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Chapter 20

Climate resilient microbes in sustainable crop production

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Chapter contents

Abstract

Climate change poses a great threat to the sustainability in agricultural crop production. Such circumstances demand the use of improved agricultural practices, environment friendly and climate resilient technologies. Microorganisms, being ubiquitous and abundant in the soil environment, are the key players regulating the earth's biogeochemical systems. The enormous potential of these microbes is being recognized and scientific community around the globe is involved in significant research towards the selection and commercialization of the microbes of biotechnological and environmental relevance. These microbes may be helpful in sustainable crop production by providing protection to plants from harmful pests and pathogens, by enhancing plant growth, by alleviating environmental and nutritional stresses, thus facilitating plants to

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cope up with the different abiotic and biotic stress conditions in view of the changing climatic scenario and alleviating its dire consequences.

Keywords: Bacteria, Climate change, Mycorrhizae, Resilience, Soil microbes, Stress, Sustainable agriculture

Introduction

Microorganisms are the heart of all ecosystems. There is a huge diversity and abundance of microorganisms in soil; 1 gram of soil may contain more than 10^8–10^9 cells of bacteria, 10^7–10^8 cells of actinobacteria and 10^5-10^6 cells of fungi with thousands of different species (Microbes, 2010). These microorganisms are the key players of many soil functions and mediate 80-90% of the functions important in soil activities to maintain fertility of soil and perform various ecosystem services, including acquisition of plant nutrients, cycling of nitrogen and carbon, formation of soil etc. (Sacca *et al.,* 2017). Climate change is probably the most complex and challenging environmental problem faced by the world today. It is recognized as a global issue. The changing patterns of climatic parameters like rise in atmospheric temperature, changes in precipitation patterns, excess UV radiation and higher incidence of extreme weather events like droughts and floods are emerging major threats for the sustainable crop production (Tirado *et al.,* 2010). Climate change can have various consequences, ranging from global warming to local cooling, increased extreme weather events and shifting vegetation zones. All these changes will indirectly influence soil organisms and microbial processes (Philippot *et al.,* 2013). The Indian climate has undergone significant changes showing increasing trends in annual temperature with an average of 0.56°C rise over last 100 years (Rao *et al.,* 2009). In future, the climate associated stress events like high temperature, limited soil moisture and salinity stress will get magnified by climate change impacts (Singh and Bainsla, 2015). To mitigate the adverse impact of climatic change on productivity and quality of various crops, there is need to develop sound adaptation strategies. The future crop farming techniques and food production systems will have to be better adapted to a range of abiotic stresses such as greater heat accumulation, dwindling water and salinity availability as well as biotic stresses including pests and diseases, in order to cope with the consequences of progressively changing climate phenomena. In this scenario, climate smart agriculture sustainably enhances achievement of national food security and development goals (FAO, 2010). Due to the growing concern over climate change, it has become essential to successfully exploit the beneficial soil microbes and their interactions for enhancing the agrosystems resilience to climate change and for improving the soil fertility and health, in turn maximizing the crop production. In this review, various properties of soil microbes will be discussed which makes them important in agriculture keeping in view of the effects of the changing climatic scenario on crop production and the need to eliminate many problems associated with the use of chemicals in this sector.

Soil microbial communities- effect of climate change and their resilience

The direct effects of climatic change on microbial composition and function have been studied extensively by investigators. To predict the response of a microbial community to a disturbance, various drivers of the microbial community stability, including resistance and resilience have been studied (Shade *et al.*, 2012). Soil microbial communities may be more resilient to environmental change than their aboveground plant counterparts, and changes to soil microbial communities may occur only when abiotic variables are outside the range normally experienced by the communities (Cruz-Martínez *et al.*, 2009). Microbial communities respond to warming and other perturbations through resistance, enabled by microbial trait plasticity, or resilience as the community returns to an initial composition after the stress has passed (Allison and Martiny, 2008). Resilience is the capacity or ability of a system or individual to react (respond) to an external force (disturbance) while fulfilling some further conditions at the end of the response (outcome). The word 'resilience' is derived from Latin word *resilire* meaning 'to jump back'. The degree to which soil organisms are impaired after a stress can be defined as the resistance of the soil system, and the rate and extent of recovery is considered as its resilience (Doring *et al.*, 2015).

