REVIEW

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REVIEW

Diversity of arbuscular mycorrhizal fungi in mangrove ecosystem – A review

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Mangroves form a special habitat occupying the marine intertidal zone in tropical and sub-tropical regions. These forests are one of the highly productive ecosystems in the world. However, there are several factors affecting their growth especially the availability of nutrients like phosphorus. Arbuscular mycorrhizal (AM) fungi are Glomeromycotan fungi capable of enhancing the uptake of nutrients especially P in higher plants. Additionally, these fungi also assist plants in stress tolerance and reduced nutrient leaching. However, several factors like flooding, salinity and pH influence the colonization and sporulation of AM fungi. This review considers aspects of AM fungal diversity in mangrove ecosystem. Interaction of AM fungi with other rhizosphere microbes, glomalin related soil protein (GRSP), studies on the importance of AM fungi in mangrove plant growth are discussed. It is concluded that the exploration of microbial diversity in crucial habitats like mangroves plays a significant role towards the establishment of conservation and restoration strategies.

Keywords: arbuscular mycorrhizal fungi, P uptake, mycorrhiza helper bacteria, glomalin related soil protein, growth studies

INTRODUCTION

Mangroves form a plant community growing in saline habitats of tropical and subtropical regions. The term ‘mangrove’ describes both the ecosystem and the plants that have adapted to tolerate extreme tides, fluctuating salinity, high temperatures, and low oxygen (Arunprasath and Gomathinayagam 2014; Hogarth 2015). These forests are the most diverse and productive tropical ecosystems in the World (Kathiresan 2000). They serve as breeding and nurturing sites for not only marine organisms but also for terrestrial ones (Igulu *et al*. 2014; Alongi 2012). Mangrove ecosystem is known as ‘carbon sinks’ where C is decomposed and exported to neighbouring habitats (Alongi 2012).

These forests also provide economic benefits in the form of food sources, timber, fuel, and medicine (Alongi 2002). Besides these ecological and economic services, they play a major role in offering protection against natural calamities such as tsunami, cyclones, and tidal bores (Alongi 2008; Alongi 2014). Anthropological pressure such as aquaculture, mining, and overexploitation of timber, fuelwood, fodder, and other non-wood forest products (NWFPs) and climate change (sea level rise) constitute key threats for the degradation of mangrove habitats (Ellison and Zouh 2012).Although phosphorus (P) is the chief element of seawater, its availability is limited to the plants as it is bound to sediment particles (Dastager and Damre 2013) and this results in poor growth of mangrove plants (Reef *et al*. 2010). The immobile property of P makes it unavailable for the plants as it gets adsorbed by carbonate compounds (Kothamasi *et al*. 2006). Also, the available P is continuously used by the growing plants which result in the formation of a phosphate-free zone in the rhizosphere (Smith and Read, 2008). Arbuscular mycorrhizal fungi can colonize the plant roots and promote better nutrient uptake, especially P (Yinan *et al*. 2017). This can increase plant productivity, diversity, and enhance the plant

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resistance to biotic and abiotic stresses (Ijdo *et al*. 2011).

ARBUSCULAR MYCORRHIZAL (AM) FUNGI

Arbuscular mycorrhizal fungi are obligate symbionts belonging to the phylum Glomeromycota having a ubiquitous worldwide distribution in various ecosystems (Redecker *et al*. 2000). In this association, the fungus receives sugars from the plant while facilitating the plant uptake of nutrients (Schüßler *et al*. 2007). It is estimated that around 90% of higher plants form this type of association (Loccoz *et al*. 2015). Earlier wrorkers named the intra-radical spores as 'vesicles' and the inter-cellular structures 'arbuscules'. Accordingly, the name 'vesicular-arbuscular mycorrhiza' was determined which persisted until recently (Goltapeh *et al*. 2008). However, species belonging to the family Gigasporaceae (*Scutellospora* and *Gigaspora*) do not produce vesicles and hence the name 'arbuscular mycorrhiza' persisted (Smith and Read 2008).

SIGNIFICANCE OF AM FUNGI IN MANGROVES

It was suggested that AM fungi play a minor role in wetlands due to anoxic conditions that tend to reduce fungal activity (Šraj-Kržiè *et al.* 2006). However, several studies have indicated the occurrence of AM fungi in wetland habitats (Radhika and Rodrigues 2007; D'souza and Rodrigues, 2013a,b; Wang *et al*. 2010, 2011, 2014 a,b; Gaonkar and Rodrigues, 2020, 2021). It is well evident that AM fungi not only occur in wetlands but enhance nutrient uptake and photosynthesis and hence the diversity and productivity of mangrove plants (Wang *et al*. 2010). Wang *et al.* (2011) suggested that AM fungi acquire oxygen from the root aerenchyma of mangrove plants during submerged conditions.

