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Review

Arbuscular mycorrhiza in combating abiotic stresses in vegetables: An eco-friendly approach

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ABSTRACT

Vegetable production is hampered by several abiotic stresses which are very common in this era of climate change. There is a huge pressure on the plants to survive and yield better results even in the prevalence of various environmental stresses such as cold stress, drought, heat stress, salinity etc. This necessitates the need of robust plant growth which is possible with mycorrhizal association. Mycorrhiza improves plants tolerance to several abiotic stresses by various physiological, functional and biochemical changes in plants. The application of arbuscular mycorrhiza (AM) as vegetable biofertilizers doesn't only influence the plant health, but moreover discursively it lowers the demand for harmful chemical fertilizers. Overall, it may be concluded that inoculation of vegetables with arbuscular mycorrhizal fungi can be used, as it easily guards plants against undesirable abiotic stresses. In this work, information is provided based on several examples from the literature based on the application of AM to combat harmful abiotic stresses in vegetable crops. This paper reviews the impacts of AM fungi on the plant parameters, its functional activities and molecular mechanisms which makes it more adaptable and underline the future prospects of using AM fungi as a biofertilizer in the stress condition.

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1. Introduction

A nutritious and healthy diet is an important means to maintain good health. The nutritional security which is often less valued than food security by authorities can be achieved with the consumption of vegetables and pulses. Low vegetable consumption is often linked with malnutrition in children and other susceptible group. Vegetables are an importance source of nutrients namely vitamin A, C, K, thiamin, pyridoxine, folate, carotenes, minerals and trace elements etc. Vegetables have essential bioactive compounds such as phenolics (flavonoids) and antioxidant activity which plays a significant role in prevention of chronic and degenerative diseases and maintaining health (. World health Organization (WHO) recommends an intake of 200–250 g of vegetables intake in a day but the average consumption of vegetables in the world lacks far behind the recommendations. There are several reporting indicating the effect of low vegetable consumption on weight gain and thereby necessitates the consumption of fiber rich and low glycemic load having food (Nour et al., 2018).

Mainly due to limited arable land, vegetable crops of solanaceae and cucurbitaceae family are frequently cultivated in unfavourable conditions under thermal stress, drought, flooding and contaminated organic pollutant. The abiotic stress is mainly responsible for reducing yield loss causing more than 50% losses worldwide. These are often interrelated and cause significant distortion in the morphological, biochemical, physiological and molecular parameters of plants. Along with reducing yield, it has detrimental effect on the quality and nutritional status of fresh fruits and vegetables. There are certain indicators such as increased respiration, discoloration, flavor loss, off-odours developments, loss in weight, breakdown of membranes etc which shows the impression of abiotic stress. The serious abiotic stresses faced by the vegetables are drought, salinity, heat and cold. Around 96.5% of global rural land area is affected by abiotic stresses (Cramer et al., 2011). The drought can cause yield losses from 13% to 94% in several conditional to the drought intensity and duration (Bulgari et al., 2019).

Mycorrhizal symbiosis is a reciprocally beneficial association between soil fungi with plant roots. Arbuscular mycorrhizal fungi start a symbiotic union with roots of 80% land crops (Prasad et al., 2017). In AMF, the plants symbiotically associate with glomeromycete fungi mainly developed to improve the uptake of nutrients and water by plants. Genus *Glomus* is one of the most abundant genera of AM fungi. AM fungi produce symbiotic signals (lipochitooligosaccharides) so as to stimulate better root growth and branching. The chitooligosaccharides triggers the calcium spiking which is perceived via kinases. The cells hereby accommodate the fungal infection in the cells and nutrients are being taken by arbuscules of the plant cells. Mycorrhizal symbiosis is one of the initial symbiotic relationships on earth. It helps in the growth and development of the plant by supplementing the plant growth with an appropriate supply of mineral, and in return, the fungi draw food from the plant roots. AM fungi has a positive impact on the plants' stress tolerance along with enhanced productivity. The fungi obtained sugars and carbohydrates from the plants and

plants avert 20% of photosynthetic products to the fungi which is obligatory biotrophic (Keymer et al., 2017). By observing nature around us, people have slowly found extra benefits which mycorrhizal fungi have to host plants. AM fungus facilitates carbon sequestration and increase the carbon content of soil via aggregation and prevent decomposition of organic carbon. Nevertheless, we do not realize everything about mycorrhiza. Apart from providing nutrients and water to plants, mycorrhiza provides additional benefits of combating biotic and abiotic stresses (Jung et al., 2012). Moreover, AM fungi associates with terrestrial plants and has significant role in nutrients (carbon, nitrogen and phosphorus) cycling of ecosystem. Mycorrhizal symbiosis is a remarkably complicated relationship. AM fungus also interact with growth promoting rhizobacteria, other soil microorganisms, mycorrhiza helper bacteria and deleterious bacteria which has a significant importance in agriculture. Although Mycorrhizal symbiosis is universal in nature. Previous investigations have mentioned that low temps' impact AM fungal development (Zhu et al., 2010a, 2010b), while high temps have a terrible or perhaps zero influence on mycorrhizal colonization (Compant et al., 2010).

Drought has a massive impact on plant productivity internationally and is more likely to enhance with climatic changes. Lots of ecophysiological studies indicate that arbuscular mycorrhizal (AM) symbiosis is a crucial component in helping plant life to cope with water demands (Garg and Chandel, 2011). The fungi control the root water uptake by plants. It also enables the plants to maintain bigger organ hydration and turgor, which will sustain general cell natural activity, mainly linked to the photosynthetic machinery. Mycorrhizal fungi furthermore affect the hydraulic conductivity and gas exchange within the root and foliage. Molecular mechanisms activated by the effect of AM symbiosis in response to drought generally leads to favourable transport of water along with improved accessibility to nutrients. These fungi might be referred to as biotrophic symbionts that are powerless to exist without their growing partner and also cannot be artificially raised in vitro. The alleviating effect of AM symbiosis in response to drought generally is determined by the positive consequences of AM fungi on the uptake and transport of water along with improved nutrient absorption, especially of accessible soil phosphorus (P) along with other immobile minerals. It results in the hydration of developing tissues, sustainable physiology and a clear promotion of growth.