The concept of resilience has become more important in the presence of climate changes, both in semi-natural and agricultural ecosystems. It has been referred to as a dynamic and relevant criterion of health across all levels and areas of agriculture (Doring *et al.*, 2015). For the growth and development of plants as well as microbes, soil is an excellent medium. Insight into the nature of the biological basis of resistance and resilience of soil functions has been growing. In fact, it has been suggested that resistance and resilience might be related to microbial communities and properties of the resident soil microorganisms (Griffiths and Philippot, 2013).

The soil microbial communities are, indeed, an excellent way to study resilience as their response to disturbances can be relatively fast that is within days or weeks (Griffiths and Philippot, 2013; Cregger *et al.*, 2012). According to Allison and Martiny (2008), even if microbial composition is sensitive to a disturbance, the community might still be resilient and quickly return to its predisturbance composition. This may be due to several features of microorganisms like their fast growth rates, the rapid evolution through mutations or horizontal gene exchange. So, microbial communities could be among the fastest components of an ecosystem to respond to changing environmental conditions with relatively short generation times and rapid growth under favorable conditions. On the other hand, the high functional and genetic diversity, potentially rapid evolutionary rates and vast dispersal capabilities of microbes may mitigate responses to environmental change. Microbial community composition itself can be robust both to changing climate and to associated changes in plant production and species composition (Cruz-Martınez *et al.*, 2009).

Among bacteria and fungi, fungal communities showed the ability to dynamically adapt to changing environments without a loss of diversity (Yuste *et al.*, 2011). Fungal diversity was less sensitive to seasonal changes in moisture, temperature and plant activity than bacterial diversity.

Specific functional traits, for example, the ability to resist dehydration via synthesis of the sugar trehalose to maintain cell membrane integrity e.g., for drought resistance, the ability to use specific C or N forms that are released when a drought ends, might inform about resilience (Mouillot *et al.*, 2013). In contrast, more general stress-response pathways, such as the sporulation pathway of *Bacillus subtilis* (Higgins and Dworkin, 2012) may be universally useful for maintaining stability in the face of a variety of disturbances. Resistance and adaptation of micro-organisms to increased temperature are most often owing to the synthesis of heat shock protein folding and unfolding other proteins. Interestingly, induction of heat shock proteins is triggered by exposure to other environmental stressors such as osmotic shock or the presence of heavy metals and aromatic compounds which provides a molecular basis for cross-protection where exposure to one disturbance increases resistance to a different disturbance (Ramos *et al.*, 2001).

Need for microbial inoculation

In general, there is a need for microbial inoculation as a component of agricultural practice because of loss of topsoil, soil infertility, poor plant growth, low yield index and insufficient diversity of indigenous microbes. Harnessing plant-microbe interactions will not only help in climate change mitigation but also strengthening the green economy for achieving economic stability. It leads to developing plant cultivars that have the potential to grow under the stress of warming climate and elevated CO_2 (Philippot and Hallin, 2011). Beneficial soil microorganisms can also offer substantial socio-economic benefits to the global economy by reducing the dependency on synthetic fertilizers and pesticides while supporting various ecosystem functions and processes. Therefore, soil environment can be manipulated with the beneficial microbes to: (i) increase nutrient availability for production of high yielding, high quality crops; (ii) protect crops from pests, pathogens, weeds; and (iii) manage other factors limiting production, provision of ecosystem services, and resilience to stresses like droughts (Lehman *et al.*, 2015).

Various soil microorganisms like plant growth promoting rhizobacteria (PGPR) have emerged has an environment-friendly approach to promote plant growth effectively under abiotic and biotic stress conditions. Moreover, various microbial inoculants that can facilitate plant growth are known to reduce the toxicity of heavy metals, contribute to nitrogen fixation, facilitate nutrient transformation, produce siderophores which help the plant to obtain sufficient levels of iron, synthesize indole acetic acid (IAA) and other plant hormones and provide protection against a range of different pathogens (Mohanty and Swain, 2018; Olanrewaju *et al*,. 2017).

In cultivated soils, the activity of soil microorganisms is an important determinant of effective nutrient cycling and plant growth (Kumar *et al.*, 2012). These PGPRs are being developed as efficient biofertilizers for commercial exploitation. Increased use of natural microbes in the form of biofertilizers, biopesticides, biofungicides, and so on can reduce the chemical load and sustain productivity. Moreover, the use of farm yard manure enhances resistance and resilience of soil microbial activity against heat stress as applying only nitrogen fertilizer may be weakening the resistance and resilience of soil functions (Kumar *et al.*, 2013). Increased use of natural microbes in the form of biofertilizers, biopesticides, biofungicides, etc. can reduce the chemical load and sustain productivity in conservation agriculture which constitutes an integrative approach to address multiple challenges facing the agriculture and environmental sectors – enhancing productivity in the face of acute and widespread problems of resource degradation (soil erosion, declining water availability and quality, declining diversity) and increasingly stressed ecosystems and climate change (Singh and Reddy, 2013) It has been emphasized earlier, subsistence farmers, who face famine, would consider a successful technology to be one that produces some yield in the worst year rather than one that produces high yields in the best (Lal, 1987).