The accessibility to nutrients in mangrove plants is controlled by several biotic and abiotic factors such as flooding, soil type, soil microbial activity, plant diversity, litter production, and litter decomposition. The immobile form of P makes it gets adsorbed by sediment particles and its available form is continuously used up by the plant forming a phosphate-free zone in the rhizosphere (Roy-Boldoc and Hijrii, 2011). AM fungi can enhance nutrient uptake especially P (Aggarwal *et al.* 2012, Willis et al. 2013). AM fungi form an extraradical hyphal network that can penetrate beyond the P depletion zone thereby extending the P absorption area of the host roots (Xie *et al*. 2014).

In an environment that is distinguished by various biotic and abiotic stresses, the AM plants can thrive better than non-mycorrhizal plants (Genre *et al*. 2005). An individual plant can be colonized by several AM fungi and *vice versa*, bringing about common mycorrhizal networks (CMN) (Jakobsen and Hammer 2015). The interconnections between plant communities can expand stability as weaker plants could gain nutrient supply through CMN at the cost of stronger individuals that entertain CMN (Van der Heijden and Horton 2009).

Nutrient uptake– the association of plants with their fungal partners can establish an enhanced uptake of nutrients such as P, Cu, Zn, S, Mg, Mn, Fe, etc. that are essential for their growth. Also, they are known to help in N transport taken from organic matter to the host (Leigh *et al*. 2008). It has been proved that the increase in C supply often upturns the absorption of P by the AM fungi (Smith and Read 2008).

Stress tolerance – AM fungi are known to offer an ecological competitive benefit to their host plants enabling survival and improved plant growth under environmental stress conditions such as temperature, pH, moisture, salinity, etc. (Mohammadi *et al*. 2011). They can also improve the response of a plant to water scarcity by enhancing the uptake of water from the soil by hyphal extensions (Entry *et al*. 2002). Nevertheless, it is evident from previous studies that, AM fungi can uphold plant salinity tolerance by various mechanisms such as improving uptake of nutrients (Evelin *et al*. 2012), by regulating the plant physiology (Chang *et al*. 2018), besides others.

Reducing leaching of nutrients – AM fungi are capable of modifying the soil structure by developing ramified hyphal networks that entangle and bind soil particles together forming stabilized aggregates of soil (Leifheit *et al.* 2014). Correspondingly, it is known that AM fungi help in the reduction of nutrient leaching by sequestration of nutrients in soil aggregates and by absorption of soil nutrients (Clark and Zeto 2008; George 2000).

P UPTAKE BY AM FUNGI

Phosphorus (P) is a vital nutrient for plant growth but is a limiting factor in most habitats (Bucher 2007). It is present in the soil as inorganic (Pi) and organic (Po). Inorganic P is sequestered by cations like Fe, Al at lower pH levels and by Ca at higher pH which are insoluble forms. This results in a reduction of sequestered phosphate mobility thus making P unavailable to plants (Smith and Read 2008).

Mycorrhizal plants possess two pathways of nutrient uptake *viz.,* direct pathway in which nutrients from the rhizosphere are taken up by epidermal cells and the mycorrhiza-associated pathway which functions *via* AM fungal partners in AM plants (Smith *et al*. 2003). AM fungi help their host in the uptake of P, N, Cu, Zn, etc. However, it is suggested that P acquisition occurs at higher levels (Harrison *et al*. 2010). Non-mycorrhizal plants solely depend upon direct uptake by Pi transporters that are expressed in the epidermal cells while functioning of both the pathways take place in AM plants wherein Pi transporters are expressed in a cortical cell of colonized roots (Javot *et al*. 2006). Phosphate transporter genes (Pht1) get activated at the commencement of colonization by extra-radical hyphae of AM fungi (Karandashov and Bucher 2005; Bucher 2007; Javot *et al*. 2006). The transporters involved in the Pi transfer are H^+ symporters whose function is regulated by the H^+ gradient released by H^+-ATPase in the plasma membrane (Ferrol *et al*. 2002a). After P uptake by extra-radical hyphae, a substantial quantity of polyphosphates is synthesized. Besides, some amounts of these polyphosphates are stored in fungal vacuoles. Based onearlier explanations, Ferrol *et al.* (2002b), and Buée *et al.* (2000), it can be inferred that peri-arbuscular membrane (PAM) plays a vital role in delivering phosphate to cortical cells of their host plant (Ferrol *et al.* 2002a).