Soil salinization is one of the most detrimental abiotic stress globally which reduces the plant development and consequently decreases the overall agricultural production. The regions under the salt affected soils are increasing mainly due to various natural and anthropogenic factors such as low rainfall, high temperature, poor quality irrigation water (Zia-ur-Rehman et al., 2017). The anthropogenic factors responsible for soil salinization include unsustainable agricultural practices and industrial wastes. Along with natural and man-made factors, climate and climate change is also important driver of salinization in the changing environment (Daliakopoulos et al., 2016). Soil salinization is a major issue in arid and semi-arid areas which is mainly due to meager precip-

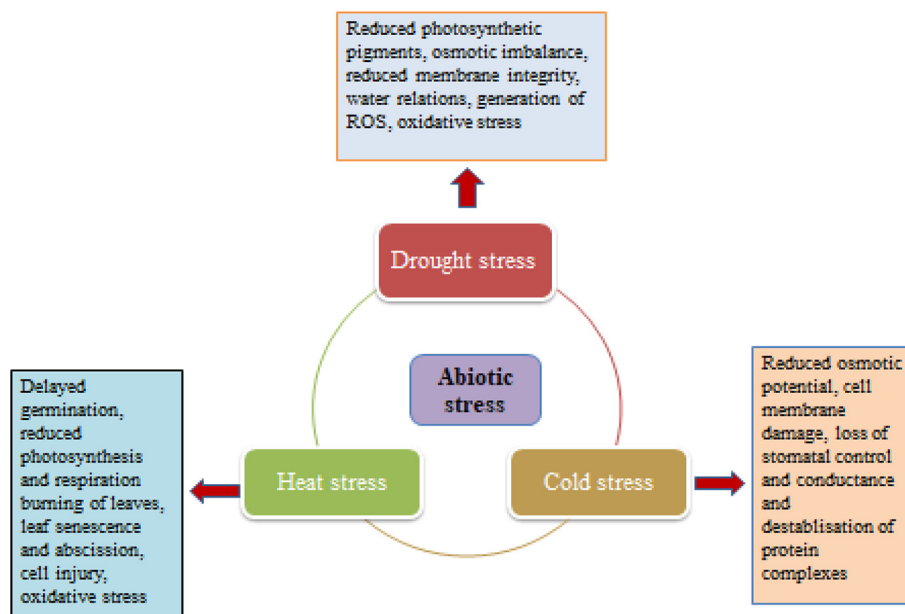


Fig. 1. Impact of abiotic stress on the vegetables.

itation, high temperature and increased rate of evaporation. The serious issue of salinity arises as the concentration of Na^+ and Cl^- increases than the standard levels as it disturbs the plant physiology by altering the metabolic activities and osmotic functions required for growth and development. High salinity disrupts the ionic and osmotic balance of the cell (Tuteja, 2007). Na^+ and Cl^- ions have toxic effects on plants and disrupt the enzymes structure, metabolic activities and damage cells' organelles and hinders protein synthesis (Saxena et al., 2017). Most vegetable crops are sensitive to salt stress as their salinity threshold is very low (Machado and Serralheiro, 2017). The plants, however, have developed adaptive responses to salinity by modification at molecular, cellular, physiological and metabolic levels. AM fungi application to the soil helps to eliminate the salinity stress encountered by the vegetable crops. Inoculation with AM fungi led to higher amounts of electrolytes and a diminished level of electrolyte leakage under salt stress. Moreover, the advancement of proline, chlorophyll *a* and chlorophyll *b* were significantly impacted under salinity stress (Nazarbeygi et al., 2011). AM fungi enhance plant growth by improved nutrient uptake, significantly P, in addition to inadequately soluble nutrients in the soil. AM fungi have the potential to lessen the detrimental effect of salinity stress on the growth parameters of the plants. The AM fungal association helps in enhanced plant growth by increasing their tolerance against saline stress by enhancing its photosynthetic activity, phosphatase activity, antioxidant enzymes and osmotic adjustments (Borde et al., 2011). This paper overviews the role of arbuscular mycorrhizal fungus in enhancing abiotic stress tolerance of vegetable crops in this changing environment. Limited reviews has been done in this particular field and therefore a detailed review of the ultrastructural and molecular mechanisms associated is attempted in this paper along with reviewing the gene expression involved in mycorrhizal association and suitability of particular fungi species with the crop (Fig. 1).

2. Drought tolerance by AM inoculation in vegetables

2.1. Impact of drought stress on vegetables

Water scarcity is a severe limiting factor to crop productivity and drought cause huge losses in productivity of vegetable crops

mainly depending upon the duration and severity of the drought stress. Vegetables are considered very sensitive to droughts and droughts mainly complemented with high temperature increases evapotranspiration losses and effects photosynthesis of the plants thereby affecting the crops yield. The yield of indigenous leafy vegetable crops mainly consumed in water stressed conditions of Africa was significantly reduced as the drought reduced the fresh weight and dry weights of leaves. However the nutritional quality as assessed by phytonutrients accumulation such as α -carotene, β -carotene, ascorbic acid, α -tocopherol, zinc and iron per 100 g of edible portion was not significantly reduced or altered in water deficient conditions (Luoh et al., 2014). The drought stress mainly reduce the water potential, free water, bound water and transpiration rate of the plants thereby reducing the stomatal conductance, photosynthetic rate and intercellular CO_2 which ultimately reduces the yield. In drought conditions, plants generally generate reactive oxygen species (ROS) which leads to oxidative damage in plants. This oxidative damage to the lipids, nucleic acids and proteins was augmented by the production of antioxidant enzymes by plants in response to drought stress (Kusvuran et al., 2016). The drought stress therefore can lead to serious physiological glitches in plant and can severely affect growth and yield of vegetable crops by affecting the biomass production.

2.2. Effect of AM fungi inoculation on vegetables for drought tolerance

AM fungi are vital for vegetable production since they affect plant water relations and therefore increase the drought tolerance of host plant life. Plants generally alter their cellular metabolism and incite the defense mechanisms so as to ensure their adaptability in drought conditions (Bahadur et al., 2011). AM inoculation of plants increased the root hair density and root hair length in drought conditions. These plants also showed an increased concentration of methyl jasmonate, indole-3-acetic acid, calmodulin and nitric oxide content of roots so as to make them more adaptable to the drought stress (Zou et al., 2017). AMF helps in absorption and translocation of nutrients in plants outside the root zone (rhizosphere) and moreover bring changes in plant metabolism to tolerate drought stress. The AM fungi function as biofertilizers, bioprotectors and bioregulators and improve the nutrient composition of plants (Rouphael et al., 2015). Improved plant water stip-

Table 1
Impact of AM fungi on management of drought stress in vegetables.