Role of soil microbes in plant growth nutrition

The growth and health of plants is dependent upon the availability of requisite composition and concentration of various macronutrients, micronutrients and trace elements in the soil (Hodges, 2010). It is also important that these nutrients should be present in a biologically available form to affect the growth and productivity of plants. For example, though phosphate and sulphate are available in abundance in the soil, but only the soluble ionic form of these nutrients is taken up by the plants using different mechanisms and the rest remains unutilized (Solomon *et al.*, 2003; White and Hammond, 2008).

Microorganisms play an important role in the mobilization and uptake of nutrients by the plants (Sahu *et al.*, 2018). Soil microorganisms like arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) are known to positively affect plant health, growth, and nutrition. The balance of soil microbial population has been greatly disturbed by the excess use of chemicals to improve the crop yield. This has consequently affected geochemical cycling of nature and also led to environmental pollution. Their use was often suggested in order to reduce the input of chemicals in agriculture. To promote the yield and quality of crops and restore the soil nutrients for sustainable agriculture and environment, the use of microorganisms as bioinoculants is the better alternative for chemicals (Alori and Babalola, 2018).

Role of fungi

There are various groups of fungi like plant growth promoting fungi, endophytic, ecto-mycorrhizal, arbuscular that play an important role in increasing plant growth and obtaining nutrition through various means like solubilisation of phosphorus, production of plant growth promoting hormones, increased above ground photosynthesis etc. (Prakash *et al.*, 2015). Among these, arbuscular mycorrhizal (AM) fungi are an important component of the soil microbial community and form mutualistic associations with the roots of over 80% of all land plants and have a worldwide distribution (Öpik *et al.*, 2010). AM fungi are a group of beneficial micro-organisms that are known for their obligate symbiotic associations with the roots of higher plants (Salvioli *et al.*, 2016) particularly members of phylum Glomeromycota with angiosperms (except

Pinaceae), bryophytes, pteridophytes and gymnosperms. Through symbiotic associations with plant roots, AM fungi facilitates mobilization and uptake of carbon, phosphorus, nitrogen, etc. (Smith and Smith, 2012; Walder *et al*., 2012), as well as other essential minerals such as Zn, Mg, S, Ca, K, etc. (Mohammadi *et al*., 2011; Alizadeh, 2012) and make them available for the growing plants besides their other benefits, for example, they improve water availability in plants, protects the plants from pests, provide tolerance to environmental stresses and serve a major role in biogeochemical cycling of nutrients in soil (Hashem *et al*., 2018).

Arbuscular Mycorrhizae: AM fungi supply phosphorus and other nutrients to plants and fungi, in return, take carbohydrates from plants (van der Heijden *et al*., 2016). Reduction in the carbon flow to the fungi reduces the absorption of phosphorus by AM (Abiala *et al*., 2013) which also depends on the species of AM fungi. P is the most studied nutrient absorption by AM roots and its absorption is increased in plants associated with AM by 3–5 times more than direct root absorption and also when grown in soils low in P, AM-infected plant roots with mycorrhizal associations absorb and accumulate more P as compared to roots of plant without AM symbiosis (Smith and Smith, 2012). The several metres extended mycelia of AM increases surface of absorption many times to obtain the same nutrients which plant roots are trying from their proximate area. The fine structure of hypha than plant root helps it to penetrate within the soil and thus increases the surface area for absorption which helps in growth and development of associated plants (Olsson *et al*., 2014). The easily available supply of nutrients in plants as a result of the AM plant symbiosis increases the photosynthetic rate and overall biomass of the plant as has been reported by studies in greenhouse-grown lettuce (Baslam *et al*., 2013). Although P is the most studied nutrient absorption by AM roots, some reviews have also reported absorption of other nutrients (Mohammadi *et al*., 2011; Alizadeh, 2012).

