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Promising Role of Fungal Symbiosis for Eco-Friendly Green Technology and Future Research: A Review

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Abstract : Fungi are plant like organisms that do not have chlorophyll also known for mutualistic association with plants. Fungi have recently attracted considerable interest worldwide due to their mutualistic nature along with advance in technology pique one's interest in green technology. Green technology is cost effective, environmentally friendly, locally available, socially acceptable and sustainable technology. The motto of bringing fungal symbiosis with green technology is to minimize the negative impacts of human involvement, their synthetic procedures, accompanying chemicals and derivative compounds. The exploitation of different types of chemicals and fertilizer degrades the quality of soil as well as plant product. At this time, biological resources like fungi, bacteria, plants and composting fertilizer have been used for the production of low cost, energy efficient and nontoxic environment friendly plant products which is considered a valuable approach in green technology. Fungal symbiosis also opens a way to pollution free environment by playing a significant role in salinity, drought, nutrients water uptake and heavy metal contamination which can be also helpful in agriculture development. During the development stage of world, we continually destroying the natural habitat of world. So based on the available information, this review article describes the basic understanding of fungal symbiosis in association with green technology.

Keywords: mutualistic association, sustainable technology, friendly plant products, nutrients, heavy metal contamination.

(1) Introduction

Earth would have been monochromatic without green patches and devoid of life in absence of interactions. Studies have unravelled how simple molecules interacted with each other to form complex compounds which acted as a raw material for biogenesis on earth. Unicellular organisms interacted with their surrounding environment and later evolved to complex multicellular forms that is plant and animal life. These events show that interactions- both inter and intra biotic is key driving force for evolution and sustainability on earth. Among that googol of interactions, fungal symbiosis holds key position due to its significant and productive impact on plant kingdom (mycorrhizal association) (Figure 1). Most of the species of plant including crop plants depend on mycorrhizal symbioses for their numerous fruitful services. Fungal symbioses perform several productive functions such as decomposition of organic material, nutrient cycling, mineral channelisation, enhancing water holding capacity thus improving soil fertility and plants growth. They also suppress phytopathogen growth (Sommermann et al., 0218). Species of *Trichoderma (T. asperellum, T. atroviride, T. harzianum,* *T. virens, and T. viride*) are frequently used in biocontrol and are known as biostimulants for horticultural crops (López-Bucio et al., 2015). They play pivotal role in agroecosystems, quality and quantity of food production and the efficacy of cropping system (Begum et al.,0219). Many species of fungi act as an effective biosorbent of toxic metals such as cadmium, copper, mercury, lead, and zinc, by accumulating them in their fruiting bodies and thus keeping a check on soil toxicity (Fr ͺac M et al., 2018). It is an established fact the fungal association with plants also enhances plant's tolerance to various abiotic stress such as drought, salinity and fluctuation in temperature (Begum et al.,0219). Importance fungal symbioses in soil management is well studied as it prevents soil from erosion (Chen et al., 2018). Furthermore, mycorrhizal fungi keep a check on emission of greenhouse gas that is N20 and thus indirectly helps in protection of ozone layer (Bender et al. ,2014). These potential impact of the fungal symbioses on plant productivity and soil health gives a new direction to the management of agro-economics and agro-ecosystem by cultivating soil fungal biodiversity to augment soil fertility and productivity which maycome to be called "2nd green revolution" (Bagyaraj and Ashwin, 2017). In this review, we emphasised on the role of the mycorrhizal fungi as a potent tool for eco-friendly green technology to enhance agricultural productivity. `

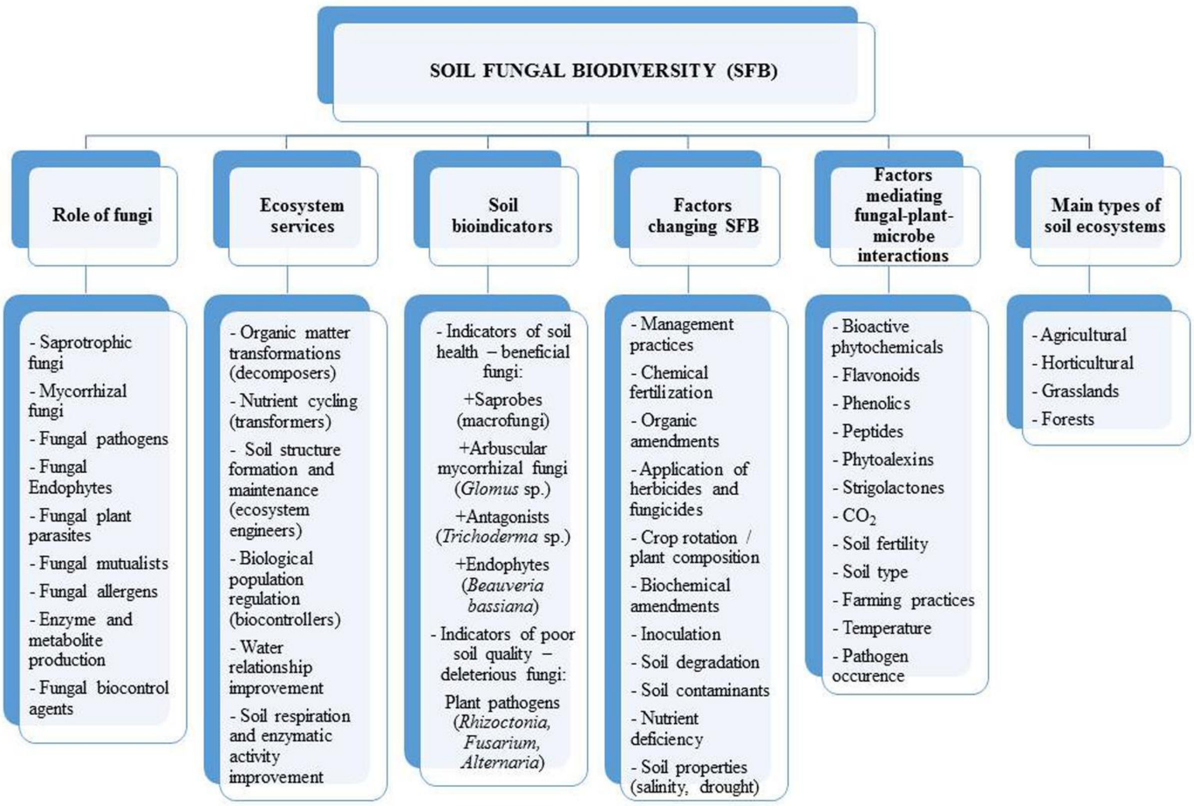

Figure 1: Ecosystem function and plant growth regulation by mycorrhizal symbiotes

Source: Fr ͺac M et.al (2018)

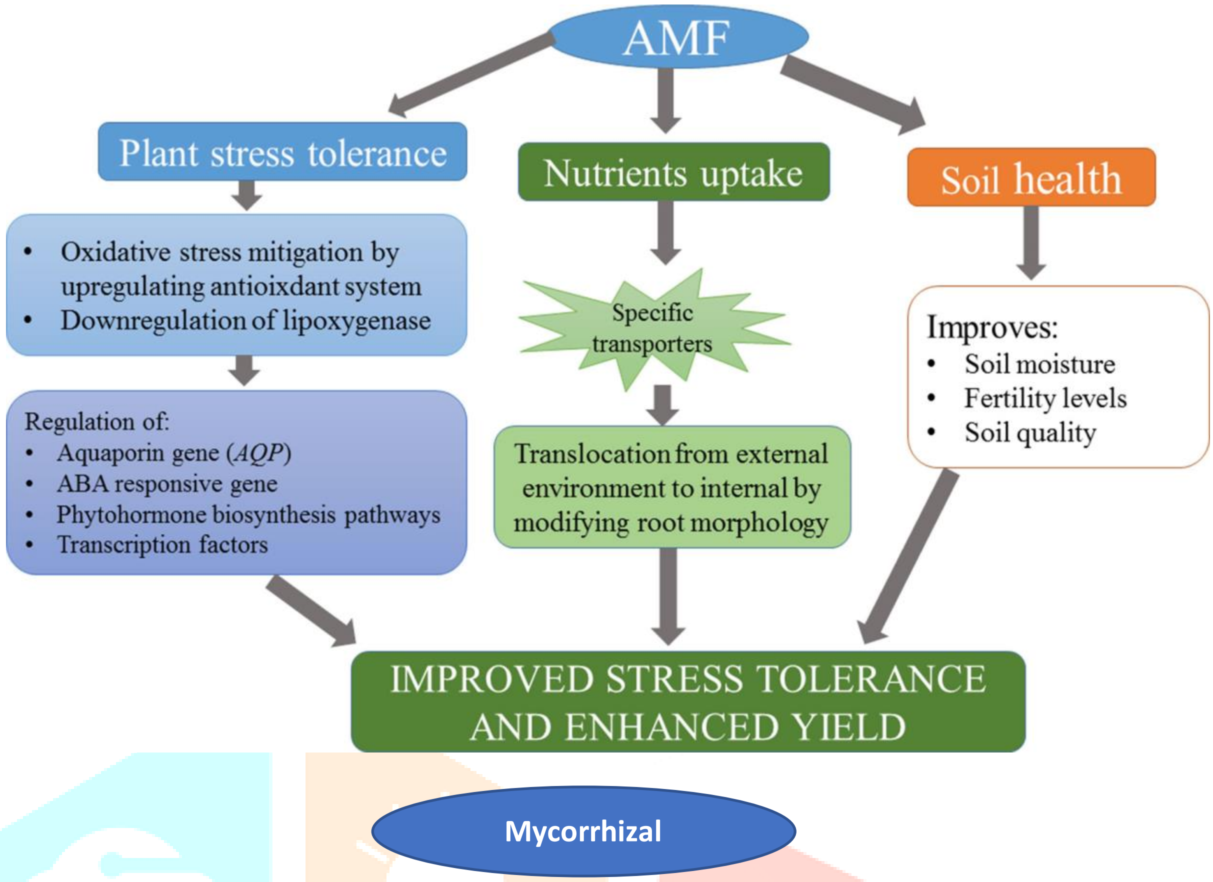

Figure 2: Ecosystem function and plant growth regulation by mycorrhizal symbiotes

(2) Importance of fungi in aspect of plant.

Recent studies have revealed that the early plant evolved from non-photosynthetic eukaryotes by engulfing photosynthetic cyanobacterium which further evolved to chloroplast (Ponce-Toledo et al., 2017). They required specific adaptations such as protection from high radiation, cuticle, vascular system and most importantly certain adaptations to facilitate plants to extract and absorb water and nutrient from the substrate in absence of well-developed root system which evolved later (Brundrett, 2002). Fungal symbioses may have played some crucial role in the settlement of land by descendants of freshwater algae (de Vries and Archibald, 2018). Evidence from recent studies indicates that the appearance of mycorrhizal fungi in early land plants was a remarkable event and thus, mycorrhizal fungi appear to be a monophyletic innovation that may have facilitated the rapid colonisation of landmass by vascular plants (Delaux, 2018). Thus, it is plausible to conclude that early rootless plants were involved in various fungal associations (Read et al., 2000) and are still observed today as the roots coevolved with the mycorrhizal symbioses in vascular plants (Brundrett, 2002). The mycorrhizal association effectiveness and productive services led to selection of this association by majority of the land plant in almost all the ecological niches. Most of the plant species including crop plants depend on mycorrhizal symbioses including ectomycorrhizae, ericoid and arbuscular mycorrhizae (Michaelson et al., 2008) for resource acquisition and defence. Among the most ancient and widespread of plant symbiosis are the mycorrhizal associations of plant roots and fungi (Brundrett, 2002). The term “mycorrhiza” is derived from the Greek words for “fungus” and “root”: attractive philological evincing of such biological interactions. The root of the plant releases specific compound for the selection of mycorrhizal coloniser in rhizosphere (Mendes et al.,2013). The mycorrhizal fungi can influence nearly every aspect of ecosystem function (Dighton, 2003), especially processes that occur in soils such as decomposition of organic carbon, transformations of nitrogen and phosphorus and hence maintaining the soil health (Treseder and Lennon, 2015). The breakdown of organic matter is chiefly dependent on mycorrhizal fungi which are key drivers of nutrient cycle (Dahlberg and Bültmann, 2013). Furthermore, the extracellular enzymes released by the mycorrhizal symbioses breakdown organic phosphorus and nitrogen into simper forms and facilitate phosphorus and nitrogen cycle (Sinsabaugh, 1994). Studies have revealed that plant showing mycorrhizal interaction exhibit increased resistance to pathogen (Cameron et al., 2013). They enhance the resistance to pathogen generally through improved nutrient uptake which is known as systemic acquired resistance (SAR) or through preparing the plant for faster and stronger reaction to pathogen which is known as induced systemic resistance (ISR) (Conrath et al., 2006) and thus facilitating plant in healthy growth. The mycorrhizal fungi show cosmopolitan distribution and are found in mostly all the major ecosystems (Rosendahl et al., 2006) and plays pivotal role in protecting plants against abiotic stresses (Chitarra et al., 2016) therefore provide fruitful services to the host plant both in wild and in agriculture (Nadeem et al., 2017). The mycorrhizal symbioses facilitate improved plant nutrition as they aid in absorption and translocation of nutrients beyond the depletion zone of rhizosphere of the plant. Furthermore, they interact with the phytohormone of the host plant and mediate the plant development (bioregulators) and induce tolerance to abiotic stress (bioprotector) (Rouphael et al., 2015) by promoting root system development (Gutjahr and Paszkowski, 2013). Figure 2 depicts the various fruitful services of mycorrhizal symbionts in respect to ecosystem function and plant growth. The beneficial services of the mycorrhizal fungi to the host and plant and its productivity are discussed further in detail.

