Chapter 8
Application of Arbuscular Mycorrhizal Fungi in Production of Annual Oilseed Crops

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8.1 Introduction

Oilseed crops are the second most in importance after cereals and significantly contribute to the Indian economy. Oilseeds cover about 13 % of the total arable land and generate nearly 10 % of the total value of the agricultural products in India (Singh et al. 2006). The country grows nine dominant oilseed crops, with groundnut (*Arachis hypogaea* L.), soybean (*Glycine max* L. Merrill) and rapeseed-mustard (*Brassica juncea* L.) accounting for 87 % and 75 % of total oilseed production and acreage, respectively (Agricultural Statistics at a Glance 2004). In India, soybean is the premier oilseed crop and growing parallel with groundnut followed by rapeseed-mustard. When compared to other countries, the productivity of these oilseeds per unit area is very low in India and their productivity is declining due to the recurrence of drought, low nutrient use efficiency of crop, nutrient deficiency in soil and other biotic and abiotic stresses.

Microbial interactions with plant roots may involve either endophyte or free living microorganisms and can be symbiotic, associative or casual in nature.

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Beneficial symbionts include N_2-fixing bacteria (e.g. rhizobia) in association with legumes and interaction of roots with AM fungi, with the latter being particularly important in relation to plant P uptake (Richardson et al. 2009). Legume crops are generally cultivated in nutrient poor environments in India and have a high P requirement for nodule formation, nitrogen fixation and optimum growth. The mycorrhizal condition in legume crops increases vegetative growth and seed yield in addition to improving nodulation (Mathur and Vyas 2000).

During the past 50 years, the widespread use of chemical fertilisers to supply N and P has had a substantial impact on food production and has become a major input in crop production around the world (Tilman et al. 2002). However, further increases in N and P application are unlikely to be as effective at increasing yields (Wang et al. 2011) as only 30–50 % of applied N fertiliser and 10–45 % of P fertiliser are taken up by crops (Adesemoye and Kloepper 2009; Garnett et al. 2009). In addition, the abundant use of chemical fertilisers in agriculture has had some deleterious environmental consequences and is a global concern (Bohlool et al. 1992; Tilman et al. 2002).

The scientific community must look for alternate technologies which can play a major role in sustaining and increasing the productivity of oilseed crops. One approach could be the use of combinations of plant growth-promoting microorganisms (PGPMs) that can fix atmospheric nitrogen and solubilise or mobilise phosphorus, zinc and other soil nutrients to stimulate plant growth and improve soil health (Babalola 2010; Sharma et al. 2010).

The rhizosphere is the dynamic environment where much interaction takes place and AM fungi are important biotrophic plant associates. These fungi colonise the root cortex and develop an extrametrical mycelium which is a bridge connecting the roots with the surrounding soil microhabitats (Barea et al. 2005). They are obligate symbionts and require a host plant to complete their life cycle (Wardle et al. 2004). AM fungi form a symbiotic association with most agricultural crops and are able to increase plant nutrition and plant health (Jansa et al. 2009). In addition, AM fungi establishment in the root causes changes in the microbial community of the rhizosphere (Meyer and Linderman 1986; Marschner et al. 2001) and increases plant tolerance to a wide range of biotic and abiotic stresses (Auge et al. 2004; Whipps 2004; Jansa et al. 2009). Many studies have demonstrated on field crops, including oilseeds, the benefits of AM inoculation on plant nutrition (Cardoso and Kuyper 2006; Hamel and Strullu 2006), nodulation (Meghvansia et al. 2008; Aryal et al. 2006), N-fixation (Peoples and Craswell 1992) and plant protection (Whipps 2004; Doley and Jite 2013a, b) under ideal conditions.

Certain cooperative microbial activities involving plant growth-promoting microorganisms can be exploited as a low-input biotechnology and form a basis for a strategy to help sustainable, environment-friendly practices fundamental to the stability and productivity of agricultural ecosystems (Kennedy and Smith 1995). The purpose of this review is to discuss (i) the current status of major oilseed crops in India; (ii) the application of AM fungi (single and dual inoculation) in the plant growth, nutrition and control of soil-borne diseases associated with major oil seeds; (iii) the strategies of manipulating soil and agricultural practices to manage

indigenous AM fungi and quality performance and (iv) commercialisation possibilities of AM fungi.

8.2 Oilseed Crops of Global Importance

About one-third of the land area of the world comprises arid and semiarid climates. The increasing economic and agricultural utilisation of arid lands has emerged as a critical element in maintaining and improving the world's food supply (Zahran 1999). India plays a major role in global oilseeds and vegetable oil economy contributing about 15 % of the world's oil crops area of nine oilseeds (groundnut, soybean, rapeseed, mustard, sesame, sunflower, linseed, safflower and castor), 7 % of the world's oilseeds production and 6.7 % of vegetable oils production. However, the productivity in India is only 1,005 kg/ha as compared to the world average of 1,957 kg/ha (FAOSTAT). India has the largest area in groundnut, sesame, safflower and castor and ranks first in production of safflower, castor and sesame and ranked second in groundnut, third in rapeseed, fourth in linseed, fifth in soybean and tenth in sunflower (Table 8.1). In the domestic agricultural sector, oilseeds occupy a distinct position after cereals sharing 14 % of the country's gross cropped area and accounting for nearly 1.5 % of the gross national product and 7 % of the value of all agricultural products. India encompasses diverse agro-ecological conditions ideally suited for growing nine annual oilseed crops including groundnut, rapeseed-mustard, sunflower, sesame, soybean, safflower, castor, linseed and niger and two perennial oilseed crops (coconut and oil palm) and secondary oil crops such as maize and cotton. In addition to the above, more than 100 tree species of forest origin that have the potential to yield about one million tonnes of vegetable oil are grown in the country.