AM fungi have also been found to increase the uptake of nitrogen along with phosphorus, assist in N assimilation in plants (Zhu *et al*., 2016) and induce better biological N fixation. The carbon (C) flux from the root to the fungus acts as a key trigger for N uptake and transport (Fellbaum *et al*., 2012). A substantially greater belowground C drain was confirmed in mycorrhizal plants than in nonmycorrhizal plants on quantification of carbon fluxes using a novel CO_2 collection system (Slavíková *et al*., 2017). The external hyphae may provide a significant delivery system for K, Cu and Zn in addition to P and N in many soils. The contribution of mycorrhizae to uptake of Cu, Zn, Mn and Fe by maize as influenced by soil P and micronutrient levels was evaluated by Liu *et al*. (2000) and variation in Zn, Cu, Mn, and Fe uptake by *G. intraradices* was reported.

Mycorrhizal fungi have been reported to interact with a wide range of other soil organisms, in the root, in the rhizosphere and in the bulk soil. Upon its association with other microorganisms, there is an improvement in the activity of AM. For example, the spore germination and root colonisation efficiency of AM is enhanced by the bacteria as reported by Miransari (2011). *Azotobacter chrococcum*, *Pseudomonas putida* and *Bacillus polymyxa* have been tested along with AM fungus *Glomus intraradices* on *Stevia rebaudiana* (Vafadar *et al*., 2014). Other AM fungi like *Glomus fasciculatum* have been studied in association with bacteria to enhance plant growth (Singh *et al*., 2012). Improvement in the plant growth, nutrient absorption, phytohormone and chlorophyll production and biomass (Hemavathi *et al.*, 2006) has been reported as a result of the synergy between AM and bacteria (Krüger *et al.*, 2012). The effect of AM fungi on growth and development of a variety of horticulture crop plants (Rouphael *et al.*, 2015) has been studied and described in fruits (Ortas, 2018; Rajesh Kumar *et al.*, 2015), vegetables (Ortas *et al.*, 2013; Baum *et al.*, 2015) ornamental crops such as *Petunia hybrida, Tagetes erecta, Chrysanthemum morifolium* (Schmidt *et al.*, 2015; Gouveia, 2016; Crişan *et al.* 2017) with respect to the effect of mycorrhizal application on growth and yield.

Role of bacteria

Bacteria have a number of direct and indirect beneficial effects promoting the growth in plants. The various direct effects of plant growth promoting bacteria include solubilisation of mineral nutrients such as phosphorus and potassium increasing their availability, nitrogen fixation, sequestration of iron by production of siderophores, production of plant growth regulators and synthesis of ACC-deaminase in stress control in plants and various indirect mechanisms which include depletion of iron, production of antibiotic compounds, synthesis of antifungal metabolites and extracellular cell wall degrading enzymes of phytopathogens like fungi, competition and induced systemic resistance (Alori and Babalola, 2018).

Bacteria in nutrient availability and plant growth: Bacteria increase the availability of macronutrients like N, P, K and micronutrients like Fe etc to plants for their growth and development. There is a significant role of bioinoculants in N cycling and its utilization by plants in soil (Gupta *et al.*, 2012). The biological nitrogen fixation has a great practical importance considering the use of nitrogenous fertilizers which has resulted in water pollution due to nitrates and eutrophication of water sources (Mekonnen and Hoekstra, 2015). A wide range of bacteria, can fix nitrogen which includes species of archaea, bacteria and cyanobacteria which may be symbiotic or free living (Dynarski and Houlton, 2018). The atmospheric nitrogen fixed as a result of free-living nitrogen-fixing bacteria and symbiotic association between rhizobia and legumes represents a renewable source of nitrogen and is the primary source of fixed nitrogen in land-based agriculture systems and are suitable alternates for inorganic N fertilisers in organic farming. The majority of leguminous plants forming symbiotic relationship with the members of genus *Rhizobium* and its relatives belonging to class Alphaproteobacteria as well as the phylogenetically diverse free-living nitrogen-fixing bacteria including *Acetobacter, Arthrobacter, Azoarcus, Azospirillum, Azotobacter, Bacillus, Burkholderia, Enterobacter, Herbaspirillum, Klebsiella* and *Pseudomonas,* are helpful in providing nitrogen to a wide variety of important crops. (Gyaneshwar *et al.*, 2011; Flores-Félix *et al.*, 2015).

