Microbial Inoculants and Nutrient Use Efficiency

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The use of chemical fertilizers to enhance crop productivity has affected the biogeochemical cycles negatively and the leaching and run-off of nutrients from chemical fertilizers have led to environmental degradation. One of the main reasons for these problems is the low nutrient use efficiency of chemical fertilizers (Adesemoye and Kloepper 2009). Nutrient use efficiency (NUE) can be defined in many ways like agronomic efficiency (kg grain yield increase/kg nutrient applied), physiological efficiency (kg grain yield increase/kg nutrient taken by crop) and chemical efficiency or apparent recovery (kg nutrient taken up per kg nutrient applied). Low efficiency of applied nutrients is one of the main constraints in crop production and it is a major global concern with regards to food security for an ever increasing global population (Gosh et al., 2015). In India in the past few decades use efficiencies for major nutrients like N, P and K remained constant at 30-35 %, 15-20 % and 35-40 % respectively (Tarrafdar et al., 2015). This means a large quantities of nutrients applied are lost which not only add cost by way of fertilizer application but also cause detrimental effects in the environment like eutrophication and nitrate pollution. Nutrient use efficiency can be increased through various means like manipulation of application techniques, coating fertilizers like in the case of urea; it is coated with different materials like neem, sulfur, gypsum, plastic and mud ball so as to have slow release of nitrogen. An ecologically supreme way of improving nutrient use efficiency is harnessing plant microbe interactions, as it cause zero damage to the ecosystem. It is widely believed that a vast diversity of microorganisms inhabiting rhizosphere, phylloplane and as endophytes assists plants in uptake of mineral nutrients and various other growth factors and through which they ensure better plant productivity and hence an improved nutrient use efficiency. Agriculturally important microorganisms can positively influence on the use efficiencies of different plant nutrients like N, P, K and many other secondary and micronutrients.

Microbes in P use efficiency

Phosphorus is the second most important plant nutrient after nitrogen and it's an integral component of nucleic acids, phospholipids, important in cellular membrane and provides compounds for photosynthesis in plants (Rai et al., 2013). In soil P is present in large amounts but only a fraction of it is available to plants owing to very low solubility of phosphate salts in soils. Much of fertilizer phosphate applied to crop plants is fixed in soil and the total available phosphate in soil solution is 10 mM with very low mobility (Ryan et al., 2005). Plant evolved a multitude of strategies to increase P uptake thereby increasing P use efficiency. Arbuscular mycorrhizal (AM) symbioses is the most wide spread strategy used by plants to improve P use efficiency. AM symbioses is a special kind of symbiotic relationship in which the micro partner (fungi) helps in P uptake and mobility in the macro partner (plants) and macro partner provides sugars and space for colonisation to the micro partner. AM symbioses, because of its large surface area can contribute to plant nutrition uptake especially phosphorus uptake. Since phosphorus is highly immobile element the left over phosphates which are not absorbed by plants are easily absorbed in the bulk soil and hence a phosphate free zone occurs in the rhizosphere. But, the extraradical mycelium formed by fungal partner can extend beyond this phosphate free zone and help plants in absorbing phosphate available at a far-off distance from roots thereby making the otherwise unavailable phosphates to available phosphates (Roy-Bolduc and Hijri, 2011). *Glomus*, *Gigaspora*, *Scutellospora*, *Acaulospora* and *Entrophospora* are the most commonly occurring AM fungi (AMF) and they are obligate symbionts (Bagyaraj et al., 2015). The role of AM fungi in improving P use efficiency and general growth parameters is established in different crops by various research groups. Beneficial effects seen by AM fungi inoculation in different crops are given in Table 1. Apart from AM fungi there is one more function group of microorganisms called phosphorus solubilizers which improve phosphorus use efficiency alike AM fungi. Unlike AM fungi phosphorus solubilizers are not involved in P mobilization, but they solubilize fixed phosphates to available phosphates. A number of phosphorus solubilizing microorganisms have been utilized for tackling the phosphorus fixation problem in the soil. A few to name are *Pseudomonas striata*, *P.fluorescens*, *Bacillus megaterium* and *Aspergillus* sp. Such phosphorus solubilizing microorganisms can be used singly or in combination with other microbial inoculants like AM fungi and nitrogen fixers.