Family of host plant	Host plant	Fungus species	Observed response	Reference
Solanaceae	<i>Solanum lycopersicum</i>	<i>G. mosseae</i> , <i>G. etunicatum</i> , <i>G. claroideum</i> , <i>G. microaggregatum</i> , <i>G. geosporum</i> , and <i>R. irregularis</i>	Enhanced fruit yield, water use efficiency, biomass and leaf water potential	Bakr et al. (2016)
Solanaceae	<i>Solanum lycopersicum</i>	<i>Funneliformis mosseae</i>	Improved water use efficiency and improved growth	Chitarra et al. (2016)
Solanaceae	<i>Solanum lycopersicum</i>	<i>Rhizophagus intraradices</i>	Improved rate of growth and more efficient photosystem II, increased production of strigolactone for symbiosis promotion	Ruiz-Lozano et al. (2016)
Solanaceae	<i>Solanum lycopersicum</i>	<i>Funneliformis mosseae</i> , <i>Funneliformis geosporum</i> , <i>Claroideoglomus etunicatum</i> , <i>Claroideoglomus claroideum</i> , <i>Glomus microaggregatum</i> , and <i>Rhizophagus irregularis</i>	Improved water use efficiency, stomatal conductance, more efficient photosystem II and higher water potential of leaves	Bakr et al. (2018)
Solanaceae	<i>Solanum lycopersicum</i>	<i>Septoglomus deserticola</i>	Improved stomatal conductance, relative water content and leaf water potential	Duc et al. (2018)
Solanaceae	<i>Solanum melongena</i>	<i>Glomus intraradices</i>	Enhanced crop growth, dry biomass, high water use efficiency and increased number of fruits	Badr et al. (2020)
Solanaceae	<i>Capsicum annuum</i>	<i>Rhizophagus intraradices</i> , <i>Rhizophagus fasciculatum</i>	Increased root and shoot length, higher biomass and chlorophyll content	Tallapragada et al. (2016)
Solanaceae	<i>Solanum lycopersicum</i>	<i>Glomus fasciculatum</i>	Improved shoot length and plant growth, increased biomass, increased water use efficiency	Borde et al. (2012)
Cucurbitaceae	<i>Cucumis melo</i> L.	<i>Glomus spp</i>	Improved plant height, root length, enzyme activity, biomass production and soluble sugar content, higher net photosynthetic rate and water use efficiency	Huang et al. (2010)
Cucurbitaceae	<i>Cucumis melo</i> L.	<i>Glomus intraradices</i> and <i>Glomus spp</i>	Improved physiological parameters and photosynthesis, increased chlorophyll content	Cakmakci et al. (2017)
Asteraceae	<i>Lactuca sativa</i>	<i>Glomus intraradices</i> , <i>Glomus mosseae</i>	Improved antioxidant compounds accumulation and chlorophylls and phenolics content in leaves, improved quality	Baslam and Goicoechea (2012)
Asteraceae	<i>Lactuca sativa</i>	<i>Rhizophagus intraradices</i>	Higher photosynthetic pigments, stomatal conductance and improved antioxidant enzyme level (catalase, ascorbate peroxidase and glutathione reductase)	Durán et al. (2016)
Asteraceae	<i>Lactuca sativa</i>	<i>R. irregularis</i> , strain EEZ 58	Improved rate of growth and more efficient photosystem II, increased production of strigolactone for symbiosis promotion	Ruiz-Lozano et al. (2016)
Fabaceae	<i>Phaseolus vulgaris</i> L.	<i>Glomus etunicatum</i> , <i>G. intraradices</i> and <i>G. monosporum</i>	Improved vegetative growth, proteins and sugar concentration in leaves, reduced proline content and yield	Salim and Abou El-Yazied (2015)

ulation along with modifications in a proper balance of osmotic minerals is especially critical for the growth of a vegetable. Studies in several vegetable crops have shown the direct or indirect mechanisms which control consuming water associations in AM fungus grown symbiotically with plants (Lehto and Zwiazek, 2011). In this direction, numerous studies have suggested several mechanisms whereby AM fungi alleviate drought stress either by enhancing the water use efficiency (WUE) or increasing relative water content (Farahani et al., 2008). Moreover, in several instances, significant changes in the antioxidant activities have been observed (Baslam and Goicoechea, 2012). The enhanced antioxidant activity in AM inoculated plants detoxifies the reactive oxygen species of plants and increases the nutritional quality of vegetable crops without reducing the growth and yield. AM inoculated plants showed improved performance and enhanced the inulin content of chicory plants and thereby reducing the damaging effect of drought stress (Langeroodi et al., 2020).

The negative effect of drought on the vegetable plants was significantly decreased on inoculation of vegetable plants with mycorrhiza. The mycorrhizal plants showed improved photosynthesis rate, water use efficiency, stomatal conductance and increased chlorophyll content which significantly improved plant height, shoot length, plant biomass and ultimately yield of vegetable crops (Bakr et al., 2018). Along with it, there is enhanced accumulation of antioxidant enzymes, photosynthetic pigments, increased concentration of sugar and proteins and reduced proline content (Salim and Abou El-Yazied, 2015). The affirmative influence of mycorrhizal association with vegetable crops shows the increased poten-

tial of vegetable crop in drought affected areas. Moreover the reduced proline content in the plants shows that the impact of drought on the *Phaseolus vulgaris* L. can be considerable reduced on mycorrhizal inoculation of the vegetable (Salim and Abou El-Yazied, 2015) (Table 1).

3. Thermal (heat and cold) tolerance by AM inoculation in vegetables

3.1. Impact of heat stress on vegetables

In this era of climate change, the global temperature is predicted to rise by 1.4–5.8 °C since 2021 (Arora et al., 2005). Heat stress decreased the efficiency of photosystem II and the water potential of leaves. However, it has positive influence on the levels of malondialdehyde and electrolyte leakage in tomato plants (Li et al., 2014). Under heat stress, reactive oxygen species (ROS) are manufactured in cells whose oxidative stress is a primary damaging factor to the vegetable production along with increased hydrogen peroxide content, malondialdehyde content and superoxide anions (Yuan et al., 2016). The yield of vegetables and legumes is projected to be reduced by 31.5% with a 4 °C increase in temperature taking 20 °C as the baseline temperature although the nutritional quality has mixed effect (Scheelbeek et al., 2018). Hence, the heat stress can lead to oxidative stress in plants by production of ROS and heat shock proteins and can severely affect the yield by affecting photosynthesis.

3.2. Effect of AM fungi inoculation on vegetables for heat tolerance

In vegetables, AM inoculation has found to increase the yield by enhanced biomass production (Haghighi et al., 2015; Duc et al., 2018). AM inoculation also plays a significant role in uptake of higher amount of nutrients, leaf water potential and stomatal conductance (Khan et al., 2013). However, limited work in heat tolerance by AM inoculation has been performed and efforts are needed in this section.