Besides N, another nutrient that limits plant growth is Phosphorus. Most of the agricultural soils have large amounts of inorganic and organic phosphorus but only a very low concentration of P is available to plants, and there is deficiency of phosphorus in many soils (Zhu *et al.*, 2018). P form complexes with metal ions such as iron or aluminium in low pH soils (Kiflu *et al.*, 2017) and calcium in high pH soils (Andersson *et al*., 2016) that leads to its precipitation or adsorption in the soil (Herrera-Estrella and López-Arredondo, 2016). When P fertilisers are applied to soils, most added soluble P (about 75 %) forms insoluble phosphates that is become bound in soil, resulting in lower availability of P available for crop growth and yield.

Different bacteria, reported from different environments, play significant roles in the solubilization of inorganic phosphate and mineralization of organic phosphates. A number of bacteria belonging to genera *Achromobacter, Aerobacter, Agrobacterium, Bacillus, Burkholderia, Erwinia, Flavobacterium, Gluconacetobacter, Micrococcus, Pseudomonas, Ralstonia, Rahnella, Rhizobium, Serratia* and others convert insoluble form of phosphates to soluble forms (Alori *et al*., 2017; Vyas *et al*., 2010). They solubilize by the various mechanisms like by the production of organic acids, release of other chelating substances and inorganic acids, and by releasing phosphatase enzymes.

The production of organic acids is the main mechanism for phosphate solubilization. The various organic acids produced by most of phosphate solubilizing bacteria during phosphate solubilization are gluconic acid, 2-ketogluconic, acetic, citric, glycolic, isovaleric, isobutyric, lactic, malonic, oxalic, propionic and succinic acids (Wei, 2018) which reduce pH and act as chelating agents, forming complexes with metal ions like calcium, aluminium or iron and release the phosphates which are then available to plants . The release of other chelating substances, inorganic acids such as sulphuric acid, nitric acid and carbonic acid, phosphatases including both acid phosphatase and alkaline phosphatase, phytase, phosphohydrolase are other mechanisms of phosphate solubilization by these bacteria enhancing the plant uptake of P and growth (Behera *et al*., 2017a; Behera *et al*., 2017b; Alori *et al*., 2017; Liu *et al*., 2018).

The population of phosphate-solubilising bacteria is more in the rhizosphere and found to be metabolically more active as compared with bacteria from non-rhizosphere and other locations (Wang *et al*., 2017). Increased plant growth, biomass and yield of different crops and plants have been recorded upon the inoculation of phosphate-solubilising rhizobacteria (Rizvi *et al*., 2014).

Supplementation of P in legumes has showed a positive response in leguminous plants like alfalfa, clover, common bean, cow pea and pigeon pea (Mitran *et al*., 2018). Several root-nodulating bacteria of different legumes also solubilize phosphates (Qin *et al*., 2011) and such bacteria show plant growth-promoting effect in non-legumes as well. Various inoculants are already available, and they have been used for many years without causing harm to the environment or end user (Abhilash *et al*., 2016).

Another essential macronutrient required for plant growth is potassium. It is present in soil as an abundant element but exists mainly in bound forms. It plays significant roles in many metabolic processes like photosynthetic activity, synthesis of protein, and enzymes' activation and in imparting resistance to pests (Rawat *et al*., 2016). Only 1–2 per cent of the K fertilizers applied to the fields become available to plants, the rest becomes bound with other minerals and hence not available to the plants (Prakash *et al*., 2015). Potassium-containing minerals including clay minerals (illite, kaolinite) and rock-forming minerals such as feldspars (microcline, orthoclase,) and mica (muscovite, biotite) contain potassium in bound form (Schön, 2015) which can be solubilised by several soil microorganisms by secreting organic acids. These acids either dissolve potassium directly or indirectly by chelating silicon ions releasing K into the solution (Sharma *et al*., 2016).