FACTORS AFFECTING AM FUNGI IN MANGROVE HABITAT

Effect of flooding on AM fungi

Although it is well known that AM fungi help in the uptake of nutrients, their efficiency of nutrient mobilization decreases in the mangrove ecosystem due to flooded conditions (Hackney *et al*. 2000). The arbuscule formation is suppressed in flooded conditions. Wang *et al.* (2011) reported reduced AM diversity and colonization under intensive flooding while moderate flooding had no inhibitory effects on the same. However, this is not necessarily so. There are several explanations given to these results. Firstly, some of the AM fungal species could withstand highly hypoxic conditions (Wang *et al*. 2010). Secondly, the increased number of pneumatophores in moderate flooding areas can enhance the efficacy of aerenchyma in mangrove species (Wang *et al*. 2011). Thirdly, moderate flooding could improve the photosynthetic activity thereby promoting the growth of the mangrove plants. Thus, the mangrove plants growing under moderate flooding could offer more carbohydrates supporting increased colonization and diversity of AM fungi (Wang *et al*. 2011).

AM fungi being aerobic microbes rely upon the oxygen provided by the mangrove aerenchyma during the flooded conditions.Gaonkar and Rodrigues (2020) studied AM fungal symbiosis in true and associate-mangrove plant species and recorded higher AM colonization in associate mangrove species than in true mangrove species. They suggested that the landward distribution of associate mangrove plants would have favoured higher colonization levels.

Effect of salinity on AM fungi

Soil salinity can negatively affect AM fungal spore germination, root colonization, and hyphal growth (Abdel Latef and Miransari 2014).The colonization efficiency of AM fungi reduces with increasing concentration of NaCl. Increased NaCl concentration delays spore germination (Hajiboland 2013). The presence of numerous salts in soil inhibits hyphal growth thus decreasing the spread of the hyphal network (Abdel Latef and Chaoxing, 2014). In saline soil, spores cannot get hydrated which is important for its germination and consequently delays the process (Juniper and Abbott 2006).Delvian and Rambey (2019) observed a decrease in percent colonization by *Gigaspora margarita* at a high concentration of NaCl while *Glomus etunicatum* showed a significant rate of colonization even at 10,000 ppm NaCl.

However, Yamato *et al*. (2008) observed no reduction in AM colonization at increased levels of NaCl. In an experiment, Peng *et al*. (2010) observed

Table 1: Occurrence of AM diversity in mangrove soils at different pH regimes

Authors	Soil pH range		
	4.5 – 5.5	5.5 – 6.5	6.5 – 8.0
Sengupta & Chaudhuri, 2002	-	-	*F. mosseae, R. fasciculatum*
Kumar & Ghose, 2008	-	-	*F. mossea e*
Wang et al. 2010	-	-	*R. intraradices, F. mosseae*
Wang et al. 2011	-	-	*R. intraradices*
D'souza& Rodrigues, 2013a	-	*A. laevis*	-
D'souza& Rodrigues, 2013b	*A. scrobiculata*	-	*R. intraradices*
Wang et al. 2014	-	-	*F. mosseae*
Gopinathan et al. 2017	-	-	*G. aggregatum, G. geosporum*
Gaonkar & Rodrigues, 2020	-	*A. dilatata*	-
Gaonkar & Rodrigues, 2021	-	-	*F. geosporum*

that the NaCl application decreased colonization by *Glomus mosseae* and *Claroideoglomus claroideum* whereas, it did not affect the colonization by *Rhizophagus intraradices*. Gupta *et al*. (2016) reported the occurrence of *Glomus* and *Scutellospora* across low to high saline zones while the species of *Acaulospora* inhabited low salinity areas. The high activity of superoxide-dismutase, peroxidases, and ascorbate peroxidase in AM fungi degenerates more reactive oxygen species thereby elevating their salt tolerance (He *et al*. 2007).Using meta-analyses, Bothe (2012) examined AM fungal studies on salinity stress and suggested that the germination and hyphal growth of AM fungal spores were affected by salt stress. Salt-tolerant plants exhibited increased AM colonization and were generally colonized by *R. intraradices*. *Funneliformis geosporum* showed predominance in many saline soils.