3.3. Impact of cold stress on vegetables

Plants when exposed to the low temperatures of 1–10 °C can face serious chilling injury and even death of some tropical and subtropical plants mainly vegetables. The physiological activities of plants such as nutrition, photosynthesis, water potential and respiration etc are affected severely (Jouyban et al., 2013). Low temperature negatively impacts the plant metabolism. It can cause serious damage to plant tissue and can cause chlorosis, membrane damage, necrosis, alteration in enzymatic activity, changes in viscosity of cytoplasm in vegetable plants. Chilling stress lowers the photosynthetic efficiency along with enhanced leakage of leaf electrolyte in the seedlings of watermelon (Shirani Bidabadi and Mehralian, 2020). The cold stress, hence, severely affects the plants by causing chilling injury, cell membrane damage and decreasing photosynthetic efficiency of the plants and posing a negative impact on the yield of vegetable crops.

3.4. Effect of AM fungi inoculation on vegetables for cold tolerance

AM fungi can enhance plant tolerance to cold. AMF maintains a balance of moisture within the host plant, improve secondary metabolites to boost the vegetable crops' immune system and increase protein stores for supporting the plant life to battle cold stress situations. AM inoculation has found to increase the photosynthetic efficiency and raise the biomass production in plant

either by increasing the photosynthetic pigments or by increasing the efficiency of photosystem II (Caradonia et al., 2019; Ma et al., 2019; Pasbani et al., 2020). It has also found to raise the enzymatic activity in the plants, activation of antioxidant defense mechanisms and accumulation of protecting molecules so as to reduce cell membrane damages (Liu et al., 2016; Caradonia et al., 2019; Pasbani et al., 2020). There are several reporting of increased vegetable yield on inoculation of plants with arbuscular mycorrhiza (Chen et al., 2013; Liu et al., 2014; Haghighi et al., 2015). Several studies claim that different vegetables inoculated with AMF grow better than non-AM fungi inoculated vegetation under the cold climatic conditions. The adaptations of the plants as induced by AM fungi therefore positively influence the formation of photosynthetic pigments, carbohydrates and sugars in plants and enhance the enzymatic activity and conclusively the growth and development of plants (Table 2).

4. Salinity tolerance by AM inoculation in vegetables

4.1. Impact of salinity on vegetables

Salinity has detrimental effect on plant growth and development. Majority of vegetables crops have less tolerance to salinity particularly in range 1–2.5 dSm⁻¹, however, it decreases on application of saline water for irrigation (Machado and Serralheiro, 2017). Salt tolerant vegetable species alleviate salt stress by changing their leaf development and perspective, enhancing root advancement to access deeper water sources, creating osmolytes and activating a variety of tension genetics and antioxidants. The salinity tolerance mechanism involve Na⁺ and Cl⁻ sequestration in cells' vacuoles thereby blocking the entry of Na⁺ in the cell and its elimination from transpiration. Nevertheless, these adaptive strategies begin to be inadequate to cope with the rapidly increasing salinity (Tuteja, 2007). The salinity affects the morphological development, physiological function and yield of crops and affects a significant proportion of arable land. It has been observed

Table 2
Impact of AM fungi on management of thermal stress in vegetables.

Stress	Family of host plant	Host plant	Fungus species	Observed response	Reference
Cold	<u>Solanaceae</u>	<i>Solanum lycopersicum</i>	<i>Funneliformis mosseae</i>	Higher fresh and dry weight reduced level of MDA, H2O2 and O2- and increased Ca precipitates in apoplast, enhanced enzyme activity and reduced redox state in root cells	Liu et al. (2016)
Cold	<u>Solanaceae</u>	<i>Solanum lycopersicum</i> L.	<i>Funneliformis mosseae</i> , <i>Paraburkholderia graminis</i>	Reduced cell membrane injuries, more efficient photosystem II, improved growth of seedlings	Caradonia et al. (2019)
Cold	<u>Solanaceae</u>	<i>Solanum melongena</i> L.	<i>Funneliformis mosseae</i> , <i>Claroideoglossum etunicatum</i> , <i>Rhizophagus irregularis</i> , and <i>Diversispora versiformis</i>	Improved photochemical reactions and activation of antioxidant defense mechanisms, accumulation of protecting molecules and reduction of membrane damages	Pasbani et al. (2020)
Cold	<u>Cucurbitaceae</u>	<i>Cucumis sativus</i>	<i>Funneliformis mosseae</i>	Improved dry weight and fresh weight of seedlings, enhanced secondary metabolites content and enzymatic activity, reduced hydrogen peroxide content	Chen et al. (2013)
Cold	<u>Cucurbitaceae</u>	<i>Cucumis sativus</i>	<i>Funneliformis mosseae</i>	Increased total fresh and dry weight, reduced H2O2 accumulation in cell walls and increased ATPase concentration and its activity, enhanced protein content in plasma membrane	Liu et al. (2014)
Cold	<u>Cucurbitaceae</u>	<i>Cucumis sativus</i>	<i>Glomus mosseae</i>	Increased root and shoot fresh weight, enhanced antioxidant activity and phenol content	Haghighi et al. (2015)
Cold	<u>Cucurbitaceae</u>	<i>Cucumis sativus</i>	<i>Rhizophagus irregularis</i>	Improved efficiency of photosynthesis and enhanced carbon sink strength, sugar content of leaves and nonphotochemical quenching	Ma et al. (2019)
Heat	<u>Solanaceae</u>	<i>Capsicum annum</i> L.	<i>Penicillium resedanum</i> LK6	Increased number of leaves and biomass per plant, higher nutrient content in plants, significant proline accumulation, higher amount of flavonoids synthesis	Khan et al. (2013)
Heat	<u>Solanaceae</u>	<i>Solanum lycopersicum</i>	<i>Septoglossum deserticola</i> and <i>Septoglossum constrictum</i>	Increased leaf water potential, stomatal conductance and enhanced biomass production	Duc et al. (2018)
Heat	<u>Cucurbitaceae</u>	<i>Cucumis sativus</i>	<i>Glomus mosseae</i>	Increased root and shoot fresh weight, enhanced antioxidant activity and phenol content	Haghighi et al. (2015)