Different bacteria, namely, *Pseudomonas, Burkholderia, A. ferrooxidans, B. mucilaginosus, B. edaphicus, B. circulans, and Paenibacillus spp*. solubilize and release K from potassium-bearing minerals to an easily available form (Velázquez *et al*., 2016; Basak *et al*., 2017). The plant growth promoting activity of potassium solubilizing bacteria in different crops pepper, cucumber, maize, wheat, corn, cotton, rape, soybean etc has been reported by several workers (Singh *et al*., 2010; Zahedi *et al*., 2016; Prajapati and Modi, 2016). Microbial activity in soil plays an important role in favouring iron (Fe) uptake (Colombo *et al*., 2014). Many of the proteins and enzymes such as nitrogenase, leghemoglobin and hydrogenase, involved in photosynthesis and nitrogen fixation have iron as an important structural component. Chelating agents produced by soil microbes called siderophores and by plants referred as phytosiderophores, solubilise and transport inorganic Fe (Saha *et al*., 2016; Bocchini *et al*., 2015). Siderophores chelate Fe^{3+} with high affinity resulting in an efficient bioavailable source of Fe for plants. Plant roots exude phenolic compounds under Fe-deficient conditions in soil which may lead to the selective modification of microbial flora in the rhizosphere. The development of a particular rhizosphere microbiome that favours more siderophore-producing microbes increases the availability of iron and its acquisition by plants (Pii *et al*., 2016). Many bacteria, actinomycetes secrete siderophores including *Rhizobium, Azotobacter, Azospirillum, Alcaligenes, Pseudomonas, Enterobacter, Bacillus, Streptomyces* under low-iron conditions (Prakash *et al*., 2015; Wang *et al*., 2014). Various rhizobial strains have also been reported to release siderophores. The ability of these root nodulating bacteria in iron acquisition through siderophores is highly advantageous as iron is the structural component in many proteins involved in nitrogen fixation (O'Brian and Fabiano, 2010).

Role of microbes in stress control in plants

Plants are sessile organisms exposed to natural climatic or edaphic stresses and to environmental changes. The changing climatic scenario is supposed to have a surprising effect on agricultural production and farming practices as a result of these stresses. These involve both biotic and abiotic stresses can limit the growth and development of a plant (Irulappan and Senthil-Kumar, 2018). Various biotic stresses include infection by bacterial and fungal pathogens, viruses, insect predation and nematode infection. Abiotic stresses include high and low temperature, frost, drought, flooding, high salt concentrations, high metal concentrations, organic contaminants, mechanical wounding and excessive levels of radiation.

The stress tolerance in plants can be increased by applying the microorganisms and these techniques are increasingly being sought. Many studies have reported the important role of microorganisms like bacteria and fungi in improving plant health through increased protection against environmental stresses, either biotic (*e.g.*, pathogen attack) or abiotic (*e.g.*, drought, salinity, heavy metals, organic pollutants) (Miransari, 2010; Glick, 2014). All of these stresses induce the plant to synthesize growth-inhibiting stress ethylene (Glick *et al.,* 2007). Many plant growth-promoting bacteria have been reported to synthesize the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase. When the plants are treated with such bacteria, they produce lower levels of stress ethylene as a consequence of the consumption of the ethylene precursor ACC by the enzyme (Glick, 2010; Glick, 2014). These treated plants are damaged/inhibited to a significantly lesser extent following a biotic or abiotic stress than are plants that are not treated with ACC deaminase-containing plant growth-promoting bacteria (Glick *et al.,* 2007).

Control of abiotic stress

It is known that abiotic stresses adversely affect plant growth, productivity and trigger morphological, physiological, biochemical and molecular changes in plants; often leads to massive, often complete crop failures. In hilly areas, for example, cold stress limits the agricultural productivity of plants.

Water stress: To address the climatic hazards and struggle against drought, plants develop several defense strategies; for example, mycorrhizal association with soil fungi. AM symbiosis like *Glomus intraradices*, *G. claroideum* etc. affects the water relations of host plants (Wu *et al.,* 2013; Mohammadi *et al.,* 2011). The effects of water stress and arbuscular mycorrhizal fungi *Glomus versiforme* on reactive oxygen metabolism and antioxidant production by citrus (*Citrus tangerine*) roots was studied by Wu *et al.* (2007). They showed that AM symbiosis helps in increments of enzymatic and non-enzymatic antioxidant productions which in turn help AM plants to enhance drought tolerance. Barzana *et al.* (2012) found that roots of AM plants enhanced significantly relative apoplastic water flow as compared with non-AM plants and this increase was evident under both well-watered and drought stress conditions. The presence of the AM fungus in the roots of the host plants was able to modulate the switching between apoplastic and cell-to-cell water transport pathways which could allow a higher flexibility in the response of these plants to water shortage according to the demand from the shoot. Hazzoumi *et al.* (2015) studied the influence of mycorrhizal fungi (*Glomus intraradices*) and water stress on the growth of basil plants (*Ocimum gratissimum* L.). The AM fungi stimulate growth and photosynthesis and drive the water status in plant at an optimal level. A decrease in levels of proline and phenolic compounds was noticed, confirming the role of mycorrhizal symbiosis in plant defense against biotic and abiotic stress.