8.3 AM Fungi in the Production of Oilseed Crops

8.3.1 AM Fungi Inoculation Responses for Enhanced Growth and Nutrient Uptake

AM fungi are the most common type of association involved in agricultural systems. AM fungi are associated with improved growth of many plant species due to increased nutrient uptake, production of growth-promoting substances, induced tolerance to drought, salinity and transplant shock and synergistic interaction with other beneficial soil microorganisms such as N-fixers and P-solubilisers (Sreenivasa and Bagyaraj 1989). Symbiotic associations of plant roots with AM fungi can result in enhanced growth because of increased acquisition of P and nutrients with low mobility in soil. Effective nutrient acquisition by AM fungi is generally attributed to the extensive hyphal growth beyond the nutrient depletion

Table 8.1 Area, production and yield of oilseeds: global and Indian scenario (AICRPS 2009; Damodaram and Hegde 2010)

Oilseeds	Area ('000 ha)		Yield (kg/ha)		Production ('000 MT)		India's position in the world		Percent area to total oilseed area in India	Percent production to total oilseeds production in India
	World	India	World	India	World	India	Area	Production		
Groundnut	24,590	6,850	1,554	1,071	38,201	7,338	First	Second	22.37	25.86
Soybean	96,870	9,600	2,384	942	23,095	9,045	Fifth	Fifth	34.51	35.74
Safflower	691.44	350	890	643	615.21	225	First	First	1.07	0.68
Castor	1,524.7	880	1,037	1,276	1,580.6	1,123	First	First	3.14	4.22
Sunflower	25,024	2,050	1,424	542	35,643	1,112	Fourth	Tenth	6.58	4.18
Rapeseed and mustard	30,987	5,750	1,883	1,014	58,364	5,833	Third	Third	22.85	25.98
Linseed	2,437	550	903	296	2,200	163	Second	Fourth	1.48	0.61
Sesame	7,534	1,750	478	381	3,603	666	First	First	6.56	2.31

zone surrounding the root (Tisdale et al. 1995). In this way, AM fungi enable their host plants to gather mineral nutrients from a much larger volume of soil than the roots could reach on their own (Jansa et al. 2009).

8.3.1.1 AM Responses Under Glass House/Nursery and Field Conditions

AM fungi responses vary with AM fungal species used, soil pH, experimental conditions (Clark and Zeto 1996), root-geometry/architecture of the host plant which influences the nutrient uptake particularly soil supply of P and soil temperature (Raju et al. 1990). For example, in soybean, manganese (Mn) and iron (Fe), protection was more efficient when the plants were inoculated with *Glomus macrocarpum* than with *Glomus etunicatum*, whereas *Gigaspora margarita* was not effective with the inocula used (Cardoso and Kuyper 2006). Jalaluddin et al. (2008) found that the AM fungus *Scutellospora auriglobosa* increased the uptake of P in sunflower resulting in increased yield and reduced incidence of *Macrophomina phaseolina* which causes charcoal root rot in sunflower var. Helico-250 cultivated in Sindh region of Pakistan. Wang et al. (2011) while examining the tripartite symbiotic associations with rhizobia and AM fungi and correlating their relationships to root architecture as well as N and P availability of two soybean genotypes contrasting in root architecture grown in a field showed variable responses to AM fungi. The deep root soybean genotype had greater AM fungi colonisation at low P, but better nodulation with high P supply than the shallow root genotype. Co-inoculation with rhizobia and AM fungi significantly increased soybean growth under low P and/or low N conditions as indicated by increased shoot dry weight, along with plant N and P content. Moreover, the effects of co-inoculation were related to root architecture. The deep root genotype (HN112) benefited more from co-inoculation than the shallow root genotype (HN89).

AM fungal inoculation has been shown to reduce Mn and Fe toxicity in plants, and the concentration of Mn in shoots and roots of mycorrhizal plants can be lower than in non-mycorrhizal plants (Kothari et al. 1991; Nogueira et al. 2004). Mycorrhizal soybeans grew better and had lower shoot concentrations of Fe and Mn than did non-mycorrhizal soybeans under greenhouse conditions. In roots, the results were the same for Mn and the reverse for Fe. The decrease of Mn in shoots was attributed to reduced availability, while the decrease of Fe in the shoots was attributed to its retention in the roots. In excess, both Mn and Fe can be toxic to plants; thus, mycorrhizas may protect the plants from their toxicity (Nogueira et al. 2004).

Under field conditions, AM fungal inoculation enhanced biomass, nutrient uptake and yield of sesame applied with conventional P fertiliser (superphosphate) and slow release P source (rock phosphate) (Anil-Prakash and Tandon 2002). The influence of AM fungus on P and Fe uptake of mycorrhizal groundnut (*Arachis hypogaea* L.) and sorghum (*Sorghum bicolor* L.) plants was studied by Caris et al. (1998) using radiolabelled elements (^{32}P, ^{59}Fe). Plants possessing different strategies for the acquisition of Fe (Marschner 1995) were selected for this experiment. Groundnut is dicotyledonous and is a strategy I plant (Fe-deficiency

response: enhanced net excretion of protons from the roots, increased Fe-reducing capacity), while sorghum is monocotyledonous (graminaceous) and is a strategy II plant (Fe-deficiency response: enhanced release of phytosiderophores from the roots). In both plant species, P uptake from the labelled soil increased more in shoots of mycorrhizal plants than in non-mycorrhizal plants. Mycorrhizal inoculation had no significant influence on the concentration of labelled Fe in shoots of peanut plants. In contrast, ^{59}Fe increased in shoots of mycorrhizal sorghum plants. The uptake of Fe from labelled soil by sorghum was particularly high under conditions producing a low Fe nutritional status of the plants providing evidence that hyphae of an AM fungus can mobilise and/or take up Fe from soil and translocate it to the plant.

Meghvansia et al. (2008) reported variations in efficacy of different treatments (involving AM fungal species and cultivar-specific bradyrhizobia) with different soybean cultivars indicating the specificity of the inoculation response. This provides a basis for selection of an appropriate combination of specific AM fungi and *Bradyrhizobium* which could further be utilised for verifying the symbiotic effectiveness and competitive ability of microsymbionts under particular agro-climatic conditions. Inoculation response of single or mixed species of AM fungi to soybean has shown enhanced growth, mineral nutrition and nutrient uptake (Sharma et al. 2012a, b; Ilbas and Sahin 2005; Meghvansia et al. 2008; Waceke 2003; Sanginga et al. 1999). The role of mycorrhiza-mediated *Rhizobium* symbiosis on soybean showed enhanced production of soybean under field conditions (Antunes et al. 2006). Synergistic effects of AM fungi and *B. japonicum* have a high potential to improve the nutrient supply of soybean including P and soil quality (Meghvansia et al. 2008). However, a much larger genetic variability of bradyrhizobia and AM fungi strains exist in different cultivar regions than was assumed previously (Taiwo and Adegbite 2001). Soybean can form tripartite symbiotic associations with nodule-inducing rhizobia and AM fungi, which may benefit both P and N efficiency (Lisette et al. 2003). Co-inoculation of soybean roots with *B. japonicum* 61-A-101 considerably enhanced colonisation by the AM fungus *Glomus mosseae* and increased N and P uptake (Xie et al. 1995). El-Azouni et al. (2008) studied the associative effect of AM fungi with *Bradyrhizobium* as biofertilisers on growth and nutrient uptake of *Arachis hypogaea*. The biomass and grain yield were significantly improved by using the dual bio-preparations of AM fungi and *Bradyrhizobium*. The bacterial mycorrhizal-legume symbiosis increased nodule number, nitrogenase activity, total pigments and carbohydrate, protein and lipid content. The N, P and K uptake was significantly increased due to the single or dual inoculation. Moreover, inoculation with AM fungi and *Rhizobium* enhanced nodulation and yield of groundnut applied with inorganic P fertiliser (Mandhare et al. 1995; Lekberg and Koide 2005) and organic amendments (Iyer et al. 2003).