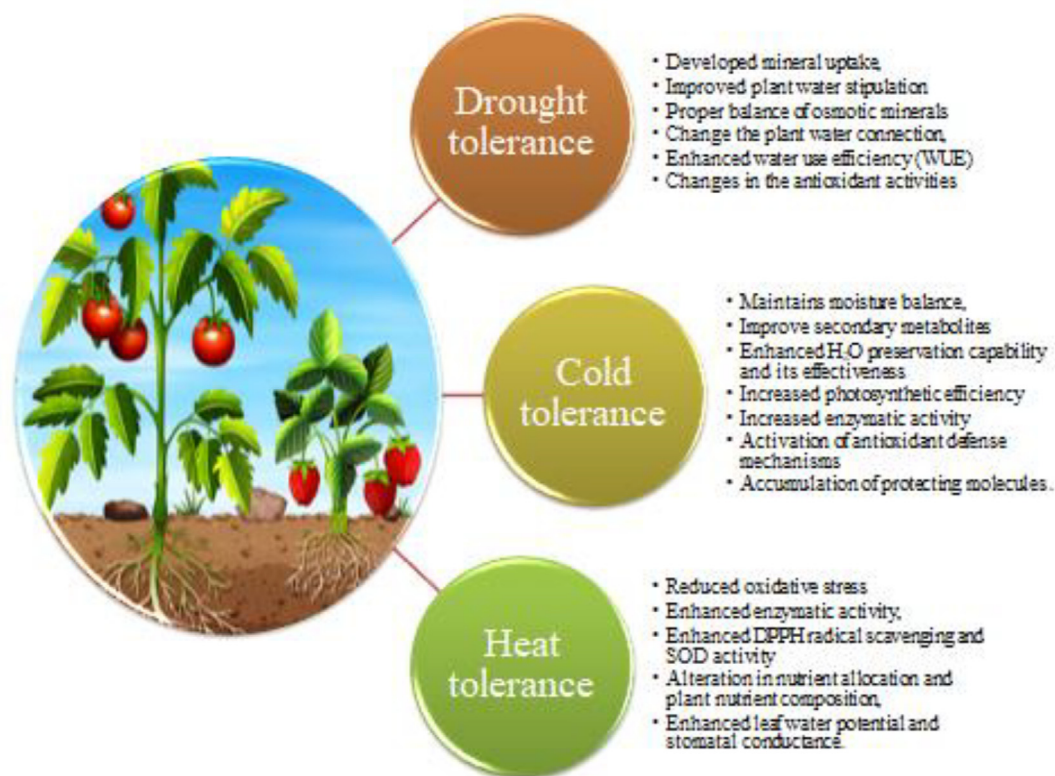


Fig. 2. Working of AM inoculation of vegetables against abiotic stresses.

that the yield of tomato crop is reduced at and above the salinity level of 5 dSm⁻¹. Salinity is found to decrease the leaf area and dry matter content in tomato plants. Moreover, the leaves are found more sensitive to salinity stress as it contained more proline and Na⁺ content in comparison to fruits (Babu et al., 2012). The resultant reduced biomass production in the plants are due to physiological and biochemical processes mainly affected by salinity. Almost all the growth stages of the plants viz. germination, seedling, vegetative phase and maturity stages are influenced by salinity. Salinity disturbs the ionic adjustment and osmotic pres-

sure of the plants and spoils cell membranes selectivity (Nawaz et al., 2010). Salinity disturbs the ionic homeostasis in the plants by enhancing ROS (Reactive Oxygen Species) in the plants which unfavourably affects the nutrient uptake and cell membranes and various ultrastructures thus leading to ionic and osmotic stress in plants (Arif et al., 2020). With increased salinity level, a higher concentration of polyphenols flavonoids, ascorbic acid, carotenoids, betalain and antioxidant capacity in *Amaranthus tricolor* was witnessed at 50 and 100 mmol L⁻¹ concentrations of NaCl (Sarker and Oba, 2018). The salinity stress is also found to enhance content

Table 3
Salt tolerance of vegetable crops as determined by soil salinity (EC_e) and irrigation water salinity (EC_w).

Family	Crops	Threshold limits		Salinity tolerance limit	
		Soil salinity EC _e (dSm ⁻¹)	Irrigation Water EC _w (dSm ⁻¹)		
Malvaceae	<i>Abelmoschus esculentus</i>	1.2	-	Sensitive	
Amaryllidaceae	<i>Allium cepa</i> L.	1.2	0.8		
Amaranthaceae	<i>Spinacia oleracea</i>	2.0	1.3		
Rosaceae	<i>Fragaria</i> × <i>ananassa</i>	1.0	0.7		
Apiaceae	<i>Daucus carota</i> L.	1.0	0.7		
Fabaceae	<i>Phaseolus vulgaris</i> L.	1.0	0.7		
Solanaceae	<i>Lycopersicon esculentum</i> L.	2.5	1.7		Moderately sensitive
	<i>Solanum tuberosum</i> L.	1.7	1.1		
	<i>Solanum melongena</i> L.	1.1	0.7		
Brassicaceae	<i>Brassica oleracea</i> var. <i>italica</i>	2.8	1.9		
	<i>Brassica oleracea</i> var. <i>botrytis</i>	-	1.9		
Cucurbitaceae	<i>Cucumis melo</i> L.	1.0	-		
Asteraceae	<i>Lactuca sativa</i> L.	2.0	0.9		
Apiaceae	<i>Apium graveolens</i> L.	1.8	1.2		
Fabaceae	<i>Pisum sativum</i>	1.5	-		
Solanaceae	<i>Capsicum annuum</i> L.	1.5	1.0		
Chenopodiaceae	<i>Beta vulgaris</i> L.	4.0	2.7	Moderately tolerant Tolerant	
Asparagaceae	<i>Asparagus officinalis</i> L.	4.1	2.7		

Source: Machado and Serralheiro (2017).

of biochemical contents and antioxidant activities in the leaves of *Amaranthus tricolor*. There was witnessed an increase in the proteins, minerals, dietary fibers, ascorbic acid, polyphenol content, flavonoids in the leaves under salinity stress (Sarker et al., 2018). Increased salinity (100 mM of NaCl treatment) enhanced the nutritional value of radish sprouts and their germination under ambient salinity stress thus can lead to developing healthy compounds in the plant food (Yuan et al., 2016) (Fig. 2).

4.2. Salt tolerance in vegetables

The plants generally use most of the energy accumulated via photosynthesis for general maintenance and only a small portion of acquired energy is used for production of biomass. But under different conditions of stress, the plants more of their energy for general maintenance and thereby biomass production is reduced. Salt tolerance in plants is the ability of plants to withstand the saline conditions and to ensure growth and development irrespective of prevalence of excess salts in the root zone. The main three salt tolerance mechanisms are ion exclusion in which the toxic ions are excluded from the shoot, tissue tolerance in which toxic ions are compartmentalized in specific tissues and cellular or subcellular organelles and shoot ion independent tolerance in which the plants maintain growth and water uptake irrespective of Na^+ accumulation in the plant. The salinity level doesn't seem to affect the relative crop yields until the salinity level exceeds a salinity threshold level (EC_e). The threshold value for salinity tolerance for major vegetable crops lies between 2.3 and 3.5 dSm^{-1} and with one unit increase, yield losses in the range of 2.3–7.6% have been observed (Sonneveld and Burg, 1991). Even then the yield losses of vegetables cultivated in saline soils vary according to the salinity level, vegetable grown and its tolerance to withstand salinity. The tolerance level of some important vegetable crops under salinity stress is mentioned in Table 3.