Salinity Stress: Salinity is one of the most severe environmental stresses as it decreases crop production of more than 20% of irrigated land worldwide. AM fungi have been shown to improve plant tolerance to salinity and arbuscular mycorrhizal plants also have improved photosynthetic and water use efficiency under salt stress (Porras-Soriano *et al.,* 2009). The significance of AM fungi in alleviating salt stress with improved host plant nutrition, higher K^+/Na^+ ratios in plant tissues and a better osmotic adjustment by accumulation of compatible solutes such as proline, glycine betaine, or soluble sugars was reported by Porcel *et al.* (2012).

According to Latef and Chaoxing (2011), AM fungi *Glomus mosseae* alleviate salt induced reduction of root colonization, growth, leaf area, chlorophyll content, fruit fresh weight and fruit yield of tomato plants and thus may protect tomato plants against salinity by reducing salt induced oxidative stress. Yaish *et al.* (2015) isolated and characterized endophytic bacteria some of which could solubilize potassium (K^+), phosphorus (PO_4^{3-}) and zinc (Zn^{2+}), from date palm (*Phoenix dactylifera* L.) seedling roots under saline conditions and found *Bacillus* and *Enterobacter* as the dominating genera. These strains also showed the ability to produce *enzyme* ACC deaminase and the plant growth regulatory hormone IAA, chelate ferric iron (Fe^{3+}) and produce ammonia which helped to promote the growth and development of date palm trees growing under salinity stress.

Heavy metal stress: The occurence of heavy metals in the environment constitute a potential hazard for water sources, soils and plants. Although some metals serve as essential micronutrients for plants and are required for their growth and development like Zn, Cu, Fe, Mn, Ni, Mo and Co, their high concentration and long term existence in soils may have adverse impact on soil and water quality thus compromising sustainable food production. AM fungi have repeatedly been demonstrated to alleviate heavy metal stress of plants. They can filter out toxic heavy metals, act as a sink reducing the metal concentrations near roots and thus keep them away from the plants, protecting them from stress and metal toxicity (Hildebrandt *et al.*, 2007; Karimi *et al*., 2011). Colonisation of plant roots by AM fungi considerably reduce the uptake of heavy metals into plant cells that may allow plants to thrive on heavy metal-polluted sites (Kumar *et al*., 2018).

Control of biotic stress

Microbes play a major role in sustainable crop production by conferring disease resistance to crop plants against a wide range of pathogenic organisms (Coninck *et al*., 2015) through their specialized and customized chemical secretions (Gourion *et al*., 2015; Bonfante and Genre, 2015), thus reducing the stress in plants due to pathogens. Recently biocontrol of phytopathogenic nematodes using nematophagous microorganisms and biocontrol of weed with AM fungi have also attracted much attention.

Microbial control of phytopathogens and nematodes: Various strategies are employed by bacteria in the rhizosphere for control of plant root pathogens, in indirect way through competition for nutrients and space on the root (Pliego *et al*., 2011), by induction of resistance in the host plant (Pieterse *et al*., 2014) and an a direct way by their antagonistic activity against the pathogen via the production of biosurfactants, antibiotics (Raaijmakers and Mazzola, 2012; Mavrodi *et al*., 2012), iron-sequestering siderophores or enzymes that hydrolyze the pathogen cell wall. Plant growth promoting bacteria which contain the enzyme ACC deaminase can modulate the level of ethylene in pathogen infected plants limiting the damage caused by the pathogen, may it be fungal/ bacterial/ nematodes (Glick, 2014; Nascimento *et al*., 2016). The siderophores produced by rhizobacteria play role in suppressing the growth of fungal pathogens (Beneduzi *et al*., 2012) which make the iron unavailable for fungal growth. Santos-Villalobos *et al*., 2012 reported *Burkholderia cepacia* or its siderophore having the potential to be used as a biological control agent against *Colletotrichum gloeosporioides*, the causal agent of anthracnose in mango. For the control of pathogens such as *Pythium ultimum* on sugar beet, *Phytophthora infestans* on tomato, *Pythium* and *Rhizoctonia spp.* on bean, and *R. solani* and *Gaeumannomyces graminis* var. tritici on wheat, cyclic lipopeptides produced by *Pseudomonas* spp. play a great role (Mishra and Arora, 2018; Yang *et al.*, 2014). Phenazine-producing strain of *Pseudomonas aureofaciens* 1393 as an active ingredient of biopesticides Pseudobacterin-2" marketed in the Russian Federation and used for the control of a wide range of phytopathogens as well as for the induction of resistance to plant diseases in organic and conventional crops (Thomashow and Bakker, 2015).