(a) Ectomycorrhizal fungi

Ectomycorrhizal (ECM) fungi form association with plant of family Fagaceae, Pinaceae, and dipterocarpaceae found in temperate and arboreal forest and have economic importance (Futai et al., 2008). Ectomycorrhizal fungi (EcMF) are mostly belonging to Basidiomycetes with Ascomycetes and Zygomycetes. The Hartig network serves as the interface for metabolic interaction between the fungus and the root in the symbiotic association with host plant. The mycorrhizal mantle is connected to fungi filaments that extend into the soil (extraradical mycelium), and it is specifically involved in the recruitment, absorption, and translocation of soil nutrients and water to the roots. EcMF plays a significant role in the maintenance of forest ecosystems by colonising the roots of most plant species (Tedersoo et al., 2010). It has been documented from studies that EcMF plays an important role in seedling survival, establishment, and growth in various forest habitats (Smith and Read, 2008). Furthermore, studies have shown that EcMF act as in regulators of global carbon and nitrogen cycles in terrestrial ecosystem (Kumar and Atri, 2018) as enzymes such as proteases and chitinases secreted by EcMF breakdown the organic matter into simpler forms for assimilation (Nehls and Plassard, 2018). They also facilitate and enhance phosphorus availability as they secrete organic acids and phosphatases and also increases their mycelium input to improve phosphorus intake by the host plant (Plassard and dell, 2010). The EcMF colonisation of the root, on the other hand, provides defence to seedlings against soil pathogens (Laliberté et al 2015). Moreover, EcMF act as potential tool to mitigate the adverse effect of abiotic stresses such as salinity stress and heavy metal stress on host plant (Zwiazek et al., 2019; Luo et al., 2014). Under the effect of global climate change, meticulous research on correlation between the nutrient functioning of EcMF and their distribution pattern can give more precise and accurate information regarding the ecological impact of EcMF on the sustainability of forest ecosystem.

(b) Endomycorrhizal fungi

Endomycorrhizal fungi mainly belong to Zygomycota, Basidiomycota and Ascomycota. These endophytic fungi enter plants by spore formation and exist friendly within plant tissues and their emergence is observed during host tissue senescence. The major form of endomycorrhiza, arbuscular mycorrhiza, has been widely researched for its role in enhancement of plant productivity (Bonfante and Genre, 2010). The establishment of endophytic mycorrhizal association with the host occurs in successive stages (Genre et al., 2005). The formation of endophytic mycorrhiza occurs in distinct stages through evolution and development of fungal hyphae during root colonisation (Harrison, 2012). The endophytic fungi form mycelial network extending under the root of the plant symbiont and facilitates nutrient uptake by the plant. The mycelial network isn’t confined to single plant but invades roots of various plants irrespective of the species and forms a common mycorrhizal network (CMN) (Begum et al, 2019). The CMN formed by these symbioses is considered as the key factor in fungal mediated channelisation of nitrogen and phosphorous to plant (Smith and Read, 2008). It is well established fact that endophytic fungi increase the tolerance of host plant to pathogens and protect them from diseases (Ownley et al., 2008). Furthermore, the studies have revealed their ability to boost and improve soil characteristics subsequently vitalise plant growth in optimum as well as in stressful condition (Navarro et al., 2014). Fungal endophytes have ability to mitigate the abiotic stress on plant such as drought, salinity and heavy metal toxicity (Shukla et al,20120; Khan et al,2011; Li et al 2012) by regulating various changes in host plant morpho-physiological traits (Hashem et al, 2015). Furthermore, endophytic fungi particularly arbuscular mycorrhizal fungi are known to act as eco-friendly and natural growth regulator for various terrestrial plants. These arbuscular mycorrhizal fungi are used in horticulture and agriculture as bio-inoculants and are promoted widely by researchers as a potent biofertilizer for sustainable crop productivity (Barrow, 2012). Studies have shown that inoculated soil was observed with higher extra radical hyphal mycelium in comparison to non-inoculated soil (Syamsiyah et al., 2018). The potency of these endophytic mycorrhizal symbioses as bioregulator and bioprotector has attracted researchers and several eco-friendly bioproducts for enhancement of the plant productivity and resistance to diseases are already available in market (Whipps and Lumsden, 2001).

(3) Fungal symbiosis and soil fertility

Soil is a finite natural resource that is vulnerable to erosion, deterioration, and pollution. Apart from this, use of extensive agrochemicals for increasing the crop productivity has put adverse effect on soil health and fertility. Furthermore, excess application of these chemical-based fertilisers may lead to contamination and pollution of neighbouring water bodies and ground water. There is need of eco-friendly tools for maintenance and improvement of soil fertility. The plant-microbe interaction found is rhizosphere is considered as a major determining factor of soil fertility (Hayat et al., 2010). The fungal component regulates various crucial soil function such as decomposition of organic matter, cycling of nutrient, mineral channelisation, soil compaction and aggregation, enhancement of water holding capacity, plant growth regulation and keeping a check on phytopathogens (Neemisha, 2020). The mycorrhizal fungi facilitate carbon cycle (Fernandez et al., 2016) through reallocation of carbon either via priming the organic matter mineralisation pathway (Lindahl and Tunlid, 2015; Fernandez et al., 2016) or by fixing of carbon in recalcitrant organic compounds ((Sousa et al., 2012). During development, fungal symbionts form extensive network from the mycorrhizal roots leading to formation of a mesh or complex with the surrounding soil (Wilson et al., 2009). This mycelial network of the mycorrhizal fungi is major contributor to total soil microbial biomass (Leake et al. 2004). The network formed by the mycorrhizal symbionts play a significant role in binding action on the soil particle and enhance the structure of soil. Furthermore, a hydrophobic proteinaceous substance that is glomalin (Rillig et al., 2002) which is secreted by the symbionts facilitate soil stability and improves water holding capacity of the soil (Bedini et al., 2009). The mycorrhizal fungi are known to enhance the phosphorus uptake in plant growing in phosphorus deficient soil (Parewa et al., 2010). Studies have shown that mycorrhizal association can improve nitrate ion assimilation under abiotic stress such as drought (Azcon et al., 1996). Mycorrhizal symbionts have shown to boost supply and uptake of micronutrients such as nitrogen, phosphorus, zinc, magnesium, manganese and calcium to the root of host plant and thus aid in improving soil quality and fertility (Smith et al., 1994). It is well established fact that addition of biopolymers such as chitin can improve suppressive nature of the soil as it can destroy pathogenic fungal cell wall. The soil fungal and microbial diversity regulate the suppressiveness of the soil (Cretoiu et al., 2013) and can be used as an eco-friendly technique for eradication of soil pathogen. Moreover, studies have shown that mycorrhizal endophytic fungi can improve tolerance of host plant to biotic and abiotic stress via ethylene or salicylic acid pathways (Lahlali et al., 2014). The evaluation and determination of the soil fungal diversity can be used as an important indicator not only for the biodiversity indexes but also to analyse the significance of the fungal diversity in soil quality and soil health.

(4) Fungal symbiosis in Plant production

The excessive use of chemical fertilisers to enhance the plant productivity especially the crop plants has led to deterioration of soil health and also has nettled the effect of abiotic stress on plant productivity (Begum et al., 2019). The symbiotic fungi specially the arbuscular fungi come to the rescue as it acts as bio-fertilisers without having any ill-effect on soil ecosystem. Several studies have shown positive impact of fungal symbiosis on plant's tolerance to abiotic stresses such as drought, salinity, herbivory, temperature, heavy metal toxicity and diseases due to pathogenic fungus (Abdel-Salam et al., 2017). They facilitate plant to grow vigorously under stressful condition by mediating a series of complex communication events between the plant and the fungus leading to enhanced photosynthetic rate and other gas exchange-related traits (Birhane et al., 2012).

Most of the plant species including crop plants depend on fungal symbioses for resource acquisition and defence. Among the most ancient and widespread of plant symbioses are the mycorrhizal associations of plant roots and fungi (Brundrett, 2004). The term "mycorrhiza" is derived from the Greek words for "fungus" and "root": an attractive philological evincing of such biological interactions. Fungi can influence nearly every aspect of ecosystem function (Dighton, 2003), especially processes that occur in soils such as decomposition of organic carbon, transformations of nitrogen and phosphorus and hence maintaining the soil health (Treseder and Lennon, 2015). Both partners benefit from the relationship: mycorrhizal fungi improve the nutrient status of their host plants, influencing mineral nutrition, water absorption, growth and disease resistance, whereas in exchange, the host plant is necessary for fungal growth and reproduction (Facelli et al., 2009). Soil fungi produce different types of extracellular enzymes which aid in decomposition of organic and soil components thus regulating the balance of carbon and nutrients (Zifcáková et al., 2016). The extensive hyphal network developed in the soil by the symbiotic fungi, termed as wood-wide web, connect the whole plant communities of that habitat facilitating efficient linear transfer of nutrients (Helgason et al., 1998) and thus enriching the soil quality and enhancing the plant productivity. Keeping in view the productive services of the fungal symbioses towards the plant productivity, we can hypothesise that the fungal symbioses can be an effective tool for eco-friendly and sustainable management of plant productivity with major emphasise on crop plant productivity. It has potency to enhance agricultural productivity to meet the growing demand of the population without having detrimental effect on the agri-ecosystem that is soil health and can serve as platform for the establishment of green technology.

(5) Role of different type of fungi in plant productivity

(i) Saprophytic fungi

Saprophytic fungi are considered as initiator of decomposition process (Maltz et al., 2017) as they act as primary decomposer on cellulose, lignin and other complex organic macromolecules (Berg and McClaugherty, 2014). The potent lignocellulolytic enzymes secreted by the saprophytic fungi helps breakdown of the complex organic compounds and plant litter into simple inorganic molecules such as sugars, amino acids, NH_4^+, PO_4^{-3}, H_2O and CO_2 which can be easily assimilated by the plants (Baldrian and Valášková, 2008). The complex hyphal network of the saprophytic fungi facilitates soil mineralisation and carbon cycling (Francioli et al., 2020). Several studies have revealed that the hyphal chord of the saprophytic fungi have ability to translocate carbon, phosphorous and nitrogen thus helping in nutrient distribution in soil (Crowther et al., 2012). The mycelial system of the saprophytic fungi helps the plant to counteract the negative effect of the herbivory and grazers by increasing nutrient uptake through fine hyphae (Bengtsson et al., 1993). We can conclude that the saprophytic fungi enrich the soil with nutrient through decomposition and also helps in channelisation of these nutrients through their hyphal chord and thus enhancing the plant productivity.

(ii) Pathogenic fungi

Fungal pathogen are the organisms which can incite disease in its host. They are important agents in shaping structure, composition, succession, and landscape patterns of a particular habitat. Most of the fungal pathogens have detrimental effect on the plant productivity. But some of the pathogenic fungi share friend and foe relationship with the plants. Soil pathogens are considered an important part of the negative microbial feedback that helps to determine species richness over large environmental gradients. When looking at the complex niche level, negative impacts on one species can favour another by reducing competition or improving nutrient cycling. Mutualistic and symbiotic advantages (e.g., mycorrhizal fungi and endophytic antagonists contained in grasses) or useful attributes as biological control agents are often found in organisms with pathogenic conduct (Winder and Shamoun, 2006). For example, the wood-rotting fungus *Phlebiopsis gigantea* has been used as a biological control tool to check the spread of *Heterobasidion annosum* which is causative agent of annosus root and butt rot, (Roy et al., 2003). The chemical herbicides and weedicides used in agri-system also eliminates the useful microbes with the target leading to deterioration of soil health. Studies have revealed the potency of fungal pathogen as mycoherbicides which can be used to keep a check on growth of weed population (Wall et al., 1992) which can reduce the competition for nutrient thus improving the plant productivity of that particular area. The comprehensive research studies of niche of pathogenic fungi could reveal more beneficial role of these pathogens.

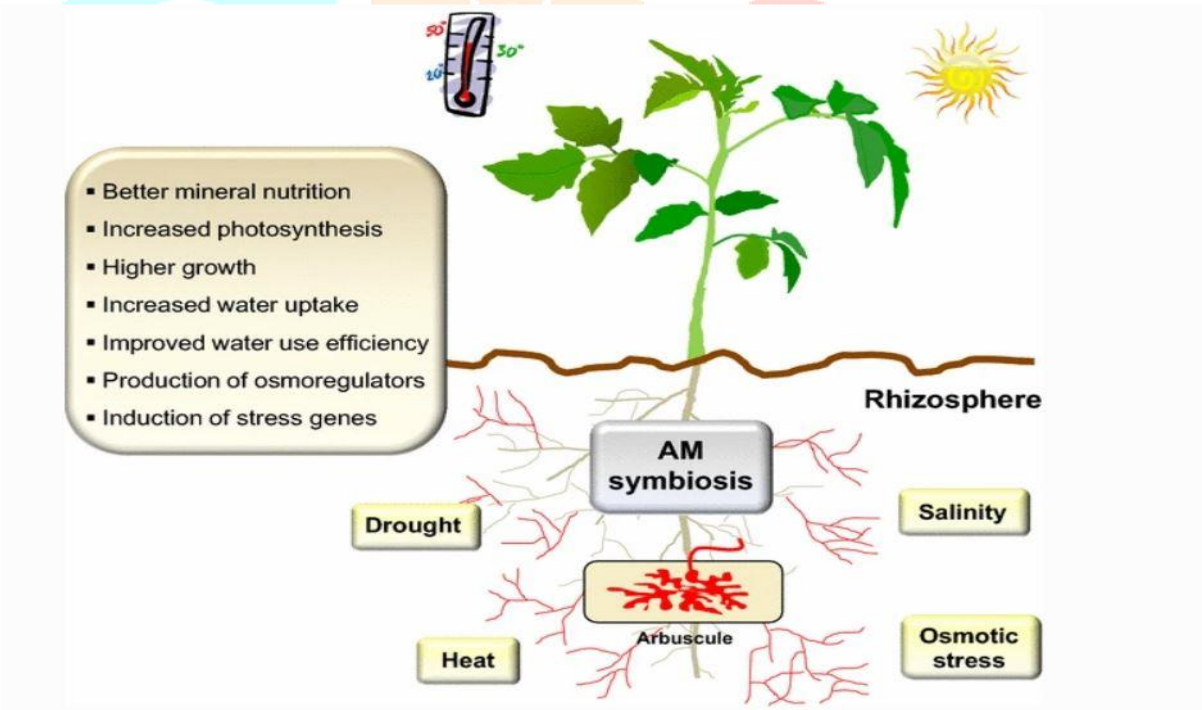

Figure 3: Shielding effect of mycorrhizal symbiosis against various stresses.