4.3. Effect of AM fungi inoculation on vegetables for salinity tolerance

The harsh saline conditions make it difficult for the plants to survive mainly due to osmotic stress and AM fungi spores didn't considerably reduce the soil salinity levels (Selvakumar et al., 2013). The quantity of AM fungi spores decreased with raising soil depth within the rhizosphere. A good relationship between spore density as well as organic carbon and soil pH continues to be determined by several workers (Yang et al., 2011). The plant nutrition is sponsored by AM fungi by absorption and translocation of nutrients and minerals in deeper depths and changes the metabolic activities so as to improve the nutraceutical compounds formed. AM acts as bioregulators and bioprotectors in the plants by interfering with the phytohormones of the plants (Rouphael et al., 2015). Moreover, it was also determined that under saline growth conditions, AM inoculated plant has similar biomass as non-AM plants in non-saline conditions. A beneficial impact of AM fungal symbiosis was also found on growth and osmolytes of several crops. Under saline conditions, the recommended mycorrhizal benefit occurs primarily through enhanced mineral content of the plant (Porcel et al., 2011). Moreover, AM inoculation improves the net assimilation rates (NAR) by increasing stomatal conductance and improved photosystem II (Hajiboland et al., 2009; Vicente-Sánchez et al., 2013). There are various reportings that vegetable crops inoculated with AM fungi has increased the growth, nutrient acquisition and enzymatic activity (Huang et al., 2010; Altuntas et al., 2016; Hashem et al., 2018). The use of AM inoculated rootstocks in tomato increased the yield. It has also shown considerable increase in vitamin C (Oztekin et al., 2013). VAM (vascular arbuscular mycorrhiza) maintained the plant length, increased fresh weight of stem and roots in tomato under

salinity stress but could not influence dry weight of stem and root (Demir et al., 2011). The plant height, fresh and dry weight has shown an increase of 38.46%, 60% and 92.3% on inoculation of AM and magnetized water in onion plants (Suhail and Mahdi, 2013). AM inoculation in the plants of pepper enhances the growth of plants, number of fruits and fruit yield (Kapoulas et al., 2019). A favourable modification in morphological parameters of the vegetable crops viz. tomato, brinjal, chilli and bhendi was observed on inoculation of plants with AM fungi. The root and shoot length, dry weight, fresh weight, number of leaves, leaf area was increased. Moreover, biochemical parameters such as chlorophyll content, proteins and nutrient content are also enhanced by AM inoculation whereas the mycorrhizal seedlings have lower value of starch and sugar than non-mycorrhizal seedlings (Lenin et al., 2010). The inoculation of AMF in cucumber seedlings improved the nutrient uptake and their rate of establishment under salinity stress. This is mainly due to enhanced nutrient uptake in the early vegetative phase (Sallaku et al., 2019). The AMF inoculated rootstocks of tomato also showed improved growth and increased yield. Salinity tolerance thus can be enhanced in the plants by grafting combined with mycorrhizal inoculation (Oztekin et al., 2013). AM colonization in the tomato plants showed increased activity of antioxidant enzymes such as superoxide dismutase and peroxidase which makes the plants more productive (Dudhane et al., 2013). Improved photosynthesis and relative water content of leaves along with reduced electrolyte leakage has been observed in AM inoculated plants (Ahmad et al., 2019). In greenhouse conditions, the AMF inoculated tomato plants showed enhanced nutrient uptake under moderate salt stress (Balliu et al., 2015). AMF inoculated plants have known to reduce the effect of stress and increase the photochemical capacity of the plant. The sweet pepper plants inoculated with mycorrhizal fungus showed enhanced vegetative growth, total dry weight and fresh weight along with increased chlorophyll and antioxidant content. The concentration of carotenoids also increased with increased salinity (Hegazi et al., 2017). AM inoculation of lettuce plants lowers their ABA level which shows they are relatively less stressed than the non-inoculated plants. AM inoculation, therefore, alters the hormonal profile of the plant and affects their physiology to make it better suited to the saline conditions (Aroca et al., 2013) (Table 4).

4.4. Molecular mechanism of stress tolerance in vegetables

The AM symbiosis play a significant role in drought resistance but the molecular mechanism mainly the role of metabolites and metabolic pathways in drought resistance by gene regulation is yet to be explored. Two patterns are witnessed in the AMF induces responses in genes for drought stress; downregulation or upregulation of genes. PIP gene expression can be minimized by changing the composition, profusion and activity of other aquaporins. Yet, the expression of PIP gene was enhanced under salt stress, suggesting that the effect of AM on PIP gene expression depends upon the inherent characteristics of the osmotic strain. (Ruiz-Lozano and Aroca, 2010). However, there are plenty of researches indicating upregulation of gene expression mainly caused by AM inoculation in the plants. The upregulation of BiP encoding gene of *Glomus intraradices* was observed in plants under drought stress during both in vitro and ex vitro conditions. The gene GiBiP help in drought stress tolerance mainly through formation of proteins having chaperone like activity (Porcel et al., 2007).

High temperature has harmful effects on the biochemical and metabolic pathways of the plants. But the response of plants to high temperature depends on the intensity and duration of the stress. Plants generally have mechanisms involving ion transporters, osmoprotectants, transcriptional control, antioxidants, proteins through which they can avoid, adapt or acclimatize to

Table 4
Impact of AM fungi on management of salinity stress in vegetables.