The impact of AMF on the reduction of soil borne diseases has mainly been evaluated in studies on fungal pathogens such as *Phytopthora, Aphanomyces, Fusarium, Verticillium* etc causing root rots and lesions (Singh and Giri, 2017) and nematodes causing galls (Lamovsek *et al.*, 2013). Arbuscular mycorrhizal (AM) fungi can confer protection to host plants against some root pathogens by inhibiting their growth and enhancing plant nutrition and health. Several other mechanisms including the production of phytohormones, siderophores, accumulation of defensive plant compounds, expression of defense related genes and increasing the colonization of plant growth promoting rhizobacteria also play an important role in disease suppression (Pozo *et al.*, 2008; Lioussanne, 2010). Interaction between arbuscular mycorrhizal fungi as a bio-agent and *Rhizoctonia* root rot disease of common bean plant was investigated by Abdel-Fattah (2011) demonstrating that colonization of bean plants with AM fungi significantly increased growth and yield parameters, and mineral nutrient concentrations and reduced both disease severity and disease incidence. Different physical and biochemical mechanisms have been shown to play a role in enhancement of plant resistance against *Rhizoctonia solani*, namely, improved plant nutrition, improved plant growth, increase in cell wall thickening, cytoplasmic granulation, and accumulation of some antimicrobial substances (phenolic compounds and defense related enzymes). A diversity of microorganisms including fungi, bacteria, and viruses exist in nature that shows antagonistic activity against phytopathogenic nematodes which cause serious losses in a variety of agricultural crops worldwide. Nematophagous microorganisms employ a variety of physical, chemical, and biochemical mechanisms to attack nematodes (Lamovsek *et al.*, 2013). Several commercial products based on the bacteria and fungi have been developed to control the root-knot nematodes like Meloidogyne spp. (Lamovsek *et al.*, 2013; Kiriga *et al.*, 2018) viz. bacteria like *Pasteuria penetrans, Bacillus firmus, Burkholderia cepacia and Bacillus* spp., and fungi like *Purpureocillium lilacinus, Pochonia chlamydosporia and Myrothecium verrucaria*. Using two commercially available arbuscular mycorrhizal fungal (AMF) products based on *Funneliformis mosseae* and *Glomus dussii*, Tchabi *et al.* (2016) assess their effect on yam growth and ability to suppress nematode damage. The presence of AMF tended to lead to improved growth of yam as compared to non- AMF control plantlets.

Control of weeds: The environmental-friendly weed control methods that can contribute to effective weed management in sustainable agricultural systems are being explored due to the problem of herbicide resistant in weeds as a result of the use of chemical control methods (Fialho *et al.*, 2016). Biological weed control refers to the action of biocontrol agents (parasites, predators or pathogens) to maintain weed population at a lower average density than would occur in their absence. AM fungi were found to suppress the competitiveness of the other type of plant population that is weeds in sunflower field. This ability of AM fungi can be exploited for biological control of weeds. AM fungi reduced the total biomass of a weed community and that this effect was even stronger in the presence of the crop sunflower (Rinaudo *et al.*, 2010). Veiga *et al.* (2011) investigated the effect of AM fungi (*Glomus intraradices, Glomus mosseae* and *Glomus claroideum*) on the growth of individual weed species and on weed-crop interactions and showed that AM fungi can negatively influence the growth of some weed species. Mycorrhizal weed growth reductions can be amplified in the presence of a crop. So, the maintenance and promotion of AM fungi activity may thereby contribute to sustainable management of agroecosystems.

Conclusion

The changing climatic scenario creates a great challenge to agricultural sustainability and requires an integrated approach for developing strategies in the years to come that aim at sustainable increase in agricultural production. Soil is a home to diverse microbial flora that plays key roles in ecosystem services. The existing agricultural management practices may affect their role in soil fertility and productivity in this changing climatic scenario. In the absence of potential management strategies to deal with the climate change, the microbes may lose their natural capacity to perform various biological activities like suppressing soil-borne plant pathogens, making nutrient pool in plant available forms etc, important for the growth, development, protection and productivity of crop plants. Harnessing plant-microbe interactions for the agricultural practices like integrated nutrient and soil management, integrated pest and weed management, organic agriculture involving the use of microorganisms in the form of bionoculants, biofertilizers, biopesticides, biological control of weeds etc along with other practices like conservation agriculture, use of cover crops, crop rotation, water and irrigation management practices etc, will help to contribute to climate change adaptation and building resistance and resilience in soil microbes.

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