(6) Fungal symbiosis and Soil management

Soil management is a crucial step for enhancement of productivity of plant species especially the crop plants and also for the maintenance of soil health (Bhardwaj et al., 2014). Plant experience both abiotic and biotic stress such as drought, salinity, heavy metal toxicity, extreme temperature hampers the plant's growth and productivity (López-Ráez, 2016). Dependency on chemical-based fertilizers as a soil management strategy has aggravated the negative effect of these abiotic stress on plant's productivity and soil health (Begum et al., 2019). Of the known fungal symbiotes, the arbuscular mycorrhizal fungi (AMF) play a pivotal role as bioengineer to maintain the soil structure and enhances the plant's plasticity to the changing unfavourable external condition apart from enriching the soil with essential nutrients (López-Ráez, 2016). AMF has ability to regulate certain traits of the host such as growth, flowering and root structure thus helps the plant to enhance its plasticity to overcome abiotic and biotic stress (Pozo and Azcón, 2007) (Figure 3). During drought, AMF ameliorate plant's sturdiness possibly by increasing surface area for water absorption through extension of its hyphal network (Smith, S.E) or by improving the apoplastic flow of water (Bárzana et al., 2012). Evelin et. Al (2009) hypothesised that AMF alleviate the salinity stress by improving the ion homeostasis, enhanced phosphorous intake and hyperactivity of antioxidant enzymes. Under heavy metal stress, the colonisation of AMF with root of the host plant leads to expression of specific genes which regulate the synthesis of proteins (metallothionein) which increases the tolerance of the plant to the stress (Rivera-Becerril et al., 2005). Temperature is one of the most importance abiotic stress which can hamper the plant's growth. Studies have shown that AMF improves the tolerance of plant to extreme heat or cold (Hajiboland et al., 2019) by increasing accumulation of osmolytes, enhancing the photosynthetic capacity and protecting the plant from oxidative damage (Zhu et al., 2011). The role of fungal symbioses particularly the AMF in different abiotic stress is discussed below.

(i) Soil erosion

Agricultural malpractices decrease the aggregation and stability of soil particles resulting in increased dispersal of soil particles and hence adversely affecting the soil structure (Cardoso and Kuyper, 2016). Studies have shown that the members of soil biota decrease the soil erosion by formation and stabilisation of soil aggregates (Rillig and Mummey, 2006). AMF improves the soil structure by creating a three-dimensional matrix through it dense hyphal network of highly branched mycelium which cross-links the soil particles (Rillig et al., 2002). Apart from forming the mesh to crosslink the soil particles, the AMF hyphae produce glomalin glycoprotein which also contributes to maintenance of soil structure (Singh and Tripathi, 2013). Glomalin in soil increases the carbon storage which affects the soil compaction and stability and hence, soil structure (Cardoso and Kuyper, 2016). Glomalin related soil proteins (GRSP's) play a vital role in aggregation of soil particles (Wilson et al., 2009). Thu the AMF plays a pivotal role in maintenance of soil structure and prevention of soil erosion. The fruitfulness of AMF is especially important for plants growing in dry sandy soils in arid climates. Soil found in these regions are mainly low in fertility and extremely susceptible erosion caused due to wind and rain. In such regions, planting mycorrhizal plants may be a long-term solution for erosion control and soil fertility improvement.

(ii) Salinity

Soil salinity has become one of the most severe abiotic factors in many countries of the world (Pitman and Läuchli, 2002). The use of chemical fertilisers and improper irrigation techniques has intensified the salinity stress (Daei et al., 2009) posing a serious threat to the global food security. Salinity stresses supress the plant productivity by reducing the assimilation rate (Hasanuzzaman et al., 2013) and also promotes excessive formation of reactive oxygen species (Ahanger and Agarwal, 2017). Studies have shown the potency of AMF in mitigating the adverse effect of salinity on plant growth (Latef and Chaoxing, 2011). Plants show increased dependency on AMF symbiosis which indicates its significance in alleviation of salinity stress on plant growth (Tian et al., 2004). AMF enhance the tolerance of plant to salinity stress by improving ion balance (Asghari et al., 2005) and also protects the soil enzymes (Giri and Mukerji, 2004). Recently, it has been reported that AMF have valuable effect on photosynthetic rate, stomatal conductance and leaf water retention of plants growing under salinity stress (Ait-El-Mokhtar et al., 2019). High sodium adversely affects the chlorophyll concentration in the leaf by inhibiting the magnesium absorption. AMF has shown capability to increase the magnesium absorption required for the synthesis of chlorophyll thus alleviating the adverse effect of sodium on photosynthetic rate (Miransari et al., 2009). The hyphal network of mycorrhizal symbioses prevents plant dehydration and turgor loss by increasing the water intake by plant (Latef et al., 2014). Organic solutes such as proline, glycine, betaine and soluble sugars are accumulated in arbuscular mycorrhizal plants which contribute to adjustment of cellular osmotic balance, detoxification of reactive oxygen species and stability of useful enzymes (Sanchez et al., 2008). AMF inoculated plants have shown higher concentration of key growth regulators such cytokinin under salinity stress (Asiya et al., 2014). Studies have also revealed that AMF inoculated plant show enhanced production strigolactone which mitigates the adverse effect of salinity stress on plants. The above-mentioned role of the fungal symbioses particularly the AMF shows that these symbioses can play crucial role in coping up with the salinity stress and have potency to increase the plant productivity by mitigating the adverse effect of the salinity stress.

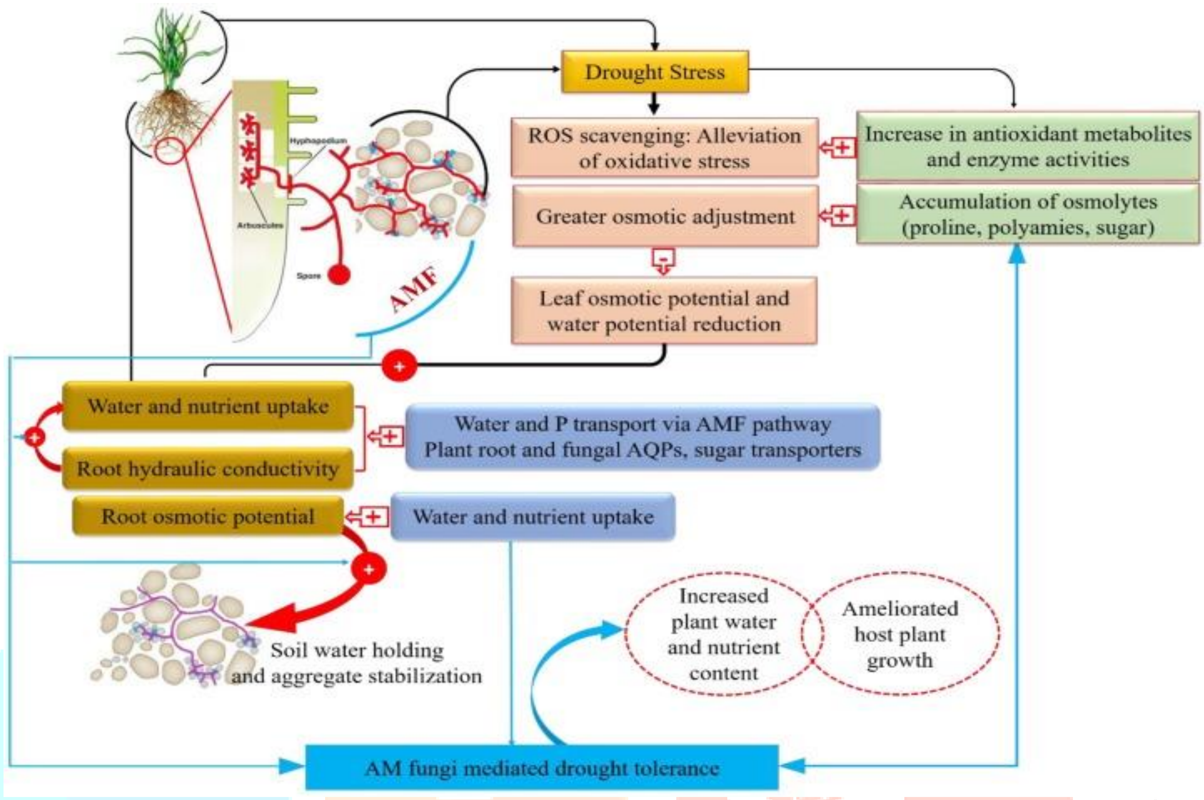

Figure 4: Process involved in alleviation of drought stress by mycorrhizal symbiotes (AMF).

Source: Bahadur et. Al (2019)

(iii) Drought

Due to irregular precipitation, drought is becoming one of the major abiotic stress which has deleterious effect on plant growth and productivity (Posta and Duc, 2020). It has harsh impact on crop productivity and hence puts the global food security in jeopardy (Zhang et al., 2018). Drought or water scarcity stress act as constraint for enzyme activity, ion uptake and nutrient assimilation causing detrimental effect on plant's growth (Ahanger et al., 2017). Water scarcity induces stomatal closure, which decreases CO2 influx and, as a result, reduces photosynthetic activity and carbon partitioning (Osakabe et al., 2014). Apart from these, drought stress can cause osmotic stress leading to turgor loss which results in inhibition of growth and development in plant (Selmar and Kleinwaechter, 2013). Several studies have also revealed that drought stress induces increased production of reactive oxygen species which leads to membrane damage and cell death in plants (Gill and Tuteja, 2010). Studies have provided strong evidence regarding the potency of the AMF to alleviate the stress caused to plant due to drought (Moradtalab et al., 2019). The extended network of AMF hyphae increases the water absorption by providing efficient access to small soil pores or by improving apoplasticity (Auge,2001). AMF association with plant regulate certain key physiochemical processes such as osmotic adjustment (Dar et al., 2018). Abscisic acid (ABA) is one the major stress phytohormonal signal which governs key physiological activities such as transpiration rate and aquaporin expression. The ABA responses control the stomatal conductance and cause closure of stomata leading to reduced water loss. The AMF symbioses regulate the stomatal conductance by controlling ABA metabolism (Ouledali et al., 2019). AMF also mediates modifications in some other phytohormones such as strigolactones and jasmonic acid which mitigates the water stress by improving hydraulic conductivity (Fernando lizaro and Moreno-Fonseca, 2016). Plant with AMF colony show increased concentration of antioxidant such as superoxide dismutase, catalase and peroxidase which detoxifies the reactive oxygen species (Ruiz-Lozano, 2003). Sustainable agricultural practices and management of natural resources are catching attraction due to their eco-friendly nature and economic viability. AMF can be used as an effective tool to formulate cost effective and eco-friendly strategies to mitigate the adverse effect of drought stress on the plant and thus enhancing their productivity (Figure 4).

(iv) Temperature extremities stress

Anthropological activities such deforestation, fossil fuel combustion and emission of greenhouse gases from industries has put adverse effect on climate. These has caused abrupt seasonal duration and has led to fluctuation in optimum temperature range. The change in temperature beyond the optimum range has deleterious stress on plant growth (Zhu et al., 2011). Exposure of plant to low or high temperature stress disturbs many essential physiological and biochemical mechanisms (Zhu et al., 2017). Several studies have proven the efficacy of the AMF to enhance the tolerance of AMF inoculated plant to the extreme temperature (Caradonia et al., 2019). AMF protects the plant from the unfavourable condition by enhancing the water and nutrient absorption rate, photosynthesis efficiency, osmolyte accumulation and protective plant from oxidative damage (Zhu et al., 2017). The heat stress adversely affects the plant productivity by imparting retarded growth, wilting of leaves, abscission and senescence of leaves, discolouration of fruits, increased oxidative stress, cell death and reduced yield (Wahid et al., 2007). Studies have revealed that AMF inoculated plants show better growth under heat stress in comparison to the non-inoculated plants (Gavito et al., 2005). Under heat stress AMF facilitate development of the plant's root system which provides increased uptake of water and nutrient and protects the photosynthetic apparatus from getting damaged (Mathur and Jajoo, 2019). Cold stress severely affects the plant growth as it induces membrane damage due to dehydration related to freezing (Yadav, 2010). It was observed that low temperature leads to reduction of hydraulic conductance and impairment of stomatal control (Aroca et al., 2003). Plant also exhibit alteration in chlorophyll concentration and reduced chloroplast development (Farooq et al., 2009). Chen et al. (2013) in their study concluded that inoculation of plant with AMF can increase its tolerance to cold stress. AMF can absorb and retain moisture (Zhu et al., 2010) thus aids the plant in combating dehydration. The plant inoculated with the AMF show increased production of secondary metabolites which improves their immune system and also increases their protein content to tackle the cold stress condition (Latef and Chaoxing, 2011). Under cold stress, AMF symbiosis with plant have shown substantial increase in chlorophyll synthesis in the plant which help the plant to combat the unfavourable condition (Zhu et al 2010). Further research and advancement can aid in shaping the services of these fungal symbioses into an eco-friendly tool to tackle the reduction in plant growth and productivity due to extreme temperature.