Family of host plant	Host plant	Fungus species	Observed response	Reference
Solanaceae	<i>Lycopersicon esculentum</i> L.	<i>Glomus mosseae</i>	Increased dry matter and leaf area, enhance enzyme activity	Huang et al. (2010)
Solanaceae	<i>Lycopersicon esculentum</i> L.	<i>Glomus intraradices</i> , <i>Glomus mosseae</i> , <i>Glomus aggregatum</i> , <i>Glomus clarum</i> , <i>Glomus monosporus</i> , <i>Glomus deserticola</i> , <i>Glomus brasilianum</i> , <i>Glomus etunicatum</i> , <i>Gigaspora margarita</i>	Increased plant growth, fresh stem weight, enhanced chlorophyll a and b content	Demir et al. (2011)
Solanaceae	<i>Lycopersicon esculentum</i> L.	<i>Glomus fasciculatum</i>	Improved P, phosphatase enzyme activity and reduced pH	Sivakumar et al. (2019)
Solanaceae	<i>Capsicum annuum</i> L.	<i>Glomus intraradices</i>	Improved root and shoot biomass, leaf area and cell membrane integrity	Beltrano et al. (2013)
Solanaceae	<i>Capsicum annuum</i> L.	<i>Glomus clarum</i>	Regulation of ions (K, Mg, Ca, Zn, Na) uptake, increased nutrient uptake and growth	Altuntas et al. (2016)
Solanaceae	<i>Solanum meloena</i>	<i>Glomus deserticola</i>	Enhanced growth and aggressiveness colonization in roots	Mohammad and Mittra (2013)
Amaryllidaceae	<i>Allium cepa</i> L.	<i>Glomus fasciculatum</i>	Increased plant height, fresh weight and dry weight and reduced electrical conductivity	Suhail and Mahdi (2013)
Cucurbitaceae	<i>Citrullus lanatus</i> L.	<i>Funneliformis mosseae</i>	Improved photosynthetic activity, elemental and water uptake	Ye et al. (2019)
Cucurbitaceae	<i>Cucumis sativus</i> L.	<i>Glomus versiforme</i>	Enhanced growth, improved photosynthesis and growth and reduced Na toxicity	Ahmad et al. (2018)
Cucurbitaceae	<i>Cucumis sativus</i> L.	<i>Glomus etunicatum</i> , <i>Glomus intraradices</i> , <i>Glomus mosseae</i>	Enhancement of pigment synthesis, antioxidant enzyme activity, lower lipid peroxidation and electrolyte leakage, accumulation of K, Ca, Zn, Fe, Mg, Mn, Cu and reduction of Na ⁺ ions	Hashem et al. (2018)
Asteraceae	<i>Lactuca sativa</i> L.	<i>Glomus iranicum</i>	Enhanced net photosynthesis, plant biomass, root mycorrhizal colonization, leaf ion content, plant biomass and stomatal conductance	Vicente-Sánchez et al. (2013)
Asteraceae	<i>Lactuca sativa</i> L.	<i>Claroideoglomus claroideum</i>	Reduction of oxidative damage and enhanced growth, development and yield	Santander et al. (2019)
Fabaceae	<i>Phaseolus vulgaris</i> L.	<i>Glomus irradicans</i>	Enhanced vegetative growth, plant fresh and dry weight, improved chlorophyll and enzymatic activity	Abdel Motaleb et al. (2019)
Fabaceae	<i>Pisum sativum</i> L.	<i>Rhizoglomus intraradices</i> , <i>Funneliformis mosseae</i> , <i>Gigaspora</i> sp.	Enhanced nutrient uptake, increased biomass, synthesis of chlorophyll, compatible osmolytes accumulation higher growth attributes and yield	Parihar et al. (2020)

the heat stress. The plants inoculated with AMF *Septoglomus constrictum* show a higher expression or upregulation of *SIXD* in roots under exposure to drought and heat stress. However, the expression of *SINCE*D and *SIPIP2.7* was not effected under stress. AM inoculation, therefore, helps in alleviation of oxidative stress on exposure to drought and heat stress (Duc et al., 2018). There was also found increase in the trehalose content (a carbohydrate) on the exposure to heat stress in AMF inoculated plants which is mainly responsible for stress tolerance. The increased trehalose is mainly associated with the upregulation of *GlTPS2* (trehalose-6-P phosphatase transcript). However, the trehalose content resumed to basal levels on the removal of stress (Ocón et al., 2007). There are a number of genes which are responsible for heat stress tolerance in plants which are mainly activated on exposure to heat stress such as heat shock proteins (*hsp*) genes, senescence-associated genes (*sag*), dehydrins (*dhn*) and stay green genes (*sgr*) (Wahid et al., 2011). The expression of genes modifies so as to adapt to the stress condition. The plants exposed to cold stress showed 3863 differentially expressed genes out of which 1669 are upregulated and 2194 are downregulated. A total of 250 transcription factors were observed on exposure to cold stress. These DEGs are involved in the dehydration, osmoregulation, plant hormone signal transduction, biomembrane stability etc. (Kong et al., 2019). There were 3510 DEGs identifies in cold tolerant variety of Asparagus bean out of which 2103 are upregulating and others 1407 are downregulating. While in the tolerant cultivar, 2868 genes were DEGs out of which 1786 are upregulated and others are downregulated. However, 1744 genes are normally reg-

ulated in both the cultivars which establish the role of genes in cold tolerance in asparagus (Tan et al., 2016). Both upregulation and downregulation of genes was observed under cold stress in AM inoculated plants. AMF inoculated plants exposed to cold stress has 2173 differentially expressed genes compared to non-inoculated plant exposed to cold stress out of which 1128 are upregulated and 1045 are downregulated. There are 180 genes which are normally downregulated on exposure to cold stress while gets upregulated on AM inoculation (Ma et al., 2018).

The susceptibility or tolerance of plants to salinity is through the function of number of stress responsive genes which generally initiates various transduction pathways. Under salinity stress, numerous genes show upregulation whose products either directly or indirectly are involved in the protection of plants (Tuteja, 2007). AM inoculation mainly regulates the gene expression which are involved in proline synthesis. It also regulates the genes which encode for aquaporins and late embryogenesis. These enable the plants to maintain a healthy water balance in the tissues. The proteins encoded through these genes play major role in Na and other ions' uptake and distribution (Porcel et al., 2011). AM inoculation of asparagus plants under saline stress has also revealed 455 DEGs (Differentially expressed genes) out of which 41 DEGs were downregulated. The improvement of cell environment, photoprotection and nitrogen metabolic activities are modified under saline stress in AM inoculated plants (Zhang et al., 2019) Soil salinity in soybean vegetable can be improved by targeting *StNHX1* gene which is overexpressed in AM inoculated plants under salinity stress (Chen et al., 2014). Moreover, genes scavenging ROS are expressed

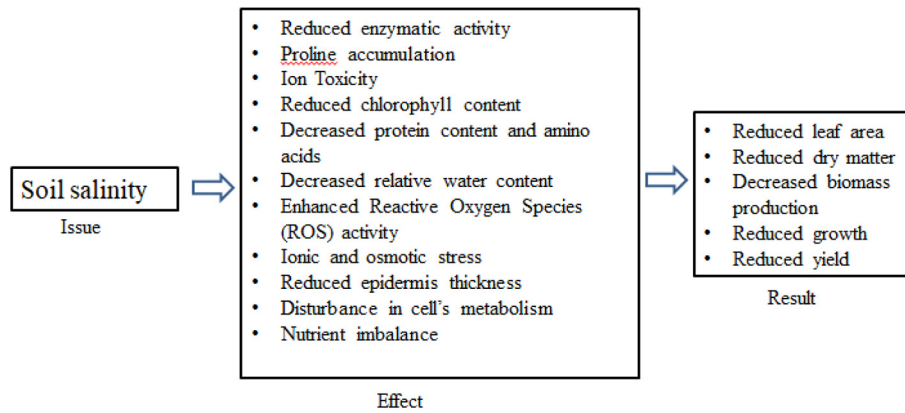


Fig. 3. Effect of salinity on vegetables.