Effect of P on AM fungi

Phosphorus is known to be an important factor determining AM fungal spore germination and root colonization (Lin *et al*. 2020). It is well evident that the abundance of P in the soil allows plants to acquire P through their roots by subsiding AM fungal symbiosis (Zhang 2003). Hence, the colonization rate and the AM fungal assistance in enhanced P uptake would be minimized (Li *et al*. 2013). Several studies have indicated reduced AM fungal colonization in wetlands due to high P content (Wang *et al.* 2010; Bohrer *et al*. 2004). Lin *et al.* (2020) reported improved colonization rates with the addition of less P. Nonetheless, the addition of an excessive amount of P results in limited P demand by the host plant, which causes less root secretion composition. This process inhibits AM fungal colonization and sporulation efficiency (Sun *et al*. 2011).

Effect of pH on AM fungi

Some of the AM fungi do not adapt easily to the soil pH dissimilar from their source soil which limits their establishment (Aggarwal *et al.* 2012).

The species of family Acaulosporaceae and Gigasporaceae show predominance in acidic soils (pH range 5-6) (Aggarwal *et al*. 2012) while that of family Glomeraceae are dominant in neutral to alkaline soils (Kumar and Ghose 2008) (Table 1).

AM FUNGAL DIVERSITY STUDIES

The AM fungal species belonging to the family Glomeraceae and Acaulosporaceae predominates mangrove rhizosphere (Gaonkar and Rodrigues, 2020; 2021; D'souza and Rodrigues, 2013a,b) (Table 2). Glomeraceae and Acaulosporaceae species produce more spores than Gigasporaceae species within the same habitat. The smaller spore size of these species facilitates faster sporulation and hence greater alteration of sporulation pattern in diverse environmental conditions (Fig.1).

INTERACTION OF AM FUNGI WITH OTHER RHIZOSPHERE MICROBES

Mycorrhizal symbiosis is not just a bipartite association between the fungus and plant but AM fungi also interact with the other associated