Mostafavian et al. (2008) showed that besides *Rhizobium*, inoculation of AM fungi with *Thiobacillus* increased soybean yield. Jackson and Mason (1984) found positive relationships among P availability, mycorrhizal colonisation and pod yield in groundnut (*Arachis hypogaea* L.). Mirzakhani et al. (2009) indicated that seed yield and yield components of safflower were influenced by inoculation with *Azotobacter* and AM fungi. They showed that inoculation of seeds with

Table 8.2 Examples of AM fungi responses (applied singly or combined) to enhance growth and mineral nutrition of major oilseed crops

AM fungi species	Interaction/significant treatments	Crop	References
G. fasciculatum	Phosphorus levels	Soybean	Ilbas and Sahin (2005)
Indigenous *Glomus* sp.	Crop rotation and *Rhizobium*	Soybean	Sanginga et al. (1999)
Mixed AM fungi	Conventional, GM soybean and *Bradyrhizobium* sp.	Soybean	Powell et al. (2007)
G. mosseae	Root architecture and *Bradyrhizobium* sp.	Soybean	Wang et al. (2011)
Glomus intraradices, *Acaulospora tuberculata*	*Bradyrhizobium japonicum*	Soybean	Meghvansia et al. (2008)
Gigaspora gigantea			
Glomus fasciculatum	*Pseudomonas striata*, P sources	Soybean	Mahanta and Rai (2008)
Glomus etunicatum	Salt stress	Soybean	Sharifia et al. (2007)
Glomus intraradices	Glyphosate, *Bradyrhizobium japonicum*	Soybean	Powell et al. (2009)
G. fasciculatum	*Pseudomonas striata*, Rock phosphate	Soybean	Mahanta and Rai (2008)
Glomus mosseae, *Glomus etunicatum*, *Gigaspora rosea*	Phosphatic fertilisers	Soybean	Bethlenflavay et al. (1997)
G. mosseae	Heavy metals, phosphatic fertilisers	Soybean	Dev et al. (1997)
G. mosseae	*Bradyrhizobium japonicum*	Soybean	Shalaby and Hanna (2000)
G. intraradices	Phosphorus application	Groundnut	Lekberg and Koide (2005)
Glomus caledonium	Salt stress	Groundnut	Gupta and Krishnamurthy (1996)
G. fasciculatum	*Rhizobium* and phosphatic fertilisers	Groundnut	Mandhare et al. (1995)
G. fasciculatum	Phosphatic fertilisers	Groundnut	Singh and Chaudhari (1996)
Glomus sp.	*Bradyrhizobium*	Groundnut	Elsheikh and Mohamedzein (1998)
G. intraradices	*Azotobacter chroococcum*	Safflower	Mirzakhani et al. (2009)
G. intraradices	*Azotobacter chroococcum*	Sunflower	Mirzakhani et al. (2009)
Glomus mosseae, *Glomus intraradices*	Heavy metals	Sunflower	Adewole et al. (2010)

(continued)

Table 8.2 (continued)

AM fungi species	Interaction/significant treatments	Crop	References
G. fasciculatum	Phosphorus levels	Sunflower	Chandrashekara et al. (1995)
G. fasciculatum	–	Linseed, niger	Srinivasulu and Lakshman (2002)
AM fungi	Rock phosphate	Sesame	Anil-Prakash and Vandana (2002)
G. fasciculatum	–	Castor	Sulochana and Manoharachary (1989)
G. constrictum			
Gigaspora sp.			

Azotobacter and AM fungi (*G. intraradices*) at the time of planting increased the grain yield of safflower to about 38 % over control plants. Groundnut is an important food legume of Egypt, and to enhance the production of groundnut, new reclaimed soils were brought under cultivation. The lack of indigenous soil populations of AM fungi and rhizobia has restricted potential yields of groundnut cultivated in this area. A summary of AM fungi inoculation responses for enhanced growth and nutrient uptake is stated (Table 8.2).

8.3.2 AM Fungi Responses in the Stressed Environments (Drought, Heavy Metals and Salinity)

AM fungal responses have also been encouraging in stressed environments like acid/salt (Gupta and Krishnamurthy 1996; Sharifia et al. 2007), drought (Ruiz-Lozano 2003; Auge et al. 2004; Manoharan et al. 2010; Liu et al. 2007), heavy metals (Göhre and Paszkowski 2006; Nogueira et al. 2004) and modified micro-environmental conditions such as genetically modified soybean (Powell et al. 2009). AM fungi have also been observed to play a role in metal tolerance (Del Val et al. 1999) and accumulation (Zhu et al. 2001; Jamal et al. 2002). For example, groundnut is a major cash crop in the semiarid tropics where it is mainly grown under rainfed conditions. Poor soil fertility, drought and diseases are important factors causing low yields. Groundnut forms symbiotic associations with two types of soil microorganisms, one with *Bradyrhizobium* and another with AM fungi. The positive effect of AM fungi on plant growth and development make mycorrhiza a potentially very useful biological resource of assuring high plant productivity, with minimum application of chemical fertilisers or pesticides. Quilambo (2002) studied the effects of two AM inoculants on root colonisation, leaf growth and dry matter accumulation and distribution in two groundnut cultivars: Local and Falcon. The indigenous Soil Mozambique inoculants significantly increased root colonisation, leaf growth and dry matter in both cultivars under drought stress conditions. The commercial Hannover inoculant increased growth

only under well-watered conditions. Drought stress effects could be alleviated by inoculation with Soil Mozambique inoculants. Therefore, peanut productivity, particularly under drought stress, may be improved by an adequate management of the AM symbiosis.