(v) Heavy metal contamination

Metals such as copper, iron, manganese, zinc, nickel, cadmium and magnesium at lower concentration act as catalyst for different important biochemical mechanism or as a cofactor of several enzymes in plant physiology (Nies,1999). Heavy metals and metalloids can accumulate in soils due to contamination from increasingly developing industrial fields, mine tailings, dumping of high metal wastes, fertiliser application, sewage sludge, pesticides and coal combustion residues (Wuana and Okieimen, 2011) and thus increasing its concentration. The high concentration of heavy metal in soil has detrimental effect on its health, plant growth and can pose serious health issues in human as they can enter the body through various agricultural products (Yousaf et al.,2016). The contamination of soil with heavy metal can cause deterioration of soil function such as filtering and buffering (Vamerali et al., 2010). On the other hand, high concentration of heavy metal in soil when absorbed plant can interfere with structure of enzyme and hence disrupting their function by affecting the protein structure (Sajedi et al., 2010). Furthermore, interaction of heavy metal with plasma membrane of plant can lead to change in its permeability and functionality as these metals can alter the structure of intrinsic protein such H+-ATPases (Hall, 2002). In addition, the heavy metal toxicity can induce oxidative stress leading to appearance of toxicity symptoms such as chlorosis, growth retardation, browning of roots and cell cycle arrest (Schützendübel and Polle, 2002). The conventional strategy for remediation mainly relies on the physical displacement, transport and storage of contaminated which is however an expensive procedure also leads to removal of soil microflora from the site. Several studies have shown that more than 80% of plants growing on mining sites exhibit AMF colonisation (Wang, 2017). AMF play a crucial role in bioaugmentation as it can alleviate the heavy metal toxicity stress on plant by soil remediation. Researcher have found that AMF has ability to mitigate adverse effect of cadmium on the plant growth by the process of phytostabilisation (Janousková et al., 2007). The roots of plant growing under heavy metal stress when colonised by AMF induces expression of certain genes which govern synthesis of proteins such as metallothioneins which alleviates the toxicity stress (Rivera-Becerril et al., 2006). The fungal hyphae have ability to immobilise the heavy metal in the cell wall by formation of vesicles or arbuscles (Weiersbye et al., 1999) which keeps heavy metals out of the plant or lowers its concentration (Hildebrandt et al., 2007). Arbuscular mycorrhizal association under heavy metal stress induces production of several antioxidant enzymes such as gluthatione S-transferase, superoxide dismutase, cytochrome P450 and thioredoxin which protects the plant from oxidative stress (Hildebrandt et al., 2007). The extensive network of the AMF hyphae allows it to absorb excess nutrients even beyond the growing zone of the plant's root (phytoremediation) (Leyval et al. 2002). The ability of plants inoculated with AMF to absorb high level of heavy metals provides a favourable platform for reduction of heavy metal from soil (phytoextraction) which contribute to positive soil health (Figure 5). These fruitful services of AMF can be used as potential tool to maintain good soil health (Christie et al. 2004) which consequently enhances growth and productivity of plant under heavy metal stress.

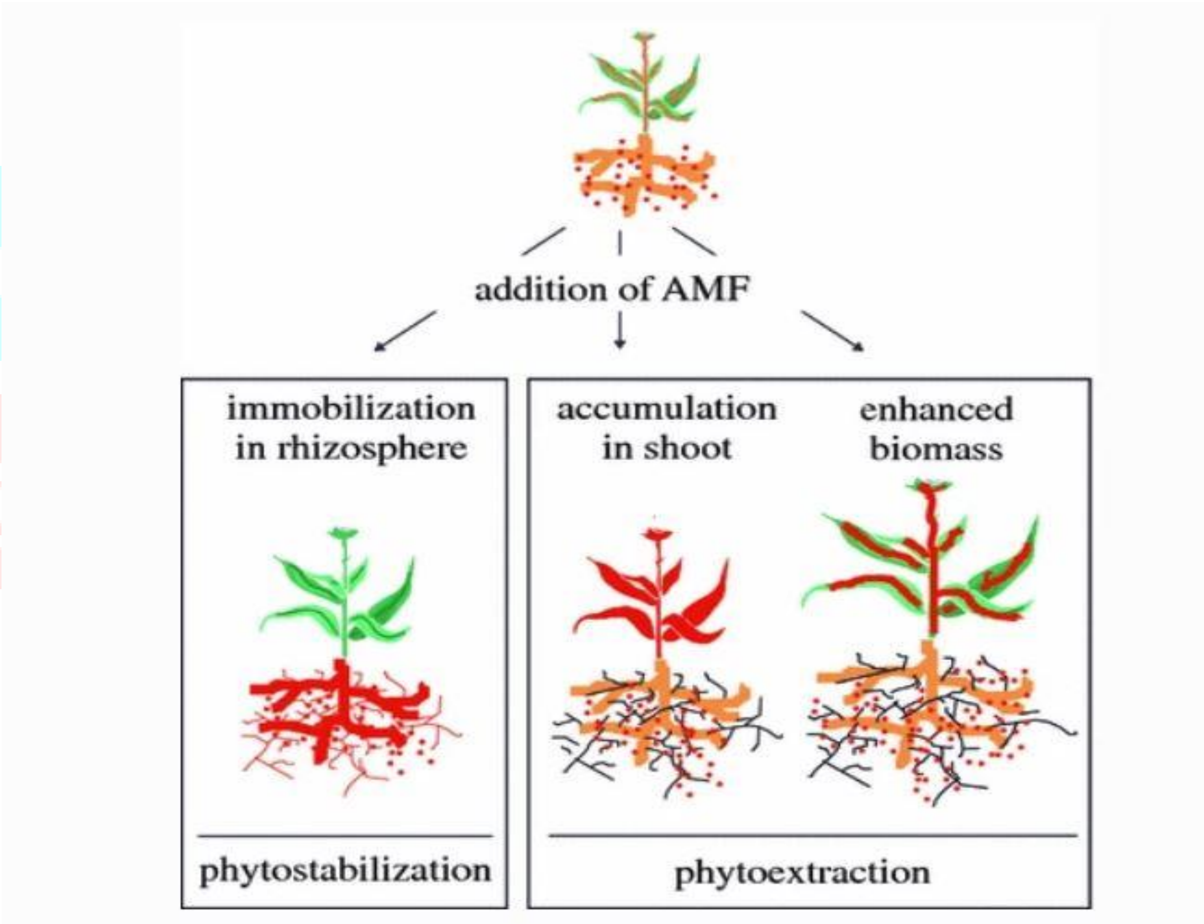

Figure 5: Role of mycorrhizal symbiotes (AMF) in coping up with heavy metal stress in plants.

Source: Göhre and Paszkowski (2006)

(7) The potential role of Mycorrhiza in Sustainable agriculture

Heavy dependence on chemical fertilisers to enhance crop productivity has adverse effect on soil microbiota, soil health and can also lead to groundwater pollution and eutrophication of waterbodies (Youssef and Eissa, 2014). The agricultural malpractices have led to plateaued crop productivity due to soil degradation (Grassini et al., 2013). Exponential growth in population has placed unparalleled pressures on agriculture and natural resources. A billion people are critically malnourished today, while the conventional agricultural practices degrade soil, water, diversity and climate on a global scale. To satisfy the world's food security and growing needs, food production must increase drastically and also agriculture's environmental footprint must decline dramatically (Foley et al., 2011). Keeping in mind the significance of soil fungal diversity in enhancement of agro-ecosystem productivity as discussed above, the management of these soil fungal diversity can be an effective novel strategy for eco-friendly acceleration of crop productivity to meet the growing demand (Ellouze et al., 2014). AMF symbiosis has got major attention from researchers around the world due it's multifunctional services in plant nutrition, protection from pathogen, stress tolerance and soil structure stability service (Leafheit et al., 0214; Gianinazzi et al., 2010). Table 1 shows some widely used inoculant which are used as eco-friendly tool to mitigate the adverse effect of abiotic stress on plants. Biofertilisation that is improving the diversity and population of micro-organisms such as AMF using microbial inoculants (biofertilisers) can be an eco-friendly alternative to chemical fertilisation as it facilitates plants to effectively utilize essential mineral elements such as nitrogen and phosphorus (Alori et al., 2017). Studies have shown that AMF can be to harness to improve nutrient level in crop and biofortification and can influence crop quality (Lehmann et al., 2014). The beneficial services of the mycorrhizal association are not just limited to the facilitation of nutrient to plants. The extensive network of the mycorrhizal hyphae plays crucial role in maintenance of soil structure, increasing soil aggregation and consequently increases the soil pore size (Mardhiah et al., 2016). Soil rich in mycorrhizal symbioses have shown better water holding capacity and increased tolerance to drought stress (Ortiz et al., 2015). Studies have shown that agricultural malpractices and disturbance caused due anthropogenic activities leads to decline in mycorrhizal fungi population (Helgason et al., 1998). In order to address the decline in mycorrhizal fungal population, researchers around the world are focused on applied research for the development of mycorrhizal technology for production and application of mycorrhizal inoculants (Vosatka et al. ,2012).

STRESS	HOST PLANT	FUNGAL SPECIES	RESPONSE	REFERENCE
Drought	*Glycine max*	Arbuscular mycorrhizal fungi	Enhancement of photosynthesis rate, relative growth rate and leaf area index.	Pavithra and Yapa (2018)
Drought	*Poncirus trifoliata*	*Funneliformis mosseae, Paraglomus occultum*	Improved hyphal length, water absorption rate and leaf water holding capacity.	Zhang et al. (2018a)
Drought	*Triticum aestivum L.*	*Glomus mosseae, Glomus fasciculatum, Gigaspora decipiens*	Increase in plant growth parameters total chlorophyll pigment concentration.	Pal and Pandey (2016)
Drought	*Pelargonium graveolens*	*Rhizophagus intraradices, Funneliformis mossea*	Enhanced nutrient concentration, glomalin related soil proteins (GRSP) and essential oil content.	Amiri et al. (2015)
Heat	*Triticum aestivum L*	*Rhizophagus irregularis, Funneliformis mosseae, Funneliformis geosporum, Claroideoglomus claroideum*	Increased nutrient channelisation and nutrient composition in root.	Cabral et al. (2016)
Heat	*Zea mays*	*Rhizophagus intraradices, Funneliformis mosseae, F. geosporum*	Increased leaf length and number,plant height, chlorophyll concentration, photosynthesis rate, stomatal conductance and transpiration rate	Mathur et al. (2016)
Metal toxicity	*Sesbania rostrata*	*Glomus mosseae*	Formation of root nodules, and increased N and P concentration.	Lin et al.(2007)
Metal toxicity	*Trigonella foenum-graecum L.*	*Glomus monosporum, G. clarum, Gigaspora nigra, and Acaulospora laevis*	Enhanced antioxidant enzyme's function.	Abdelhameed and Rabab (2019)
Metal toxicity	*Cajanus cajan L.*	*Rhizophagus irregularis*	Improved root biomass, nutrient status and proline synthesis.	Garg and Singh (2017)
Salinity	*Cucumis sativus L.*	*Glomus etunicatum, Glomus intraradices, Glomus mosseae*	Improved biomass, enhanced photosynthetic pigment synthesis and antioxidant enzyme	Hashem et al. (2018)
Salinity	*Solanum lycopersicum L.*	*Rhizophagus irregularis*	Increased leaf area, leaf number and levels of growth hormones.	Khalloufi et al. (2017)

Salinity	*Aeluropus littoralis*	*Claroideoglomus etunicatum*	Increased stomatal conductance, α-amino acids and Na+ and K+ assimilation.	Hajiboland et al. (2015)
Salinity	*Solanum lycopersicum L.*	*Glomus intraradices*	Improved ion uptake and chlorophyll content.	Hajiboland et al. (2010)

Mycorrhizal technology aims at enhancing the mycorrhizal services in context of yield improvement and sustainability of ecosystem within given socioeconomic constraints (Lamarque et al., 2014). Besides the advantages such as ease of production of inoculants, the long-term effect of these mycorrhizal inoculant on the native mycorrhizal fungal communities is still unknown (Schwartz et al., 2006). It is likely that fungal inoculation encourage competition among the fungi within the soil which facilitates propagation of species likely to offer benefit to plant to which they associate and may lead to desirable outcome for sustainable

Table 1: Widely used fungal inoculant as eco-friendly tool to mitigate the effect of abiotic stress on plants.

agricultural productivity (Field et al., 2002). In other case, there could be possibility of incompatibility between crop plant and mycorrhizal genotypes which may result in parasitic behaviour of the fungi leading to increased carbon drain on host plant consequently causing reduction in yield (Klironomos, 2003). There is a need of in-depth research and comprehension regarding impact of mycorrhizal inoculants on these factors, for analysis and assessment of the quality and efficacy of the inoculants and for formulation of proper standards and certification for such products (Schwartz et al., 2006).