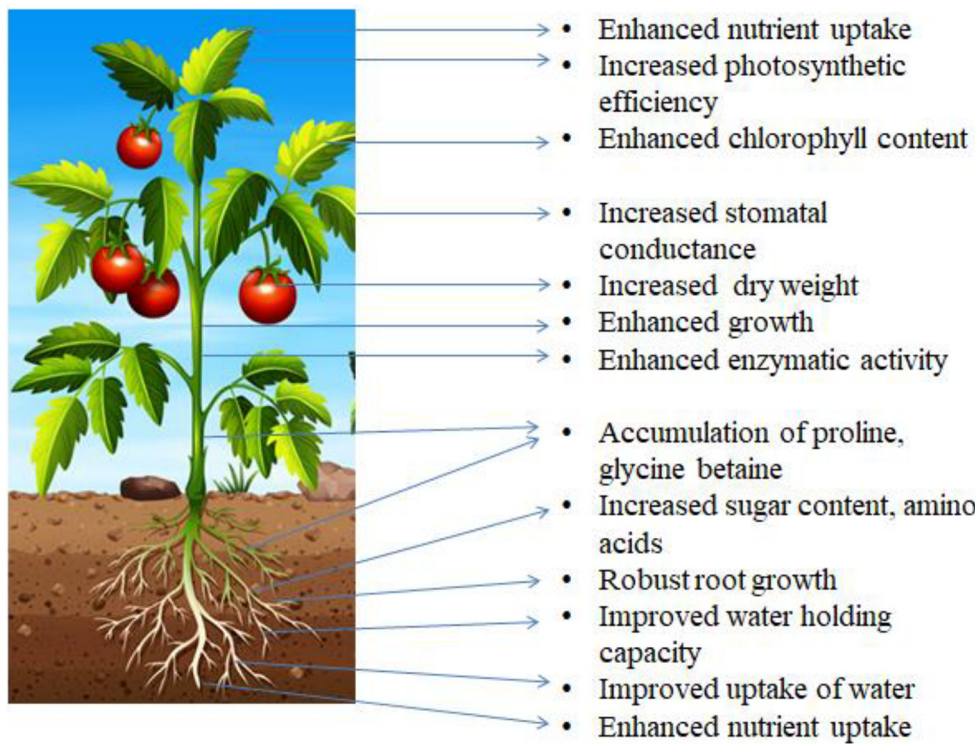


Fig. 4. Role of AM in alleviation of salinity stress.

in plants under salinity stress which shows that AMF helps to develop oxidative defense in plants (Bothe, 2012). Under salt stress, a most of PIP genes are upregulated but the PIP gene expression depend upon the ABA level of the host plants. These genes help in better plant water status regulation and thereby contribute to plant resistance in salt stressed environment (Ruiz-Lozano and Aroca, 2010). The genes linked with salt overly sensitive (SOS) signaling pathways and NHX-type Na^+/H^+ antiporter *NHX1* showed overexpression in AM inoculated plants under salt stress so as to make Pakchoi (*Brassica campestris* ssp. *Chinensis*) salt tolerant by inducing the antioxidant enzyme activity (Khalid et al., 2018) (see Figs. 3 and 4).

5. Conclusion and future prospects

With the recent climate change, a huge variation in weather parameters of an area is observed which is leading to huge stress

on plants. Moreover, the drought and salinity affected proportion of our arable area is increasing gradually due to it. With inoculation of arbuscular mycorrhiza, plants are able to survive the drought stress, salinity stress along with the stress of temperature variation. The growth of plants in such an arena becomes very important so as to raise the plants productivity. The fertilizer application to support plant growth becomes an expensive matter. Moreover, the development of new tolerant or resistant varieties by breeding or biotechnology is an expensive approach which takes a lot of time and its adaptability and suitability to farm conditions also varies to some extent. So, an ecofriendly approach of inoculation of plants with arbuscular mycorrhiza becomes a suitable alternative. AM fungi are determined to improve plant growth and nutrient absorption of the vegetables amid environmental stresses. Moreover, it also cause morphological and functional changes in the plants and increase the photosynthetic efficiency of the plants either by increasing photosynthetic pigments or by

raising efficiency of photosystem II. AM fungi also raise the nutrient uptake by plants and raise the biomass production and cause yield increase of vegetables. An increase in the antioxidant activity is also observed in the plants inoculated with AM and raises the plant yield. AM fungi, therefore, has the potential to make the plants acclimatize in the changing environment and thereby helps in providing food and nutritional security to the world. Moreover, it also adds to the cost-effective cultivation of vegetables as AM fungi is a cheaper way for sustaining plant growth compared to fertilizers. Fertilizers losses are also very common in field situation whereas AM fungi remains in association with roots in rhizosphere and helps in vigorous growth of the roots so as to extract the available nutrients, thereby, making it an alternative to fertilizers for raising plants yield in abiotic stress conditions. The industrial provision of mycorrhizal inoculum has serious issues about the quality and efficiency of the mycorrhiza and its performance in field conditions so there needs a knowledge based diffusion of information to the farmers so as to identify the suitable and required AM fungi at a well-established and certified place. There is a need of detailed research of several mycorrhizal associations in various stress conditions so as to identify the best suited AM combination for a particular crop in a particular stress condition such as pH, salinity, drought, heat, cold, etc.

6. Authors' contributions

Prashant Kaushik, Mohammed Nasser Alyemeni and Parvaiz Ahmad conceived the idea. Gurdeep Singh Malhi, Manpreet Kaur and bdulaziz Abdullah Alsahli wrote the first draft. Prashant Kaushik, Mohammed Nasser Alyemeni and Parvaiz Ahmad corrected the paper to present form. All authors read and approve the same for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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