Most studies conducted on sunflower indicate that besides growth promotion, mycorrhizal colonisation of sunflower enhanced the ability to store more heavy metals in the roots. Adewole et al. (2010) found that AM inoculation to sunflower increased pollution tolerance to cadmium (Cd) and lead (Pb) and consequently increased the yield of sunflower. External mycelium of AM fungi provides a wider exploration zone (Khan et al. 2000; Malcova et al. 2003), thus providing access to greater volume of heavy metals present in the rhizosphere. However, the effectiveness of AM fungal isolates in improving plant growth also depends on the level of heavy metals in soil (Awotoye et al. 2009). Del Val et al. (1999) reported six AM fungal ecotypes showing consistent differences with regard to their tolerance to the presence of metals in soil. AM fungi may play a role in the protection of roots from heavy metal toxicity by mediating interactions between metals and plant roots (Leyval et al. 1997). Contaminated soils, which are often nutrient poor with low water-holding capacities, may provide an advantage to plants colonised by AM fungi by enabling them to act as pioneering species (Khan et al. 2000). Wu et al. (2004) used an intercropping system to examine the interactions of mycorrhizosphere and rhizosphere on metal uptake by growing mycorrhizal non-hyperaccumulator *Zea mays* and non-mycorrhizal hyperaccumulator *Brassica juncea* in a split-pot experiment. The intercropping system achieved higher phytoremediation efficiency in metal-contaminated soil, especially with dual inoculation of beneficial rhizobacteria and AM fungi. Similar studies were conducted by Zhang et al. (2004) who grew groundnut (leguminous crop) and maize (nonleguminous crop) and found that the iron-deficient maize released phytosiderophores which improved iron nutrition of groundnut through influencing its rhizosphere processes.

Among the biological approaches to enhance plant growth in saline conditions, the role of AM fungi is well established. Most native plants and crops of arid and semiarid areas are mycorrhizal, and it has been suggested that AM fungal colonisation might enhance salt tolerance of some plants (Tain et al. 2004). Under salt (base and acid) stress conditions, AM fungi response in terms of yield on groundnut was almost tripled in mycorrhizal plants compared with non-mycorrhizal control plants. Furthermore, they showed that AM inoculation promoted the establishment of groundnut plants under acid stress conditions (Gupta and Krishnamurthy 1996). Therefore, the additional beneficial effects of AM fungi in reducing salinity stress imposed on them (*Arachis hypogaea* var. *hypogaea* cv. Florunner) were studied by Al-Khaliel (2010) to understand the growth and physiological changes of groundnut plants under induced saline conditions. These investigations indicated that the AM fungi (*Glomus mosseae*) could improve growth of groundnut under salinity through enhanced nutrient absorption and photosynthesis. Chlorophyll content and leaf water content increased significantly under salinity stress by the inoculation with mycorrhizal fungi.

8.3.3 AM Fungi Inoculation Responses on the Control of Soil-Borne Diseases and Other Plant Pathogens

8.3.3.1 Influence of AM Fungi on Soil-Borne Diseases

The potential for AM fungi to suppress root diseases caused by soil-borne pathogens (Dehne 1982; Linderman 1994) has been intensively studied. *Sclerotium rolfsii* is an important soil-borne pathogen and causes disease in numerous crops including groundnut. The loss of yield caused by pathogen infection generally is 25 %, but it can be as high as 80–90 % (Grichar and Bosweel 1987). AM fungi have been shown to influence fungal diseases caused by root pathogens (Karagiannidis et al. 2002). Most studies concluded that disease severity could be reduced by root colonisation of AM fungi through several mechanisms including increasing the mineral absorption and plant growth (Smith and Read 1997), phenolic compounds (Devi and Reddy 2002) and pathogenesis-related proteins (Pozo et al. 1999). Ozgonen et al. (2010) studied the effects of AM fungi against stem rot caused by *Sclerotium rolfsii* Sacc. in groundnut. In field trials, the effect on disease locus of AM fungi ranged between 30 and 47 % with AM fungi differing in their benefit.

Disease and poor soils are considered to be the main causes of loss in the groundnut production. Rosette virus disease (RVD) and *Cercospora* leaf spots (CLS) are the major worldwide diseases that infect groundnut plants. In Cameroon, up to 53 % loss has been estimated (Fontem et al. 1996). CLS are caused by *Cercospora arachidicola* Hori (early leaf spot) and *Cercosporidium personatum* (Berk. and Curt.) Deighton (late leaf spot). Depending on the moment of contamination during the growing season, groundnut plants infected by RVD do not produce pods and, consequently, do not give any harvest (Savary 1991). Management against phytoviruses is very difficult because viral infection can be transmitted through seeds and also through some insect vectors (*Aphis* sp.). Strullu et al. (1991) showed that the symbiosis between mycorrhizas and roots of many crops has a positive influence on the plant's nutrition and in protection against some diseases. Zachee et al. (2008) determined the effect of mycorrhizal inoculation on the development of diseases (RVD and CLS) and on the physiology of groundnut plants (variety A-26) infected by RVD. A urea treatment and an absolute control were also used. It was observed that root colonisation rate was very low in control and urea plots compared to mycorrhiza-inoculated plots. Mycorrhizal applications reduced disease infection by almost 40 % and 54 %, respectively, for RVD and CLS. It was evident that mycorrhizal symbiosis with groundnut roots increased the resistance of plants to RVD and CLS and positively influenced the physiology of groundnut plants infected by RVD.

Fungal root pathogens can be reduced in crops by AM inoculation (Caron et al. 1986), including *Phytophthora* species (Davis and Menge 1980; Cordier et al. 1996), *Rhizoctonia solani* (Yao et al. 2002) and *Pythium ultimum* (Calvet et al. 1993). Bacterial diseases may also be reduced by mycorrhiza establishment on roots (Dehne 1982). Evidence of the suppression of nematode penetration and

development following AM fungi inoculation has been reported by many workers (Elsen et al. 2001; Diedhiou et al. 2003). Harrier and Watson (2004) illustrated the role of AM fungi in organic and/or sustainable farming systems that rely on biological processes rather than agrochemicals to control plant diseases. However, the mechanisms by which AM fungi colonisation confer the protective effect are not well understood. Bio-protection within AM fungal-colonised plants is the outcome of complex interactions between plants, pathogens and AM fungi. These interactions have been shown to result in reductions in disease incidence (Matsubara et al. 2001), pathogen development (Cordier et al. 1996) and disease severity (Matsubara et al. 2001). The extent of AM fungi-induced protection of host plants against pathogens suppression ranges from complete protection (Torres-Barragan et al. 1996) to partial protection (Matsubara et al. 2001). The extent of partial protection is influenced by the AM fungal species and cultivar used (Yao et al. 2002). Information related to oilseed crops is summarised in Table 8.3. Effects may relate to direct interaction between mutualists and pathogens (Abdalla and Abdel-Fattah 2000), competition for infection sites (Abdel-Fattah and Shabanam 2002) and improved nutrition of AM fungi plants which offset the damage caused by the pathogen involved (masking effect). Inoculation with soil-based mixture of AM fungi (*Glomus fasciculatum*) decreased incidence of disease caused by *Macrophomina phaseolina* (Tassi) in groundnut and increased growth and