(8) Need, challenges and future perspectives of fungal symbiosis

The mycorrhizal symbiosis draws key attention of the researchers due to its productive services. The major areas of mycorrhizal symbiosis include mechanism supporting the development of the symbiosis, the mycorrhizal biome, the extent and function of mycorrhizal network and depth comprehension of the role of mycorrhizal symbioses in nutrient dynamics. In recent years significant progress has been made in identifying the key elements such as plant symbiotic signalling pathways, root colonisation mechanism and host-microbe interface development involved at in establishment of symbiotic interaction between plant and mycorrhizal symbioses (Martin et al., 2017). These studies have deepened our comprehension about maintenance of mycorrhizal symbiosis and has aided in enhancing our pragmatic approach. Studies related to plant physiology conducted under the light of genomics and transcriptomics have revealed the significance of intraspecific variation in host plant and mycorrhizal symbioses in their interactions with one another as well as their responses to the abiotic environment (Gehring and Johnson, 2018). Still, due to development of research on mycorrhizal symbiosis into separate disciplines has led to a void of partial understanding of mycorrhizal operations. The genes involved in establishment and maintenance of the mycorrhizal symbiosis are still ambiguous. Thus, the probing of symbiotic gene networks involved in the molecular cross talk between plant and fungus is a major challenge to comprehend their coexistence and elements involved in establishment of symbiotic interaction. Furthermore, advance research is required to associate molecular statistics and metabolic trails with eco-physiological and ecological processes to have deep insight about the mycorrhizal functioning (Van der Heijden et al., 2015). There is still void of information regarding the complete plant microbiome that is, all fungal species associating with plants (Hacquard and Schadt, 2014). With advancement in sequencing technology and bioinformatics, it might be possible to decipher precise mycorrhizal network and also their interaction in context of complete food webs (Tedersoo et al., 2014). The coevolutionary processes that occur between plants and mycorrhizal symbioses are still poorly understood, especially the physiological mechanisms underlying stability of mycorrhizal mutualism. Biological business models for describing plant-mycorrhizal fungi relationships are appealing, but they need more refinement and expansion (Van der Heijden et al., 2015). In recent years, novel strategies and technology for mass production of AMF as inoculant (Ijdo et al., 2011) has been developed making its application cheaper and more reliable in agriculture and thus giving higher output-input ratio (Ceballos et al., 2013). At present, there is need to develop biogeochemical model which can facilitate in prediction of correct timing for application of mycorrhizal technology. Furthermore, the novel mycorrhizal technologies require meticulous research support and research need for different mechanism of the technology. Defining the parameters influencing the mycorrhizal effectiveness is needed to be prioritise as it will aid in preventing agricultural management practices from interfering with mycorrhizal mediated benefit. In recent years, despite expansion in mycorrhizal technology trend, the market value of mycorrhizal products is still far from its full potential. Besides the technical hurdles, mycorrhizal technology product may face political and regulatory constraints, quality assurance and product efficacy (Chen et al., 2018). There is lack of regulatory bodies which can set quality assurance parameters to ensure its efficient application in agricultural production. There is void for information regarding formulation of optimum dosage of inoculant or propagule density. Furthermore, the customer awareness and acceptance are another major constraint in achieving full potential of mycorrhizal technology. Despite the increasing popularity of biostimulants and biofertilizers, the use of conventional chemical fertiliser products remains the most widespread practise among farmers. The strategy to tackle this case could be field trials to demonstrate the benefits of the mycorrhizal technology over chemical-based fertilisers for enhancement of production in agriculture and horticulture ((Vosatka et al, 2008). At present, monetary support for the advancement of mycorrhizal technology is hindered by unreasonable assumptions or expectation and, on the other hand, a perception of repeated failures in context to its effect. There is an immediate need for dialogue aimed at clarifying the essential difference between uncertainty and variability (Lehmann and Rillig, 2014): as they are not same but are often viewed as such by both scientists and stakeholders.

This is a great time for the mycorrhizal scientific community as availability powerful and precise instruments has eased the information collection and research. The scientist working on mycorrhiza can demonstrate the societal significance of their finding and research by emphasising on the role of fungi as biofertilizers, bioprotectors and as an eco-friendly tool enhance the agricultural productivity. The fungal fruitfulness to the crop productivity should be seen as gift and constructive measures should be taken for their efficient application and utilisation.

(9) Conclusion and future Insight

The statistical studies show that world's population will exceed approximately to nine billion by 2050 (Rodriguez and Sanders, 2015). In order to increase global agricultural production and to meet food security for growing population, global agricultural production is going to doubled. The agricultural sector heavily relies on the use of chemical-based fertilisers and pesticides for increasing the crop production. These practices have adverse effect on the soil health, ecosystem and cause biotic stress on plant. Abiotic stresses such drought, salinity, heavy metal toxicity and extreme temperature poses detrimental effect on the agricultural production. Anthropogenic activities such as heavy metal dumping from the industries contaminates the soil leading to metal toxicity. These heavy metals can also lead to ground water pollution and adverse health effect on human if it enters the food web. Thus, there in need to formulate strategies which are eco-friendly in order to achieve agricultural sustainability. The studies have revealed the significance of mycorrhizal fungi in coping up with both biotic and abiotic stresses in plants. Use of mycorrhizal fungal inoculant as bio-fertiliser is well documented. Furthermore, the capability of mycorrhizal fungi in mitigation of abiotic stresses is well established. The use of mycorrhizal technology as eco-friendly tool for enhancement of agricultural production is still in its infancy and requires more research and field demonstration. Research in the field of mycorrhiza has conventionally developed into separate disciplines addressing different organisational levels. This isolation has created a void for complete knowledge regarding mycorrhizal functioning (Ferlian et al. 2011). There is need to integrate the research on mycorrhizal research in order to have a deep comprehension regarding potential of mycorrhizal fungi as an eco-friendly tool for enhancement of agricultural production. Rodriguez and Sanders in 2015 stated that ecologist can help in effective utilisation of mycorrhizal fungi for enhanced agricultural sustainability in four different aspects. These aspects include determining the survival and infection capacity of inoculated mycorrhizal fungi among already existing indigenous mycorrhizal fungi populations, obtaining a better understanding of the adaptability of alien mycorrhizal fungi to a foreign climate, the importance of genetic diversity among mycorrhizal fungal species and its effect on plant development, and determining whether there is a direct or indirect impact on crop productivity by inoculated mycorrhizal fungi. The future research emphasise should be laid on identification of genes and gene product which regulate the mycorrhizal fungal mediated growth and development under stress condition to mitigate deleterious effect of abiotic stress on crop productivity. Furthermore, there is need of exploration of mycorrhizal symbioses at all level to comprehend their role as bio-fertilisers for sustainable agriculture practice and also to formulate strategies to use mycorrhizal fungi as a fuel to propel green technology.

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(11) References

1. Abdelhameed, R. E., and Rabab, A. M. (2019). Alleviation of cadmium stress by arbuscular mycorrhizal symbiosis. Int. J. Phytoremed. doi: 10.1080/15226514.2018.1556584

2. Abdel Latef, A.A.H., Chaoxing, H. Arbuscular mycorrhizal influence on growth, photosynthetic pigments, osmotic adjustment and oxidative stress in tomato plants subjected to low temperature stress. Acta Physiol Plant 33, 1217–1225 (2011). https://doi.org/10.1007/s11738-010-0650-32

3. Abdel Latef, Arafat & Miransari, Mohammad. (2014). The Role of Arbuscular Mycorrhizal Fungi in Alleviation of Salt Stress. 10.1007/978-1-4939-0721-2_2.

4. Abdel-Salam, Eslam & Al-Atar, Abdul-Rahman & El-Sheikh, Mohamed. (2017). Inoculation with arbuscular mycorrhizal fungi alleviates harmful effects of drought stress on damask rose. Saudi Journal of Biological Sciences. 25. 10.1016/j.sjbs.2017.10.015.

5. Ahanger, M.A., Tittal, M., Mir, R.A. et al. Alleviation of water and osmotic stress-induced changes in nitrogen metabolizing enzymes in Triticum aestivum L. cultivars by potassium. Protoplasma 254, 1953–1963 (2017). https://doi.org/10.1007/s00709-017-1086-z

6. Ahanger, M.A., Agarwal, R.M. Potassium up-regulates antioxidant metabolism and alleviates growth inhibition under water and osmotic stress in wheat (Triticum aestivum L). Protoplasma 254, 1471–1486 (2017). https://doi.org/10.1007/s00709-016-1037-0

7. Ait-El-Mokhtar, M., Laouane, R. B., Anli, M., Boutasknit, A., Wahbi, S., and Meddich, A. (2019). Use of mycorrhizal fungi in improving tolerance of the date palm (Phoenix dactylifera L.) seedlings to salt stress. Sci. Hori. 253, 429– 438. doi: 10.1016/j.scienta.2019.04.066

8. Alori, Elizabeth & Dare, Michael Olajire & Babalola, Olubukola. (2017). Microbial Inoculants for Soil Quality and Plant Health. 10.1007/978-3-319-48006-0_9.

9. Amiri, R., Nikbakht, A., and Etemadi, N. (2015). Alleviation of drought stress on rose geranium Pelargonium graveolen L Herit. in terms of antioxidant activity and secondary metabolites by mycorrhizal inoculation. Sci. Hort. 197, 373–380. doi: 10.1016/j.scienta.2015.09.06.

10. Andres Schützendübel, Andrea Polle, Plant responses to abiotic stresses: heavy metal-induced oxidative stress and protection by mycorrhization, Journal of Experimental Botany, Volume 53, Issue 372, 15 May 2002, Pages 1351–1365, https://doi.org/10.1093/jexbot/53.372.1351

11. Andrea Genre, Mireille Chabaud, Ton Timmers, Paola Bonfante, David G. Barker, Arbuscular Mycorrhizal Fungi Elicit a Novel Intracellular Apparatus in Medicago truncatula Root Epidermal Cells before Infection, The Plant Cell, Volume 17, Issue 12, December 2005, Pages 3489–3499, https://doi.org/10.1105/tpc.105.035410

12. Arafat Abdel Hamed Abdel Latef, He Chaoxing, Effect of arbuscular mycorrhizal fungi on growth, mineral nutrition, antioxidant enzymes activity and fruit yield of tomato grown under salinity stress, Scientia Horticulturae, Volume 127, Issue 3,2011, Pages 228-233, ISSN 0304-4238, https://doi.org/10.1016/j.scienta.2010.09.020.

13. Aroca R, Vernieri P, Irigoyen JJ, Sancher-Diaz M, Tognoni F, Pardosso A (2003) Involvement of abscisic acid in leaf and root of maize (Zea mays L.) in avoiding chilling-induced water stress. Plant Sci 165:671–679

14. Asghari, H.R., Marschner, P., Smith, S.E. et al. Growth response of Atriplex nummularia to inoculation with arbuscular mycorrhizal fungi at different salinity levels. Plant Soil 273, 245–256 (2005). https://doi.org/10.1007/s11104-004-7942-6

15. Augé, R. Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. Mycorrhiza 11, 3–42 (2001). https://doi.org/10.1007/s005720100097

16. Azcon, R., Gomes, M. and Tobart, R. (1996). Physiological and nutritional responses by Lactucasativa L. to nitrogen sources and mycorrhizal fungi under drought stress conditions. Biology and Fertility of Soils, 22: 156-161.

17. Bagyaraj, D. J., and Ashwin, R. (2017). Soil biodiversity: role in sustainable horticulture. Biodivers. Hortic. Crops 5, 1–18. doi: 10.1016/j.jenvman.2017. 08.001.

18. Bahadur A, Batool A, Nasir F, Jiang S, Mingsen Q, Zhang Q, Pan J, Liu Y, Feng H. Mechanistic Insights into Arbuscular Mycorrhizal Fungi-Mediated Drought Stress Tolerance in Plants. International Journal of Molecular Sciences. 2019; 20(17):4199. https://doi.org/10.3390/ijms20174199.

19. Baldrian, P. and Valášková, V. (2008), Degradation of cellulose by basidiomycetous fungi. FEMS Microbiology Reviews, 32: 501-521. https://doi.org/10.1111/j.1574-6976.2008.00106.x

20. Barrow, C. J. (2012). Biochar potential for countering land degradation and for improving agriculture. App. Geogr. 34, 21–28. doi: 10.1016/j.apgeog.2011.09.008.

21. Bedini, S., Pellegrino, E., Avio, L., Pellegrini, S., Bazzoffi, P., Argese, E., Giovannetti, M. (2009). Changes in soil aggregation and glomalinrelated soil protein content as affected by the arbuscular mycorrhizal fungal species Glomusmosseae and Glomusintraradices. Soil BiolBiochem, 41:1491– 1496.

22. Begum N, Qin C, Ahanger MA, Raza S, Khan MI, Ashraf M, Ahmed N and Zhang L (2019) Role of Arbuscular Mycorrhizal Fungi in Plant Growth Regulation: Implications in Abiotic Stress Tolerance. Front. Plant Sci. 10:1068. doi: 10.3389/fpls.2019.01068

23. Bender, S., Plantenga, F., Neftel, A. et al. Symbiotic relationships between soil fungi and plants reduce N2O emissions from soil. ISME J 8, 1336–1345 (2014). https://doi.org/10.1038/ismej.2013.224

24. Bengtsson, G., Hedlund, K., & Rundgren, S. (1993). Patchiness and Compensatory Growth in a Fungus-Collembola System. Oecologia, 93(2), 296-302. Retrieved March 13, 2021, from http://www.jstor.org/stable/4220257.

25. Berg B, McClaugherty C (2014a) Decomposer organisms. In: Plant litter: decomposition, humus formation, Carbon Sequestration. Springer Berlin Heidelberg, pp 35–52. doi: https://doi.org/10.1007/978-3-642-38821-7_3.

