation proves to be important not only for the local populations that use it but also for the conservation of biodiversity. Hence, the measurement, management and protection of ecosystems need innovative and diverse methods. For all these reasons, the aim of this book is to bring out a general view on the biogeochemical cycles, the ecological imprints, the mathematical models and theories applicable to many situations.

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