Table 8.3 Examples of AM fungi application providing protection to oilseed crops against soil-borne diseases and other plant pathogens

AM fungi	Pathogen	Plant	References
G. mosseae	*Rhizoctonia solani*	Groundnut	Abdalla and Abdel-Fattah (2000)
Glomus sp.	Rosette virus disease (RVD), *Cercospora* leaf spot (CLS)	Groundnut	Zachee et al. (2008)
Gigaspora sp.			
G. intraradices	*Fusarium oxysporum* f. sp. *lini*	Linseed	Dugassa et al. (1996)
G. mosseae	*Fusarium solani*	Groundnut	Abdalla and Abdel-Fattah (2000)
G. mosseae	*Macrophomina phaseolina*, *Rhizoctonia solani*, *Fusarium solani*	Soybean	Zambolim and Schenck (1983)
G. fasciculatum	*Sclerotium rolfsii*	Groundnut	Krishna and Bagyaraj (1982)
AM fungi	*Meloidogyne arenaria*		Carling et al. (1995)
AM fungi	*Meloidogyne incognita*	Soybean	Kellam and Schenck (1980)
Glomus sp., *Gigaspora* sp.	*Heterodera glycines*	Soybean	Tylka et al. (1991)
G. intraradices	*H. glycines*	Soybean	Price et al. (1995)
G. mosseae	*H. glycines*	Soybean	Todd et al. (2001)

production of defence-related enzymes (Doley and Jite 2013a, b). The various defence-related biochemical parameters such as protein, proline, total phenol, total chlorophyll content, acid and alkaline phosphatase activity, peroxidase and polyphenol activity showed marked increase in their content or activity in mycorrhizal healthy or diseased plants in comparison to non-mycorrhizal diseased or control ones (Doley and Jite 2013a, b). Zambolim and Schenck (1983) reported that *Glomus mosseae* reduced the influence of *Macrophomina phaseolina* (Tassi.), *Rhizoctonia solani* (Kuhn.) and *Fusarium solani* (Mart.) in soybean. The suppression of endoparasitic nematodes by AM fungi has been recently reported by many workers (Habte et al. 1999). Several mechanisms have been proposed to explain the nematode suppression by AM fungi (Pinochet et al. 1996). Carling et al. (1995) observed the individual and combined effects of two AM fungal species, *Meloidogyne arenaria* and P fertilisation on groundnut plant growth and pod yield. They found that the groundnut growth and yield were generally stimulated by AM fungi, which increased groundnut plant tolerance to the nematode and offset the growth reductions caused by *M. arenaria* at the two lower P levels. Price et al. (1995) investigated the effects of the AM fungi, *Glomus intraradices*, on the soybean cyst nematode (SCN), *Heterodera glycines*, on two soybean cultivars, cv. "Bragg" (nematode intolerant) and cv. "Wright" (moderately nematode tolerant) grown in the greenhouse in soils with low (35 μg/g) and high (70 μg/g) P. They found variable AM responses to cultivar. The cultivar "Wright" was more responsive than "Bragg" and exhibited greater nematode tolerance. Dugassa et al. (1996) demonstrated the effects of AM fungi on the health of *Linum usitatissimum* infected with wilt (*Fusarium oxysporum* f. sp. *lini*) and AM fungi showed increased resistance against the wilt pathogen; the level of these effects depended on the plant cultivars which all showed the same level of root colonisation by AM fungi.

8.3.3.2 Interaction Between AM Fungi and Other Plant Growth-Promoting Rhizobacteria (PGPR) Leading to Inhibition of Fungal Pathogens

Rhizosphere microorganisms can affect presymbiotic phases of mycorrhiza development (Barea et al. 1998). The bacteria have been found adhering to the AM fungi hyphae (Bianciotto et al. 1996) and as well as embedded within the spore walls (Walley and Germida 1996). Bacteria adhering to AM fungal mycelium may utilise hyphal exudates or use mycelium as vehicle for colonisation of rhizosphere (Bianciotto et al. 1996). Bacteria from genus *Paenibacillus*, which are antagonistic to a broad range of root pathogens and are able to stimulate mycorrhizal colonisation, were found frequently to be associated with *Glomus intraradices* mycelium (Mansfeld-Giese et al. 2002). Therefore, it should be mandatory to detect the cohesiveness of both AM fungi and PGPR participating in a particular rhizosphere while maintaining the healthy rhizosphere. The key step is to ascertain whether an antifungal biocontrol agent will negatively affect the AM fungi populations. Several studies have demonstrated that microbial antagonists of fungal pathogens,

either fungi or PGPR, do not exert antimicrobial effect against AM fungi (Barea et al. 1998). There is a need to exploit the possibilities of dual (AM fungi and PGPR) inoculation to provide plant defence against root pathogens (Barea et al. 2005). Barea et al. (1998) conducted a series of experiments to evaluate the effect of *Pseudomonas* strains producing 2, 4-diacetylphloroglucinol (DAPG) on AM fungi formation and functioning. Three *Pseudomonas* strains producing DAPG were tested under in vitro and in situ for their effects on AM fungi; it was found that there was no negative impact on AM spore germination. Rather, there was stimulation of hyphal growth of *G. mosseae*. Under field conditions, none of the *Pseudomonas* strains affected the diversity of native AM fungi in the rhizosphere soil, root colonisation and AM functional symbiosis and rather improved plant growth and nutrient (N and P) acquisition by AM-mediated plants (Barea et al. 1998). Sanchez et al. (2004) showed that a fluorescent pseudomonad and *G. mosseae* had similar impacts on plant gene induction, supporting the hypothesis that some plant cell programmes may be shared during root colonisation by these beneficial microorganisms. Gram-positive and gamma-proteobacteria are more frequently associated with AM fungi than are gram-negative bacteria (Table 8.4), but their synergistic interaction is yet to be confirmed (Artursson et al. 2005).