26. Bhardwaj, D., Ansari, M.W., Sahoo, R.K. et al. Biofertilizers function as key player in sustainable agriculture by improving soil fertility, plant tolerance and crop productivity. Microb Cell Fact 13, 66 (2014). https://doi.org/10.1186/1475-2859-13-66

27. Birhane, E., Sterck, F.J., Fetene, M. et al. Arbuscular mycorrhizal fungi enhance photosynthesis, water use efficiency, and growth of frankincense seedlings under pulsed water availability conditions. Oecologia 169, 895–904 (2012). https://doi.org/10.1007/s00442-012-2258-3

28. Bonfante, P., Genre, A. Mechanisms underlying beneficial plant–fungus interactions in mycorrhizal symbiosis. Nat Commun 1, 48 (2010). https://doi.org/10.1038/ncomms1046

29. Brundrett, M. C. Coevolution of roots and mycorrhizas of land plants. New Phytol. 154, 275–304 (2002)

30. Brundrett, M. (2004). Diversity and classification of mycorrhizal associations. Biol. Rev. 79, 473–495. doi: 10.1017/S1464793103006316

31. Cabral, C., Sabine, R., Ivanka, T. and Bernd, W. (2016). Arbuscular mycorrhizal fungi modify nutrient allocation and composition in wheat (Triticum aestivum L.) subjected to heat-stress. Plant Soil 408 (1–2), 385–399. doi: 10.1007/s11104-016-2942-x

32. Cameron, Duncan & Neal, Andrew & van Wees, Saskia & Ton, Jurriaan. (2013). Mycorrhiza-induced resistance: More than the sum of its parts. Trends in plant science. 18. 10.1016/j.tplants.2013.06.004.

33. Caradonia, F.; Francia, E.; Morcia, C.; Ghizzoni, R.; Moulin, L.; Terzi, V.; Ronga, D. Arbuscular Mycorrhizal Fungi and Plant Growth Promoting Rhizobacteria Avoid Processing Tomato Leaf Damage during Chilling Stress. Agronomy 2019, 9, 299. https://doi.org/10.3390/agronomy9060299

34. Cardoso, I., & Kuyper, T. (2006). Mycorrhizas and tropical soil fertility. Agriculture, Ecosystems & Environment, 116(1-2), 72–84. doi: 10.1016/j.agee.2006.03.011

35. Ceballos I, Ruiz M, Fernandez C, Pena R, Rodriguez A, Sanders IR. 2013. The in vitro mass-produced model mycorrhizal fungus, Rhizophagus irregularis, significantly increases yields of the globally important food security crop Cassava. PLoS ONE 8: e70633.

36. Chitarra, W., Pagliarani, C., Maserti, B., Lumini, E., Siciliano, I., Cascone, P., et al. (2016). Insights on the impact of arbuscular mycorrhizal symbiosis on tomato tolerance to water stress. Plant Physiol. 171, 1009–1023. doi: 10.1104/pp.16. 00307

37. Christie, P., Li, X. & Chen, B. Arbuscular mycorrhiza can depress translocation of zinc to shoots of host plants in soils moderately polluted with zinc. Plant and Soil 261, 209–217 (2004). https://doi.org/10.1023/B:PLSO.0000035542.79345.1b.

38. Chen, S., Jin, W., Liu, A., Zhang, S., Liu, D., Wang, F., et al. (2013). Arbuscular mycorrhizal fungi (AMF) increase growth and secondary metabolism in cucumber subjected to low temperature stress. Sci. Hort. 160, 222–229. doi: 10.1016/j.scienta.2013.05.039.

39. Chen M, Arato M, Borghi L, Nouri E and Reinhardt D (2018) Beneficial Services of Arbuscular Mycorrhizal Fungi – From Ecology to Application. Front. Plant Sci. 9:1270. doi: 10.3389/fpls.2018.01270

40. Conrath, U., Beckers, G. J. M., Flors, V., Garcia-Agustin, P., Jakab, G., Mauch, F., et al. (2006). Priming: getting ready for battle. Mol. Plant-Microbe Interact. 19, 1062–1071. doi: 10.1094/MPMI-19-1062

41. Cretoiu, M. S., Korthals, G. W., Visser, J. H. M., and van Elsas, J. D. (2013). Chitin amendment increases soil suppressiveness toward plant pathogens and modulates the actinobacterial and oxalobacteraceal communities in an experimental agricultural field. Appl. Environ. Microbiol. 79, 5291–5301. doi: 10.1128/AEM.01361-13

42. Crowther, T. W., Boddy, L., & Hefin Jones, T. (2012). Functional and ecological consequences of saprotrophic fungus-grazer interactions. The ISME journal, 6(11), 1992–2001. https://doi.org/10.1038/ismej.2012.53, T. W., Boddy, L., & Hefin Jones, T. (2012). Functional and ecological consequences of saprotrophic fungus-grazer interactions. The ISME journal, 6(11), 1992–2001. https://doi.org/10.1038/ismej.2012.53

43. Daei G, Ardekani MR, Rejali F, Teimuri S, Miransari M. Alleviation of salinity stress on wheat yield, yield components, and nutrient uptake using arbuscular mycorrhizal fungi under field conditions. J Plant Physiol. 2009 Apr 1;166(6):617-25. doi: 10.1016/j.jplph.2008.09.013. Epub 2008 Dec 18. PMID: 19100656.

44. Dahlberg, A., and Bültmann, H. (2013). "Fungi," in Arctic Biodiversity Assessment. Status and Trends in Arctic Biodiversity, ed. H. Meltofte, (Akureyri: Conservation of Arctic Flora and Fauna), 303–319.

45. Dar, Zaffar Mahdi & Masood, Amjad & Asif, Malik. (2018). Review on Arbuscular Mycorrhizal Fungi: An Approach to Overcome Drought Adversities in Plants. International Journal of Current Microbiology and Applied Sciences. 7. 1040-1049. 10.20546/ijcmas.2018.703.124.

46. Delaux, P. M. (2017). Comparative phylogenomics of symbiotic associations. New Phytol. 213, 89–94. doi: 10.1111/nph.14161

47. de Vries, J., and Archibald, J. M. (2018). Plant evolution: landmarks on the path to terrestrial life. New Phytol. 217, 1428–1434. doi: 10.1111/nph.14975

48. Dighton J. 2003. Fungi in ecosystem processes, vol 17. Marcel Dekker, New York, NY.

49. Ellouze, W., Esmaeili Taheri, A., Bainard, L. D., Yang, C., Bazghaleh, N., Navarro-Borrell, A., … Hamel, C. (2014). Soil Fungal Resources in Annual Cropping Systems and Their Potential for Management. BioMed Research International, 2014, 1–15. doi:10.1155/2014/531824

50. Evelin, Heikham & Kapoor, Rupam & Giri, Bhoopander. (2009). Arbuscular mycorrhizal fungi in alleviation of salt stress: A review. Annals of botany. 104. 1263-80. 10.1093/aob/mcp251.

51. Facelli, E., Smith, S.E. & Smith, F.A. Mycorrhizal symbiosis — overview and new insights into roles of arbuscular mycorrhizas in agro- and natural ecosystems. Australasian Plant Pathology 38, 338–344 (2009). https://doi.org/10.1071/AP09033

52. Farooq, Muhammad & Aziz, Tarik & Wahid, Abdul & Lee, Dong-Jin & Siddique, Kadambot. (2009). Chilling tolerance in maize: Agronomic and physiological approaches. Crop & Pasture Science. 60. 501-516. 10.1071/Cp08427.

53. Ferlian, O., Biere, A., Bonfante, P., Buscot, F., Eisenhauer, N., Fernandez, I., Hause, B., Herrmann, S., Krajinski-Barth, F., Meier, I. C., Pozo, M. J., Rasmann, S., Rillig, M. C., Tarkka, M. T., van Dam, N. M., Wagg, C., & Martinez-Medina, A. (2018). Growing Research Networks on Mycorrhizae for Mutual Benefits. Trends in plant science, 23(11), 975–984. https://doi.org/10.1016/j.tplants.2018.08.008,

54. Fernandez CW, Langley JA, Chapman S, McCormack ML, Koide RT. 2016. The decomposition of ectomycorrhizal fungal necromass. Soil Biology & Biochemistry 93: 38-49.

55. Fernández-Lizarazo, J.C.; Moreno-Fonseca, L.P. Mechanisms for tolerance to water-deficit stress in plants inoculated with arbuscular mycorrhizal fungi. A review. Agron. Colomb. 2016, 34, 179–189.

56. Field, KJ, Daniell, T, Johnson, D, Helgason, T. Mycorrhizas for a changing world: Sustainability, conservation, and society. Plants, People, Planet. 2020; 2: 98– 103. https://doi.org/10.1002/ppp3.10092.

57. Foley, J., Ramankutty, N., Brauman, K. et al. Solutions for a cultivated planet. Nature 478, 337–342 (2011). https://doi.org/10.1038/nature10452.

58. Fr ˛ac M, Hannula SE, Bełka M and J ˛edryczka M (2018) Fungal Biodiversity and Their Role in Soil Health. Front. Microbiol. 9:707. doi: 10.3389/fmicb.2018.00707.

59. Francioli, D., van Rijssel, S.Q., van Ruijven, J. et al. Plant functional group drives the community structure of saprophytic fungi in a grassland biodiversity experiment. Plant Soil (2020). https://doi.org/10.1007/s11104-020-04454-y.

60. Futai K., Taniguchi T., Kataoka R. (2008) Ectomycorrhizae and Their Importance in Forest Ecosystems. In: Siddiqui Z.A., Akhtar M.S., Futai K. (eds) Mycorrhizae: Sustainable Agriculture and Forestry. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-8770-7_11

61. Garg, N., and Singh, S. (2017). Arbuscular mycorrhiza Rhizophagus irregularis, and silicon modulate growth, proline biosynthesis and yield in Cajanus cajan, L. Millsp. (pigeon pea) genotypes under cadmium and zinc stress. J. Plant Growth Regul. 37, 1–18. doi: 10.1007/s00344-017-9708-4

62. Gavito, M.E., Olsson, P.A., Rouhier, H., Medina-Peñafiel, A., Jakobsen, I., Bago, A. and Azcón-Aguilar, C. (2005), Temperature constraints on the growth and functioning of root organ cultures with arbuscular mycorrhizal fungi. New Phytologist, 168: 179-188. https://doi.org/10.1111/j.1469-8137.2005.01481.x.

63. Gehring, C.A., Johnson, N.C. Beyond ICOM8: perspectives on advances in mycorrhizal research from 2015 to 2017. Mycorrhiza 28, 197–201 (2018). https://doi.org/10.1007/s00572-017-0818-4.

64. Gianinazzi, S., Gollotte, A., Binet, MN. et al. Agroecology: the key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza 20, 519–530 (2010). https://doi.org/10.1007/s00572-010-0333-3.

65. Gill SS, Tuteja N. Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem. 2010 Dec;48(12):909-30. doi: 10.1016/j.plaphy.2010.08.016. Epub 2010 Sep 15. PMID: 20870416.

66. Giri, B., Mukerji, K.G. Mycorrhizal inoculant alleviates salt stress in Sesbania aegyptiaca and Sesbania grandiflora under field conditions: evidence for reduced sodium and improved magnesium uptake. Mycorrhiza 14, 307–312 (2004). https://doi.org/10.1007/s00572-003-0274-1.

67. Göhre V, Paszkowski U. Contribution of the arbuscular mycorrhizal symbiosis to heavy metal phytoremediation. Planta. 2006 May;223(6):1115-22. doi: 10.1007/s00425-006-0225-0. Epub 2006 Mar 23. PMID: 16555102.

68. Grassini, P., Eskridge, K. & Cassman, K. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat Commun 4, 2918 (2013). https://doi.org/10.1038/ncomms3918.

69. Gutjahr, C., and Paszkowski, U. (2013). Multiple control levels of root system remodeling in arbuscular mycorrhizal symbiosis. Front. Plant Sci. 4:204. doi: 10.3389/fpls.2013.00204

70. Hall J.L., Cellular mechanisms for heavy metal detoxification and tolerance, Journal of Experimental Botany, Volume 53, Issue 366, 1 January 2002, Pages 1–11, https://doi.org/10.1093/jexbot/53.366.1.

71. Hacquard S, Schadt CW. 2014. Towards a holistic understanding of the beneficial interactions across the Populus microbiome. New Phytologist 205: 1424–1430.

72. Hajiboland, R., Aliasgharzadeh, N., Laiegh, S. F., and Poschenrieder, C. (2010). Colonization with arbuscular mycorrhizal fungi improves salinity tolerance of tomato Solanum lycopersicum L. plants. Plant Soil. 331, 313–327. doi: 10.1007/ s11104-009-0255-z.

73. Hajiboland, R., Dashtebani, F., and Aliasgharzad, N. (2015). Physiological responses of halophytic C4 grass, Aeluropus littoralis to salinity and arbuscular mycorrhizal fungi colonization. Photosynthetica 53 (4), 572–584. doi: 10.1007/ s11099-015-0131-4.

74. Hameed, Asiya & Egamberdieva, Dilfuza & Abd-Allah, Elsayed & Hashem, Abeer & Kumar, Ashwani & Ahmad, Parvaiz. (2014). Salinity Stress and Arbuscular Mycorrhizal Symbiosis in Plants. 10.1007/978-1-4614-9466-9_7.

75. Harrison, Maria. (2012). Cellular programs for arbuscular mycorrhizal symbiosis. Current opinion in plant biology. 15. 10.1016/j.pbi.2012.08.010.