Microbes in N use efficiency

Nitrogen is the primary nutrient and it is an important constituent of proteins, enzymes, nucleic acids and plays an major role in establishment and maintenance of photosynthetic capacity, photosynthetic activity and sink capacity. Hence nitrogen is the fundamental nutrient for crop production and global food security (Herera et al., 2016). Since the availability of nitrogen in the easily absorbable form is limited in soil external application of nitrogen becomes an absolute need. But much of the N applied to soil does not find its fate in plant absorption. Only 30-35 % of the applied nitrogen is taken up by plants and the remaining is either fixed in soil or lost to the environment in the form of leaching and gaseous loss. Considering the cost of fertilizer nitrogen and the ill effects of lost nitrogen it is necessary to improve the nitrogen use efficiency. The use of microbial inoculants to improve nitrogen use efficiency is an ecofriendly option available to the farmers. Inoculation with rhizobacteria, *Bacillus simplex* and *Bacillus flexus* in wheat has shown to improve nitrogen use efficiency and grain quality (Barneix et al., 2005).In another study Adesemoye and his group of researchers have shown that reduction of chemical fertilizers by 25 % then the recommended dose and supplementing with application of a PGPR formulation (*Bacillus amyloliquefaciens* IN937a and *Bacillus pumilus* T4), has resulted in the same level of plant growth, yield, nitrogen and phosphorus uptake as that of full dose of fertilizers. When it was further supplemented with AMF *Glomus intraradices* the same effect was achieved even with 70% of recommended dose of fertilizers (Adesemoye et al., 2009). Nitrogen fixing bacteria both symbiotic (Rhizobia) and free living (*Azotobacter*, *Azospirillum* and various N fixing cyanobacteria) are also known to improve nitrogen use efficiency and also can provide atmospheric nitrogen. Hence inoculation with nitrogen fixing bacteria either at the time of sowing or at frequent intervals in the crop growth stages can reduce the application of chemical fertilizers. Arbuscular mycorrhizal fungi is known for increasing uptake of nitrogen and other plant nutrients just as they improve the uptake of phosphorus

Microbes for use efficiency of potassium

Potassium (K) is the third most important plant nutrient which plays a key role in growth, metabolism and development of plants. An adequate supply of potassium to crop plants leads to well-developed roots, fast growth and increased resistance to pests and diseases. Potassium, once thought of being adequate in Indian soils has been reported to be low in 21 % of Indian soils and medium in 51 % of arable land (Hasan 2002). Hence there is a need of immediate K fertilization of 72 % of Indian agricultural soils. Since the cost of potash fertilizer is dependent on global market it's getting costlier every year which increases the cost of cultivation. An alternate option is use of microbe mediated technologies to improve potash use efficiency so that the input of potash fertilizer can be kept at a bare minimum. K use efficiency can be improved by inoculation of crop plants with potash solubilizing microorganisms and AM fungi. Organic acids produced by microbial inoculants are able to chelate metal and mobilize K from K containing minerals and it was reported that inoculation of PGPR *Bacillus edaphicus* NBT improved K uptake (Sheng and He 2006). Field trial were carried out with a PGPR (*Bacillus* sp.) and AMF (*Glomus intraradices*) in maize across two tillage system (no till and conventional tillage). It was shown that treatment of AMF in combination with PGPR improved the uptake of K along with N and P across the tillage systems (Adesemoye et al., 2008). Co-inoculation of K solubilizing microorganisms with K and P bearing minerals improve plant K and P uptake in sorghum across three different types of soils (Badar et al., 2006).

Microbes in use efficiency of other minerals

Microbial inoculants have been shown to improve use efficiency of many other elements in addition to N, P and K. *Mesorhizobium mediterannium* when inoculated in barley and chickpea has shown to improve uptake of Ca and Mg along with N, P and K uptake (Peix et al., 2001). *Pseudomonas mendocina* in combination with AMF (*Glomus intraradices* and *G. mosseae*) have shown to improve the uptake of Ca, Fe and Mn along with improved uptake of N and P in lettuce (Kohler et al., 2008). Application of AMF (*Glomus macrocarpum*) to *Sesbania aegyptiaca* and *Sesbania grandiflora* has shown an increased Mg uptake (Giri and Mukerji 2004). Mycorrhizal fungi are also shown to improve uptake of Zn, Fe, Cu and Mn in maize (Liu et al 2000). AM fungi have been shown to improve use efficiency of all major and micronutrients since they increase the surface are of roots.

Conclusion

Incorporation of microbial inoculants technology as a component of integrated nutrient management has dual benefit of high crop productivity in the short term and sustained production without deteriorating the soil health in the long term. Although a plenty of microbial inoculants are available to increase nutrient use efficiency, it has to be considered that no microbial inoculant is universal as their activity depends on soil type, plant grown and various other edaphic and climatic factors. Hence there is a need for widespread studies on different microbial inoculants for improving nutrient use efficiency of different crops under varied agro-climatic conditions.

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Table 1: Effect of AM fungi inoculation on P use efficiency of different crop plants.

Crop	**AM fungi inoculated**	**Response**	**Research group**
Wheat	*Glomus mosseae*	Increased grain yield of up to 25.8 %; Increased protein content and wet gluten content	Kumar et al., 2011
Rice and Mung bean in intercrop	*Glomus caledonium*	Intercropping and AM inoculation increased total P uptake by 57% in rice, total P and N acquisition by 65% and 64% respectively in mung bean, and nodulation by 54% in mung bean	Li et al., 2009
Maize	*Glomus intraradices*	Increased available phosphate in the rhizosphere and in the bulk soil	Cozolino et al., 2013
Green gram	*Glomus fasiculatum, Glomus mosseae*	Grain yield (by 14.8 and 13.5%) and grain P content was significantly increased (by 21.95 and 20.97%), respectively.	Bhat et al. 2011
Tomato	*Glomus intraradices*	Increased N and P uptake in both drought stress and normal conditions	Subramanian et al., 2006
Chickpea	*Glomus fasciculatum*	Increase plant yield and nutrient uptake when AM fungi was inoculated with *Rhizobium* and a Phosphorus solubilizer *Pseudomonas striata*	Zaidi et al., 2003

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