Table 8.4 Examples of synergistic interactions between AM fungi and bacteria or PGPR leading to inhibition of fungal pathogens

Bacterial species	AM fungi species	Interaction effect	Inhibition of fungal pathogen	References
Bacillus pabuli	*Glomus clarum*	+	ND	Xavier and Germida (2003)
B. subtilis	*G. intraradices*	+	ND	Toro et al. (1997)
Paenibacillus validus	*G. intraradices*	+	ND	Hildebrandt et al. (2002)
Paenibacillus sp.	*G. mosseae*	+	+	Budi et al. (1999)
Paenibacillus sp.	*G. intraradices*	+	ND	Mansfeld-Giese et al. (2002)
Pseudomonas sp.	*G. versiformis*	+	ND	Mayo et al. (1986)
Pseudomonas sp.	*G. mosseae*	+	+	Barea et al. (1998)
Pseudomonas putida	Indigenous mixed AM fungi	+	ND	Meyer and Linderman (1986)
P. fluorescens	*G. mosseae*	+	+	Edwards et al. (1998)

Modified from Artursson et al. (2006)
+ positive, *ND* not determined

8.3.4 *Soil and Agricultural Management Practices Influencing AM Fungi Response*

To benefit from mycorrhizal associations (or more generally beneficial biological processes in the rhizosphere), emphasis has to be on agricultural practices that promote the occurrence and functioning of soil organisms, including AM fungi. The low host specificity of AM fungi may allow mycelial networks of a particular fungus in the soil to be connected directly to roots of plants of different species, forming hyphal links between their mycorrhizal roots. It has been shown that in fragile tropical agroecosystems, conventional agriculture, relying on tillage and external inputs (mineral fertilisers, biocides) for increase of productivity, may result in large ecological disturbances and may not be sustainable in the long term. Most of the cultivated plant species are able to form the mycorrhizas. However, the plant families *Brassicaceae* and *Chenopodiaceae* include species that do not usually form mycorrhizal symbiosis; among them, sugar beet and rape (Tester et al. 1987) are important. Growing these crops subsequently does not lead to multiplication of AM fungi, unless there are weeds that can act as hosts (Abbott and Robson 1991; Jansa et al. 2002).

8.3.4.1 Fertilisers, Manures, Fungicides and Tillage Practices

Application of farmyard manure can increase densities of AM fungal spores, although this depends on the soil types (Harinikumar and Bagyaraj 1989). Several studies indicated that cumulative P fertilisation decreases the spore density under Northern European field conditions (Martensson and Carlegren 1994; Kahiluoto et al. 2001). Another study showed that AM fungal colonisation was not affected by P addition when plants were deficient in N, but, when N was sufficient, P addition suppressed root colonisation (Sylvia and Neal 1990). Thus, there are agronomic soil management practices available for the farmer to regulate the AM fungi at the field site. An important measure, apart from the choice of cropping systems in conventional agriculture, is the use of fungicides particularly systemic fungicides applied in the field has shown to reduce the functioning of the AM fungi (Menge et al. 1978; Kling and Jakobsen 1997). AM fungi can be sensitive to certain but not all fungicides. Mancozeb, thiram and ziram are all dithiocarbamates and, as a group, appear to be deleterious to mycorrhizal fungi, at least when tested in groundnut (Sugavanam et al. 1994). Emisan (a mercuric treatment) and carbendazim (a benzimidazole) were both negative for AM fungi when tested in groundnut. Copper, however, appeared to provide a stimulus to mycorrhizae in groundnut. Application of fungicide to soil reduced sporulation and the root length colonised by AM fungi, although interaction of AM fungi and fungicide was observed to be highly variable depending on fungus-fungicide combination and on environmental conditions (Turk et al. 2006).

Fungicide seed treatments alter the microbial population dynamics in the rhizosphere by reducing root pathogen infection but may also affect nontarget organisms (Rodriguez-Kabana and Curl 1980; Trappe et al. 1984). Soil applications of metalaxyl have been reported to favour AM colonisation in corn and soybeans (Groth and Martinson 1983). Seed-applied captan had no effect on AM colonisation in studies conducted by Kucey and Bonetti (1988), and it reduced symptoms of *Fusarium solani* when applied along with AM inoculum in *Phaseolus vulgaris* plants (Gonçalves et al. 1991). Other fungicides such as benomyl, captan, pentachloronitrobenzene and emisan have been reported to also have negative effects on AM colonisation when applied as soil drenches (Kjoller and Rosendahl 2000; Schreiner and Bethlenfalvay 1997; Sugavanam et al. 1994). Murillo-Williams and Pedersen (2008) showed that under natural pathogen inoculum (non-fumigated soil), seed-applied fungicides with fludioxonil seemed to favour AM colonisation due to a reduced competition with aggressive pathogens like *Rhizoctonia* spp., an organism that is targeted by this fungicide.

Function of AM fungi and species composition may also be affected by farming systems. This is evidenced from a long-term field trial established in Switzerland designed to compare long-term effects of "conventional" vs. "organic" farming systems (Mäder et al. 2002). In this trial, about 40 % more roots were colonised by AM fungi in the organic systems than in the conventional system (Mäder et al. 2000). They suggested that AM fungal species differ in functional characteristics such as spore production and plant growth promotion (Van der Heijden et al. 1998). Moreover, less efficient AM fungal species might be selected by high-input farming (Scullion et al. 1998). Tillage affects the mycorrhizal hyphal network (Cardoso and Kuyper 2006). Mulligan et al. (1985) observed that excessive secondary tillage reduced AM colonisation of *Phaseolus vulgaris* L. Mycorrhizal root colonisation of corn growing in NT (no-tilled) and ridge till plots was greater than that in CT (conventional-tilled) plots (McGonigle and Miller 1993). AM hyphae and spores were more abundant in the top 0- to 15-cm layer of the soil profile and decreased dramatically below this depth (Kabir 2005). Similar results were reported for AM spores by An et al. (1990) in Kentucky, USA, under soybean. This suggests that tilling the soil to a depth of 15 cm would affect most of the AM fungi and that ploughing below this depth would dilute the AM propagules in the zone of seedling establishment (Kabir 2005). The role of glomalin in soil aggregation (Rillig 2004) was correlated with stabilisation of soil aggregates after a 3-year transition of a maize cropping system from conventional tillage to no tillage (Wright et al. 1999), and there are indications that some crop rotations favour glomalin production and aggregate stabilisation more than others (Wright and Anderson 2000). Thus, management of cropping systems to enhance soil stability and reduce erosion may benefit from consideration of the factors controlling production and maintenance of extraradical hyphae and glomalin (Cardoso and Kuyper 2006).