76. Hasanuzzaman, M., Gill, S. S., and Fujita, M. (2013). “Physiological role of nitric oxide in plants grown under adverse environmental conditions,” in Plant acclimation to environmental stress. Eds. N. Tuteja and S. S. Gill (NY: Springer Science+Business Media), 269–322. doi: 10.1007/978-1-4614-5001-6_11.

77. Hashem, A., Abd_Allah, E. F., Alqarawi, A. A., Aldubise, A., and Egamberdieva, D. (2015). Arbuscular mycorrhizal fungi enhance salinity tolerance of Panicum turgidum Forssk by altering photosynthetic and antioxidant pathways. J. Plant Interact. 10 (1), 230–242. doi: 10.1080/17429145.2015.1052025.

78. Hashem, A., Alqarawi, A. A., Radhakrishnan, R., Al-Arjani, A. F., Aldehaish, H. A., Egamberdieva, D., et al. (2018). Arbuscular mycorrhizal fungi regulate the oxidative system, hormones and ionic equilibrium to trigger salt stress tolerance in Cucumis sativus L. Saudi J. Biol. Sci. 25 (6), 1102–1114. doi: 10.1016/j.sjbs.2018.03.009.

79. Hayat, R., Ali, S., Amara, U. et al. Soil beneficial bacteria and their role in plant growth promotion: a review. Ann Microbiol 60, 579–598 (2010). https://doi.org/10.1007/s13213-010-0117-1.

80. Helgason, T., Daniell, T. J., Husband, R., Fitter, A. H., & Young, J. P. W. (1998). Ploughing up the wood-wide web? Nature, 394(6692), 431. https://doi.org/10.1038/28764\

81. Hildebrandt U, Regvar M, Bothe H. Arbuscular mycorrhiza and heavy metal tolerance. Phytochemistry. 2007 Jan;68(1):139-46. doi: 10.1016/j.phytochem.2006.09.023. Epub 2006 Oct 31. PMID: 17078985.

82. Ijdo M, Cranenbrouck S, Declerck S. 2011. Methods for large-scale production of AM fungi: past, present, and future. Mycorrhiza 21: 1–16.

83. Janousková, Martina & Pavlíková, Daniela & Vosatka, Miroslav. (2007). Potential contribution of arbuscular mycorrhiza to cadmium immobilisation in soil. Chemosphere. 65. 1959-65. 10.1016/j.chemosphere.2006.07.007.

84. Khan A.L., M. Hamayun, Y. Kim, S. Kang, and I. Lee, "Ameliorative symbiosis of endophyte (Penicillium funiculosum LHL06) under salt stress elevated plant growth of Glycine max L.," Plant Physiology and Biochemistry, vol. 49, no. 8, pp. 852– 861, 2011.

85. Khalloufi, M., Martínez-Andújar, C., Lachaâl, M., Karray-Bouraoui, N., PérezAlfocea, F., and Albacete, A. (2017). The interaction between foliar GA3 application and arbuscular mycorrhizal fungi inoculation improves growth in salinized tomato Solanum lycopersicum L. plants by modifying the hormonal balance. J. Plant Physiol. 214, 134–144. doi: 10.1016/j.jplph.2017.04.012

86. Klironomos, J. N. (2003). Variation in plant response to native and exotic arbuscular mycorrhizal fungi. Ecology, 84(9), 2292–2301. https://doi.org/10.1890/02-0413.

87. Kumar, J., Atri, N.S. Studies on Ectomycorrhiza: An Appraisal. Bot. Rev. 84, 108–155 (2018). https://doi.org/10.1007/s12229-017-9196-z.

88. Lahlali R, McGregor L, Song T, Gossen BD, Narisawa K, et al. (2014) Heteroconium chaetospira Induces Resistance to Clubroot via Upregulation of Host Genes Involved in Jasmonic Acid, Ethylene, and Auxin Biosynthesis. PLOS ONE 9(4): e94144. https://doi.org/10.1371/journal.pone.0094144.

89. Laliberté, E.; Lambers, H.; Burgess, T.I.; Wright, S.J. Phosphorus limitation, soil-borne pathogens and the coexistence of plant species in hyperdiverse forests and shrublands. New Phytol. 2015, 206, 507–521.

90. Lamarque, P., Meyfroidt, P., Nettier, B., and Lavorel, S. (2014). How ecosystem services knowledge and values influence farmers' decision-making. PLoS ONE 9: e107572. doi: 10.1371/journal.pone.0107572.

91. Leake, J.R., Johnson, D., Donnelly, D., Muckle, G., Boddy, L., Read, D. (2004). Network of power and influence: The role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. Can J Bot., 82:1016– 1045.

92. Lehmann, J., and Rillig, M. (2014). Distinguishing variability from uncertainty. Nat. Clim. Change 4, 153–153. doi: 10.1038/nclimate2133.

93. Lehmann, A., Veresoglou, S. D., Leifheit, E. F., & Rillig, M. C. (2014). Arbuscular mycorrhizal influence on zinc nutrition in crop plants – A meta-analysis. Soil Biology and Biochemistry, 69, 123–131. doi: 10.1016/j.soilbio.2013.11.001

94. Leifheit, E.F., Veresoglou, S.D., Lehmann, A. et al. Multiple factors influence the role of arbuscular mycorrhizal fungi in soil aggregation—a meta-analysis. Plant Soil 374, 523–537 (2014). https://doi.org/10.1007/s11104-013-1899-2.

95. Leyval C., Joner E.J., del Val C., Haselwandter K. (2002) Potential of arbuscular mycorrhizal fungi for bioremediation. In: Gianinazzi S., Schüepp H., Barea J.M., Haselwandter K. (eds) Mycorrhizal Technology in Agriculture. Birkhäuser, Basel. https://doi.org/10.1007/978-3-0348-8117-3_14.

96. Lin, A. J., Zhang, X. H., Wong, M. H., Ye, Z. H., Lou, L. Q., and Wang, Y. S. (2007). Increase of multi-metal tolerance of three leguminous plants by arbuscular mycorrhizal fungi colonization. Environ. Geochem. Health 29, 473–481. doi: 10.1007/s10653-007-9116-y.

97. Lindahl BD, Tunlid A. 2015. Ectomycorrhizal fungi - potential organic matter decomposers, yet not saprotrophs. New Phytologist 205: 1443-1447.

98. Li X., N. Bu, Y. Li, L. Ma, S. Xin, and L. Zhang, "Growth, photosynthesis and antioxidant responses of endophyte infected and non-infected rice under lead stress conditions.

99. López-Bucio, J., Pelagio-Flores, R., and Herrera-Estrell, A. (2015). Trichoderma as biostimulant: exploiting the multilevel properties of a plant beneficial fungus. Sci. Hortic. 196, 109–123. doi: 10.1016/j.scienta.2015.08.043.

100. López-Ráez, J.A. How drought and salinity affect arbuscular mycorrhizal symbiosis and strigolactone biosynthesis. Planta 243, 1375–1385 (2016). https://doi.org/10.1007/s00425-015-2435-9.

101. Luo, Z.B.; Wu, C.H.; Zhang, C.; Li, H.; Lipka, U.; Polle, A. The role of ectomycorrhizas in heavy metal stress tolerance of host plants. Environ. Exp. Bot. 2014, 108, 47–62.

102. Maltz MR, Treseder KK, McGuire KL (2017) Links between plant and fungal diversity in habitat fragments of coastal shrubland. Plos One 12: e0184991. https://doi.org/10.1371/journal.pone.018499.

103. Mardhiah, U., Caruso, T., Gurnell, A., & Rillig, M. C. (2016). Arbuscular mycorrhizal fungal hyphae reduce soil erosion by surface water flow in a greenhouse experiment. Applied Soil Ecology, 99, 137–140. https://doi.org/10.1016/j.apsoil.2015.11.027.

104. Martin FM, Uroz S, Barker DG (2017) Ancestral alliances: plant mutualistic symbioses with fungi and bacteria. Science 356(6340): eaad4501. https://doi.org/10.1126/science.aad4501.

105. Mathur, S., Sharma, M. P., and Jajoo, A. (2016). Improved photosynthetic efficacy of maize Zea mays plants with arbuscular mycorrhizal fungi (AMF) under high temperature stress. J. Photochem. Photobiol. B 180, 149–154. doi: 10.1016/j. jphotobiol.2018.02.002.

106. Mathur, S., & Jajoo, A. (2019). Arbuscular mycorrhizal fungi protect maize plants from high temperature stress by regulating photosystem II heterogeneity. Industrial Crops and Products, 111934. doi: 10.1016/j.indcrop.2019.111934.

107. Michaelson, G. J., Ping, C. L., Epstein, H., Kimble, J. M., & Walker, D. A. (2008). Soils and frost boil ecosystems across the North American Arctic Transect. Journal of Geophysical Research, 113(G3). doi:10.1029/2007jg000672.

108. Miransari M., H.A. Bahrami, F. Rejali, M.J. Malakouti, Effects of arbuscular mycorrhiza, soil sterilization, and soil compaction on wheat (Triticum aestivum L.) nutrients uptake, Soil and Tillage Research, Volume 104, Issue 1,2009, Pages 48-55, ISSN 0167-1987, https://doi.org/10.1016/j.still.2008.11.006.

109. Moradtalab, Narges & Hajiboland, Roghieh & Aliasgharzad, Nasser & Hartmann, Tobias & Neumann, Günter. (2019). Silicon and the Association with an Arbuscular-Mycorrhizal Fungus (Rhizophagus clarus) Mitigate the Adverse Effects of Drought Stress on Strawberry. Agronomy. 9. 41. 10.3390/agronomy9010041.

110. Nadeem, Sajid & Khan, Muhammad & Waqas, Rashid & Binyamin, Rana & Akhtar, Sohail & Zahir, Zahir. (2017). Arbuscular Mycorrhizas and Stress Tolerance of Plants.

111. Navarro, J. M., Perez-Tornero, O., and Morte, A. (2014). Alleviation of salt stress in citrus seedlings inoculated with arbuscular mycorrhizal fungi depends on the root stock salt tolerance. J. Plant Physiol. 171 (1), 76–85. doi: 10.1016/j. jplph.2013.06.006.

112. Neemisha (2020) Role of Soil Organisms in Maintaining Soil Health, Ecosystem Functioning, and Sustaining Agricultural Production. In: Giri B., Varma A. (eds) Soil Health. Soil Biology, vol 59. Springer, Cham. https://doi.org/10.1007/978-3-030-44364-1_17.

113. Nehls, U., & Plassard, C. (2018). Nitrogen and phosphate metabolism in ectomycorrhizas. New Phytologist. doi:10.1111/nph.15257.

114. Nies, D. Microbial heavy-metal resistance. Appl Microbiol Biotechnol 51, 730–750 (1999). https://doi.org/10.1007/s002530051457.

115. Ortiz, N., Armada, E., Duque, E., Roldan, A., & Azcon, R. (2015). Contribution of arbuscular mycorrhizal fungi and/or bacteria to enhancing plant drought toleranceunder natural soil conditions: Effectiveness of autochthonous or allochthonous strains. Functional Biotechnology, 174, 87–96. https://doi.org/10.1016/j.jplph.2014.08.019.

116. Osakabe, Y., Osakabe, K., Shinozaki, K., & Tran, L.-S. P. (2014). Response of plants to water stress. Frontiers in Plant Science, 5. doi:10.3389/fpls.2014.00086.

117. Ouledali, S., Ennajeh, M., Ferrandino, A., Khemira, H., Schubert, A., & Secchi, F. (2019). Influence of arbuscular mycorrhizal fungi inoculation on the control of stomata functioning by abscisic acid (ABA) in drought-stressed olive plants. South African Journal of Botany, 121, 152–158. doi: 10.1016/j.sajb.2018.10.024.

118. Ownley BH, Griffin MR, Klingeman WE, Gwinn KD, Moulton JK, Pereira RM. Beauveria bassiana: endophytic colonization and plant disease control. J Invertebr Pathol. 2008 Jul;98(3):267-70. doi: 10.1016/j.jip.2008.01.010. Epub 2008 Mar 15. PMID: 18442830.

119. Pal, A., and Pandey, S. (2016). Role of arbuscular mycorrhizal fungi on plant growth and reclamation of barren soil with wheat (Triticum aestivum L.) crop. Int. J. Soil Sci. 12, 25–31. doi: 10.3923/ijss.2017.25.31.

120. Parewa, H.P., Rakshit, A., Rao, A.M., Sarkar, N.C. and Raha, P. (2010). Evaluation of maize cultivars for phosphorus use efficiency in an Inceptisol. International Journal of Agriculture Environment & Biotechnology 3(2): 195-198.

121. Pavithra, D., and Yapa, N. (2018). Arbuscular mycorrhizal fungi inoculation enhances drought stress tolerance of plants. Ground Water Sust. Dev. 7, 490– 494. doi: 10.1016/j.gsd.2018.03.005.

122. Pitman M.G., Läuchli A. (2002) Global Impact of Salinity and Agricultural Ecosystems. In: Läuchli A., Lüttge U. (eds) Salinity: Environment - Plants - Molecules. Springer, Dordrecht. https://doi.org/10.1007/0-306-48155-3_1.

123. Plassard C., B. Dell, Phosphorus nutrition of mycorrhizal trees, Tree Physiology, Volume 30, Issue 9, September 2010, Pages 1129–1139, https://doi.org/10.1093/treephys/tpq063.

124. Ponce-Toledo, R. I., Deschamps, P., Lopez-Garcia, P., Zivanovic, Y., Benzerara, K., and Moreira, D. (2017). An early-branching freshwater cyanobacterium at the origin of plastids. Curr. Biol. 27, 386–391. doi: 10.1016/j.cub.2016.11.056.

125. Posta, K.; Duc, N.H. Benefits of Arbuscular Mycorrhizal Fungi Application to Crop Production under Water Scarcity. Drought Detect. Solut. 2020.

126. Pozo MJ, Azcón-Aguilar C. Unraveling mycorrhiza-induced resistance. Curr Opin Plant Biol. 2007 Aug;10(4):393-8. doi: 10.1016/j.pbi.2007.05.004. Epub 2007 Jul 19. PMID: 17658291.

127. Read, D. J., Duckett, J. G., Francis, R., Ligrone, R., and Russell, A. (2000). Symbiotic fungal associations in 'lower' land plants. Philos. Trans. R. Soc. Lond. Ser. B-Biol. Sci. 355, 815–830. doi: 10.1098/rstb.2000.0617.

128. Rillig, M.C., Wright, S.F., Nichols, K.A., Schmid, W.F., Torn, M.S. (2002). The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of five plant species. Plant Soil, 238:325–333.

129. Rillig, M.C. and Mummey, D.L. (2006), Mycorrhizas and soil structure. New Phytologist, 171: 41-53. https://doi.org/10.1111/j.1469-8137.2006.01750.x.

130. Rivera-Becerril, Facundo & van Tuinen, Diederik & Martin-Laurent, Fabrice & Metwally, Ashraf & Dietz, Karl-Josef & Gianinazzi, Silvio & Gianinazzi-Pearson, Vivienne. (2006). Molecular changes in Pisum sativum L. roots during Arbuscular mycorrhiza buffering of cadmium stress. Mycorrhiza. 16. 51-60. 10.1007/s00572-005-0016-7.

131. Rodrigo Mendes, Paolina Garbeva, Jos M. Raaijmakers, The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms, FEMS Microbiology Reviews, Volume 37, Issue 5, September 2013, Pages 634–663, https://doi.org/10.1111/1574-6976.12028.

132. Rodriguez, A., Sanders, I. The role of community and population ecology in applying mycorrhizal fungi for improved food security. ISME J 9, 1053–1061 (2015). https://doi.org/10.1038/ismej.2014.207.

133. Roghieh Hajiboland, Arshad Joudmand, Nasser Aliasgharzad, Roser Tolrá, Charlotte Poschenrieder "Arbuscular mycorrhizal fungi alleviate low-temperature stress and increase freezing resistance as a substitute for acclimation treatment in barley," Crop and Pasture Science, 70(3), 218-233, (4 March 2019).

134. Rosendahl, S., McGee, P., and Morton, J. B. (2009). Lack of global population genetic differentiation in the arbuscular mycorrhizal fungus Glomus mosseae suggests a recent range expansion which may have coincided with the spread of agriculture. Mol. Ecol. 18, 4316–4329. doi: 10.1111/j.1365-294X.2009. 04359.x.

135. Rouphael, Youssef & Franken, Philipp & Schneider, Carolin & Schwarz, Dietmar & Giovannetti, Manuela & Agnolucci, Monica & De Pascale, Stefania & Bonini, Paolo & Colla, Giuseppe. (2015). Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. Scientia Horticulturae. 196. 91-108. 10.1016/j.scienta.2015.09.002.

136. Roy, G., Laflamme, G., Bussières, G. and Dessureault, M. (2003), Field tests on biological control of Heterobasidion annosum by Phaeotheca dimorphospora in comparison with Phlebiopsis gigantea. Forest Pathology, 33: 127-140. https://doi.org/10.1046/j.1439-0329.2003.00319.x.

137. Ruiz-Lozano, J.M. Arbuscular mycorrhizal symbiosis and alleviation of osmotic stress. New perspectives for molecular studies. Mycorrhiza 13, 309–317 (2003). https://doi.org/10.1007/s00572-003-0237-6.

138. Sajedi, N. A., Ardakani, M. R., Rejali, F., Mohabbati, F., & Miransari, M. (2010). Yield and yield components of hybrid corn (Zea mays L.) as affected by mycorrhizal symbiosis and zinc sulfate under drought stress. Physiology and molecular biology of plants: an international journal of functional plant biology, 16(4), 343–351. https://doi.org/10.1007/s12298-010-0035-5.

139. Sanchez, D.H., Siahpoosh, M.R., Roessner, U., Udvardi, M. and Kopka, J. (2008), Plant metabolomics reveals conserved and divergent metabolic responses to salinity. Physiologia Plantarum, 132: 209-219. https://doi.org/10.1111/j.1399-3054.2007.00993.x.

140. Schwartz, M. W., Hoeksema, J. D., Gehring, C. A., Johnson, N. C., Klironomos, J. N., Abbott, L. K., & Pringle, A. (2006). The promise and the potential consequences of the global transport of mycorrhizal fungal inoculum. Ecology Letters, 9(5), 501–515. https://doi.org/10.1111/j.1461-0248.2006.00910.x.

141. Selmar, Dirk & Kleinwaechter, Maik. (2013). Influencing the Product Quality by Applying Drought Stress During the Cultivation of Medicinal Plants. Industrial Crops and Products. 42. 558–566. 10.1016/j.indcrop.2012.06.020.

142. Shukla N., R. P. Awasthi, L. Rawat, and J. Kumar, "Biochemical and physiological responses of rice (Oryza sativa L.) as influenced by Trichoderma harzianum under drought stress," Plant Physiology and Biochemistry, vol. 54, pp. 78–88, 2012.

143. Singh, P.K., Singh, M. & Tripathi, B.N. Glomalin: an arbuscular mycorrhizal fungal soil protein. Protoplasma 250, 663–669 (2013). https://doi.org/10.1007/s00709-012-0453-z.

144. Sinsabaugh, R.S. Enzymic analysis of microbial pattern and process. Biol Fert Soils 17, 69–74 (1994). https://doi.org/10.1007/BF00418675.

145. Smith, J., Barau, A.D., Goldman, A. and Mareck, J.H. (1994). The role of technology in agricultural intensification: the evolution of maize production systems in the Northern Guinea Savanna of Nigeria. Economic Development and Cultural Change, 42: 537-554.

146. Smith SE, Read DJ. (2008) Mycorrhizal symbiosis, 3rd edn. Repr. Elsevier/Academic Press: Amsterdam, Netherlands.

147. Sommermann L, Geistlinger J, Wibberg D, Deubel A, Zwanzig J, Babin D, et al. (2018) Fungal community profiles in agricultural soils of a long-term field trial under different tillage, fertilization and crop rotation conditions analyzed by high-throughput ITS-amplicon sequencing. PLoS ONE 13(4): e0195345.

148. Sousa CD, Menezes RSC, Sampaio EVDB, Lima FD. 2012. Glomalin: characteristics, production, limitations and contribution to soils. Semina-Ciencias Agrarias 33: 3033-3044.

149. Syamsiyah, J., Herawati, A., and Mujiyo. (2018). The potential of arbuscular mycorrhizal fungi application on aggregrate stability in alfisol soil. IOP Conf. Series: Earth Environ. Sci. 142, 012045. doi: 10.1088/1755-1315/142/1/012045.

150. Tedersoo L, Bahram M, Põlme S, Kõljalg U, Yorou NS, Wijesundera R, Villarreal Ruiz L, Vasco-Palacios AM, Quang Thu P, Suija A et al. 2014. Global diversity and geography of soil fungi. Science 346: 1256688.

151. Tian, C.Y & Feng, Gu & Li, X.L & Zhang, F.S. (2004). Different effects of arbuscular mycorrhizal fungal isolates from saline or non-saline soil on salinity tolerance of plants. Applied Soil Ecology. 26. 143-148. 10.1016/j.apsoil.2003.10.010.

152. Treseder, K. K., & Lennon, J. T. (2015). Fungal Traits That Drive Ecosystem Dynamics on Land. Microbiology and Molecular Biology Reviews, 79(2), 243–262. doi:10.1128/mmbr.00001-15.

153. Vamerali T, Bandiera M, Mosca G (2010) Field crops for phytoremediation of metalcontaminated land. A review. Env Chem Lett 8:1–17.

154. Van der Heijden, M.G.A., Martin, F.M., Selosse, M.-A. and Sanders, I.R. (2015), Mycorrhizal ecology and evolution: the past, the present, and the future. New Phytol, 205: 1406-1423. https://doi.org/10.1111/nph.13288.

155. Vosatka, M., Albrechtova, J., and Patten, R. (2008). "The international market development for mycorrhizal technology," in Mycorrhiza, ed. A. Varma (Berlin: Springer).

156. Vosatka, M., Latr, A., Gianinazzi, S., and Albrechtova, J. (2012). Development of arbuscular mycorrhizal biotechnology and industry: current achievements and bottlenecks. Symbiosis 58, 29–37. doi: 10.1007/s13199-012-0208-9.

157. Wahid, a., Gelani, s., Ashraf, m., & Foolad, M. (2007). Heat tolerance in plants: an overview. Environmental and experimental botany, 61(3), 199–223. Doi: 10.1016/j.envexpbot.2007.05.011.

158. Wall, R., Prasad, R., & Shamoun, S. (1992). The development and potential role of mycoherbicides for forestry. Forestry Chronicle, 68, 736-741.

159. Wang, Fayuan (2017) Occurrence of arbuscular mycorrhizal fungi in mining-impacted sites and their contribution to ecological restoration: Mechanisms and applications, Critical Reviews in Environmental Science and Technology, 47:20, 1901-1957, DOI: 10.1080/10643389.2017.1400853.

160. Weiersbye, I.M., Straker, C.J., & Przybylowicz, W.J. (Sep 1999). Micro-PIXE mapping of elemental distribution in arbuscular mycorrhizal roots of the grass, Cynodon dactylon, from gold and uranium mine tailings. Nuclear Instruments and Methods in Physics Research Section B, Beam Interactions with Materials and Atoms, 158(1-4), 335-343.

161. Whipps J.M. and R. D. Lumsden, "Commercial use of fungi as plant disease biological control agents: status and prospects," in Fungi as Biocontrol Agents: Progress, Problems and Potential, T. M. Butt, C. Jackson, and N. Magan, Eds., pp. 9–22, 2001.

162. Wilson, G.W.T., Rice, C.W., Rillig, M.C., Springer, A. and Hartnett, D.C. (2009), Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments. Ecology Letters, 12: 452-461. https://doi.org/10.1111/j.1461-0248.2009.01303.x.

163. Winder, R. S., & Shamoun, S. F. (2006). Forest pathogens: friend or foe to biodiversity? Canadian Journal of Plant Pathology, 28(sup1), S221–S227. doi:10.1080/07060660609507378.

164. Wuana, R. A., & Okieimen, F. E. (2011). Heavy Metals in Contaminated Soils: A Review of Sources, Chemistry, Risks and Best Available Strategies for Remediation. ISRN Ecology, 2011, 1–20. doi:10.5402/2011/402647.

165. Yadav, Sudesh. (2010). Cold stress tolerance mechanisms in plants. A review. http://dx.doi.org/10.1051/agro/2009050. 30. 10.1051/agro/2009050.

166. Yousaf, B., Liu, G., Wang, R. et al. Bioavailability evaluation, uptake of heavy metals and potential health risks via dietary exposure in urban-industrial areas. Environ Sci Pollut Res 23, 22443–22453 (2016). https://doi.org/10.1007/s11356-016-7449-8.

167. Youssef MMA, Eissa MFM: Biofertilizers and their role in management of plant parasitic nematodes. A review. E3 J Biotechnol. Pharm Res 2014, 5:1–6.

168. Zhang, F.; Zou, Y.N.; Wu, Q.S. Quantitative estimation of water uptake by mycorrhizal extraradical hyphae in citrus under drought stress. Sci. Hortic. 2018, 229, 132–136.

169. Zhang, F., Jia-Dong, H. E., Qiu-Dan, N. I., Qiang-Sheng, W. U., and Zou, Y. N. (2018a). Enhancement of drought tolerance in trifoliate orange by mycorrhiza: changes in root sucrose and proline metabolisms. Not. Bot. Horti. Agrobot. Cluj-Napoca 46, 270. doi: 10.15835/nbha46110983.

170. Zhu X, Song F, Xu H. Influence of arbuscular mycorrhiza on lipid peroxidation and antioxidant enzyme activity of maize plants under temperature stress. Mycorrhiza. 2010 Jun;20(5):325-32. doi: 10.1007/s00572-009-0285-7. Epub 2009 Nov 20. PMID: 19936801.

171. Zhu, Xiancan & Song, Feng-Bin & Liu, Shengqun & Liu, Tie-Dong. (2011). Effects of arbuscular mycorrhizal fungus on photosynthesis and water status of maize under high temperature stress. Plant and Soil. 346. 189-199. 10.1007/s11104-011-0809-8.

172. Zhu, X.; Song, F.; Liu, F. Arbuscular Mycorrhizal Fungi and Tolerance of Temperature Stress in Plants. In Arbuscular Mycorrhizas and Stress Tolerance of Plants; Springer Science and Business Media LLC: Berlin, Germany, 2017; Volume 33, pp. 163–194.

173. Žifčáková L, Větrovský T, Howe A, Baldrian P. Microbial activity in forest soil reflects the changes in ecosystem properties between summer and winter. Environ Microbiol. 2016 Jan;18(1):288-301. doi: 10.1111/1462-2920.13026. Epub 2015 Oct 14. PMID: 26286355.

174. Zwiazek, J.J.; Equiza, M.A.; Karst, J.; Senorans, J.; Wartenbe, M.; Calvo-Polanco, M. Role of urban ectomycorrhizal fungi in improving the tolerance of lodgepole pine (Pinus contorta) seedlings to salt stress. Mycorrhiza 2019, 29, 303–312.

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