8.3.4.2 Crop Rotation and Sequences

AM fungi show only a limited degree of specificity; different plant species stimulate the amount and occurrence of different species of AM fungi; thus, through the management of plants, it is possible to modify mycorrhizal populations in the soil (Colozzi and Cardoso 2000; Hart et al. 2001). Mycorrhizal inoculum density declines when soils are kept fallow for extensive periods of time (Thompson 1987). The quantity of AM fungi in soils also differs between host species (Vivekanandan and Fixen 1991). Even the preceding crop in a crop rotation system affects the AM fungal spore densities in the field and thereby the yield of the following crop (Karasawa et al. 2001). Oehl et al. (2003) found that increased land use intensity was correlated with a decrease in AM fungal species richness and with a preferential selection of species that colonised roots slowly but formed spores rapidly. Soils used for agricultural production have a low diversity of AM fungi compared with natural ecosystems (Menendez et al. 2001) and are often dominated by *Glomus* species (Daniell et al. 2001; Oehl et al. 2003; Troeh and Loynachan 2003). One reason for this is the low diversity of hosts, which reaches an extreme in crop monoculture (Oehl et al. 2003). Monoculture may select for AM fungal species that provide limited benefits to the host plant. Johnson et al. (1992) found that maize yielded higher and had higher nutrient uptake on soils that had grown soybean continuously for the previous 5 years than on soil that had grown maize continuously for the previous 5 years. Conversely, soybean yielded higher and had higher nutrient uptake on soil which had grown 5 years of maize than 5 years of soybean. The most abundant AM fungal species in the continuous maize soil was negatively correlated with maize yield but positively correlated with soybean yield; there was a similar effect with soybean soil. They hypothesised that monocropping selects AM fungal species which grow and sporulate most rapidly and that these species will offer the least benefit to the plant because they divert more resources to their own growth and reproduction. The result can be reduced benefits of AM colonisation to the host plant while monocropping continues. Crop rotation effects on mycorrhizal functioning have repeatedly also been observed by other workers. Harinikumar and Bagyaraj (1988) observed a 13 % reduction in mycorrhizal colonisation after 1-year cropping with a non-mycorrhizal crop and a 40 % reduction after fallowing. Lack of inoculum or inoculum insufficiency after a long bare fallow (especially in climates with an extended, dry, vegetation less season) may result in low uptake of P and Zn and in plants with nutrient deficiency symptoms that have been described as long-fallow disorder. The use of mycorrhizal cover crops can overcome this disorder (Thompson 1996). Sanginga et al. (1999) found evidence for increased mycorrhizal colonisation of soybean if the preceding crop was maize and increased colonisation of maize if the preceding crop was *Bradyrhizobium*-inoculated soybean in the savanna of Nigeria. Similarly, Bagayoko et al. (2000) reported higher AM colonisation in cereals (sorghum, pearl millet when grown in rotation with legumes (cowpea, groundnut) than in

continuous cropping. Osunde et al. (2003) reported that AM colonisation in maize benefited from previously grown soybean plants.

In a long-term experiment involving three tillage systems and four soybean-based crop rotations after six cropping seasons, rotation produced significantly higher grain yield and supported higher inoculum potential of AM fungi in the rhizosphere soil (Sharma et al. 2012a). On the other hand, irrespective of crop rotations, the tillage system did not all have the same effect. Moreover, the inoculum potential of resident AM fungi in soybean rotation involving maize in conservation tillage was highly correlated with grain yield of soybean implicating the resident AM fungi in enhancing the soybean yield.

8.3.5 Inoculation vs. Field Management of Indigenous AM Fungi

Selection of the appropriate AM fungi is among one of the critical issues for the application of AM technology in agriculture (Estaun et al. 2002). Ecologically sound selected strains of AM fungi inoculum are not presently available in large quantities at a low price. Alternatively, inoculum can be produced on site (on farm) under local agronomic conditions (Sieverding 1991). The successful introduction of a foreign microorganism into the soil depends on how well it adapts, develops and competes for nutrients. AM fungal consortia isolated from organic farms were more effective in plant growth promotion under conditions of low nutrient availability than were consortia from conventional farms (Scullion et al. 1998). Therefore, it is likely that on-farm selected strains (site specific) are better due to their adaptability to edaphic conditions than selected strains produced in vitro or in vivo under controlled conditions. Given limitations of bulk inocula requirements or instances where inoculation may not be feasible, the management of native and resident AM fungi through crop sequences and soil management practices (e.g. minimum tillage) could be a better option.

8.4 Production and Commercialisation of AM Fungi

8.4.1 Conventional Methods

The obligate biotrophic nature of AM fungi has complicated the development of cost-efficient large-scale production technologies to obtain high-quality AM fungal inoculum. This is one of the bottlenecks to commercial exploitation (IJdo et al. 2011). There are various techniques currently used to culture AM fungi on hosts such as on-farm production (Douds et al. 2005, 2006; Sharma and Sharma, 2006; Sharma and Sharma 2008; Sharma and Adholeya 2011), pot culture

techniques using traps (Gaur and Adholeya 2000), nutrient film technique (Mosse and Thompson 1984) and aeroponics (Jarstfer and Sylvia 1995). The most frequently used technique for increasing propagule number has been the propagation of AM fungi on a suitable host in disinfested soil using pot cultures. Other factors for creating a favourable environment for culturing of AM fungi are a balance of light intensity, adequate moisture and moderate temperature without detrimental addition of fertilisers or pesticides (Jarstfer and Sylvia 1992; Al-Karaki et al. 1998). Cultures reaching high propagule density (e.g. 10 spores per gram) after a number of multiplication cycles can be stored using suitable methods after air-drying (Kuszala et al. 2001).

AM fungi have been cultured with plant hosts in different substrates such as sand, peat, expanded clay, perlite, vermiculite, soilrite (Mallesha et al. 1992), rockwool (Heinzemann and Weritz 1990) and glass beads (Redecker et al. 1995). They can also be produced aeroponically (Sylvia and Hubbell 1986). The aeroponic system was adopted for mycorrhiza production by the utilisation of seedlings with roots pre-colonised by an AM fungus and the use of modified Hoagland's nutrition with a very low P level (Hoagland and Arnon 1938). *Entrophospora kentinensis* was successfully propagated with bahia grass and sweet potato in an aeroponic system by Wu et al. (1995).

The nutrient film technique (NFT) was adapted for AM fungi inoculum production by Mosse and Thompson (1984). Further, Lee and George (2005) proposed a modified nutrient film technique for large-scale production of AM fungal biomass with the help of improved aeration by intermittent nutrient supply, optimum P supply and the use of glass beads as support materials.

8.4.2 In Vitro/Root Organ Culture (ROC) Method

In vitro culture of AM fungi was achieved for the first time in the early 1960s (Mosse 1962). Since then, various pioneering steps were aimed at axenic culturing of AM fungi. Continuous cultures of vigorous ROCs (Ri T-DNA-transformed) have been obtained through transformation of roots by the soil bacterium *A. rhizogenes* (Tepfer 1989) that provided the new way to obtain mass production of roots in a very short span of time. In most cases, purified and surface sterilised spores (Becard and Piche 1992) isolated from the field or from traps have been successful for establishing dual cultures under in vitro conditions. The root organ culture (ROC) is an attractive mass multiplication method for providing a pure, viable, rapid and contamination-free inoculum using less space and has an advantage over the pot culture multiplication/conventional system (Fortin et al. 2002; Cranenbrouck et al. 2005; Dalpe et al. 2005). Different production systems have been derived from the basic ROC in Petri plates. For example, root organs and AM fungi were cultured in small containers, by which large-scale production was obtained (Adholeya et al. 2005). Douds (2002) reported monoxenic culture of *G. intraradices* with Ri T-DNA transformed roots in two-compartment Petri dishes

as a very useful technique for physiological studies and the production of clean fungal tissues. Various inocula based on inert or sterilised substrata, such as peat, expanded or calcined clays or lave, are used commercially and are less susceptible to contamination with pathogen (Whipps 2004). Various forms of AM fungi are commercially produced and available in various formulations for sale throughout the world.

8.4.3 On-Farm Production

As AM fungi are obligate symbionts, they require host plants to sporulate and colonise roots to complete their life cycles. Currently, AM fungi are multiplied in various ways like monoxenic/in vitro, pot culturing/greenhouse, aeroponic system and nutrient film technique (Fortin et al. 2002; Lee and George 2005). While inocula produced by these techniques are commercially available, the pot culture or conventional method is still widely used (Saito and Marumoto 2002). There are many steps including isolation of AM fungi, the use of substrate/potting mixture and subsequent maintenance and transportation which incur costs and limit commercialisation. On-farm multiplication of indigenous and resident AM fungi removes many steps, which reduce the cost and enhance the acceptability to the farmers (Douds et al. 2006). The on-farm technology is more appropriate since it uses the indigenous AM fungi already adapted to that site and environment. Apart from this, the technology can be used for producing introduced AM fungi (applied as starter culture in beds) using one or a succession of trap plants (Sieverding 1991). Under this method, the fungal inoculum is produced on raised/elevated beds in situ; in the farmer's own nursery or his kitchen garden, a space that he generally uses for growing seedlings for field transplantation (Sharma and Sharma 2008). The mycorrhizal roots can then be harvested and used in the field as inocula. The soil left in the nursery after removing the roots contains a many AM fungal propagules which will serve as the source of AM fungi for further multiplying the inocula in the subsequent cycles. This method can produce inoculum of the indigenous AM fungi already adapted to the site. This field-based method deals with preparing beds of sterilised (solarised by polythene) soils in which either the indigenous AM fungi community or introduced isolates are increased using one or a succession of trap plants (Sieverding 1991). An important consideration in producing AM fungi is the level of available phosphorus which is critical for inoculum production and needs to be analysed before multiplication. In general, under Indian conditions, the level of Olsen P (available P in tropical soils) is low (less than 10 ppm), but high available P level (beyond 20 ppm) could be detrimental to AM sporulation and hence should be determined prior to multiplication. A unique feature of such technique is that it will not only produce mycorrhizal spores, hyphae and highly colonised roots but at the same time beds can be used for preparing seedlings for field transplantation.

8.5 Need of Regulatory Mechanisms and Quality Assurance

Currently, large-scale production of AM fungi is not possible in the absence of a suitable host, and species cannot be identified in their active live stages (growing mycelium). As a consequence, quality control is often a problem, and tracing the organisms into the field to strictly relate positive effects to the inoculated AM fungus is nearly impossible (IJdo et al. 2011). Pringle et al. (2009) have also indicated the risks associated with the transport of AM fungi around the world and have detailed the problem that can arise with the introduction of exotic material. In India, registration of biofertiliser production units is compulsory and is being done by the Ministry of Agriculture and Cooperation through a nodal agency, National Centre of Organic Farming, Ghaziabad, India.

8.6 Conclusion

Oilseeds comprise both legumes and nonlegumes, and major oilseeds like groundnut, sesame and soybean are grown under rainfed conditions in the tropics and subtropics in the marginal lands with meagre amount of external application of fertilisers. Very often, the major oilseeds crop faces vagaries of weather conditions like erratic rainfall and mid- and end-of-season drought coupled with plethora of diseases and pests severely limiting the productivity. Thus, to enhance the productivity of the oilseed crops, management of nutrients is of utmost importance to enhance availability of nutrient in suboptimal conditions of cultivation. Therefore, there is great opportunity of application of microbes especially rhizobia, PGPMs and AM fungi alone or in combinations. Considering the plant genotype as a constant factor, microbial package should be developed based on climate, soil and microbe interactions. Furthermore, formulation of biofertiliser packages should be developed not only for enhancing nutrient availability and uptake but for managing soil-borne and foliar diseases, in addition to enhancing growth by production of plant growth regulators. Within the constraints of available resources, a large number of PGPMs and AM fungi have been identified with capability to enhance growth and yield of many oilseed crops, but effective strains tolerant to abiotic stresses are few. Therefore, ongoing effort is needed to identify efficient strains of PGPMs and AM fungi which can alleviate abiotic stresses and have potential biocontrol abilities, besides enhancing nutrient availability and uptake in suboptimal conditions of cultivation. Many studies have shown large amounts of hyphal biomass and higher indigenous AM fungi in crop rotations involving maize. The large-scale production of resident AM fungi is still in its infancy and the combined application of AM fungi and PGPMs are yet to be streamlined. Finally, potential commercial formulations need to be subjected to regulatory requirements and quality checks before they are eventually registered as a commercial formulation.

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