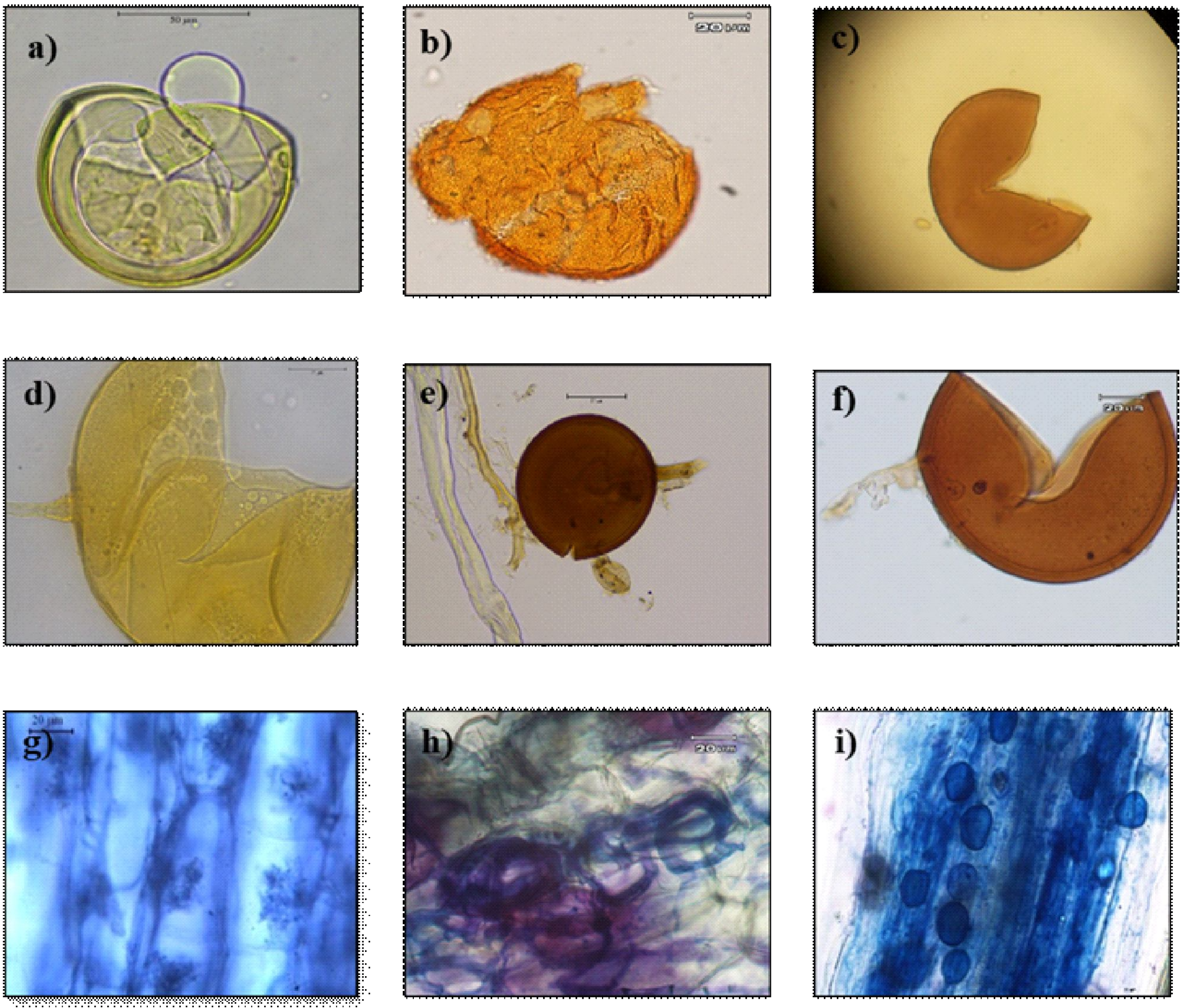

Fig. 1 : *a) Acaulospora dilatata*; b) *A. scrobiculata;* c) *A. laevis;* d) *Funnelformis mosseae;* e) *F. geosporum;* f) *Rhizoglomus intraradices;* g) *Arum*-type of abuscular colonization; h) Paris-type of arbuscular colonization; i) Vesicular colonization

microorganisms (Tarkka and Frey-Klett, 2008). These microorganisms have a mutual impact on each other forming a zone called 'mycorrhizosphere' (Frey-Klett and Garbaye 2005).

Some of the bacteria that can support the growth of mycorrhiza are known as 'Mycorrhiza Helper Bacteria' (MHB). Furthermore, AM fungi also interact with phosphate solubilizing bacteria (PSBs) by taking up the released P ions that are solubilized from the insoluble form of P by these bacteria. Studies have shown that plant growth-promoting rhizobacteria (PGPR) like *Pseudomonas putida* stimulates the root colonization by AM fungi. Several factors affect the interaction of AM fungi and rhizobacteria *viz.,* AM, bacterial and plant species, and edaphic properties (Sanon *et al*. 2009). Moreover, bacterial attachment to AM hyphae is influenced by hyphal physiology (Artursson*et al.* 2006).Some of the PGPRs like *Azospirillum* and *Rhizobium* produce extracellular polysaccharides that enable their attachment to fungal hyphae (Miransari 2011).

Some species of nematodes (*Meloidogyne javanica*) acting as plant pathogens are affected by AM fungi. AM fungi enhance nutrient uptake thereby enhancing plant resistance to pathogens (Miransari, 2011). Little work has been carried out to study the interactive effects of AM fungi and endophytic fungi. However, studies have demonstrated that AM fungi assist their hosts to overcome the parasitic effects of root-colonizing fungi.

Table 2: AM fungal diversity studies in mangrove habitats

Author	Site /host plant	pH range	EC/ Salinity range	Colonization level (%)	Spore density (spores/100g of soil)
Sengupta and Chaudhuri, 2002	Ganges river estuary, India	7.2 – 8.0	2.5 – 16.0 (dSm^{-1})	49.5 – 81.0	170 - 428
Kothamasi *et al.* 2006	Nicobar Island, India			0 – 17.6	
Kumar and Ghose, 2008	Sundarban mangroves, West Bengal, India	7.5 – 8.0	9.9 – 21.6 (ppt)	0.8 to 65.1	2.9 – 60.0
Wang *et al.* 2011	Zhuhai mangrove area, China	6.8 – 7.2	1.9 – 4.2 (dSm^{-1})	23.8 – 68.8	
Sridhar *et al.* 2011	South west coast, India	6.4 – 7.8	0.3 – 12.6 (µScm^{-1})	7.8 – 69.0	67 – 430
Balachandran and Mishra, 2012	Western coast, Maharashtra, India	8.6 – 9.8	5.3 – 20.9 (m - mho)	10 – 100	9 – 79
D'Souza and Rodrigues, 2013a	Rivers - Terekhol, Chapora, Mandovi, Zuari, Sal, Talpona and Galgibag, Goa, India	5.5 – 6.7	2.1 – 8.4 (dSm^{-1})	6 – 77	0.08 – 3.2
D'Souza and Rodrigues, 2013b	Rivers – Terekhol and Zuari, Goa, India	5.5 – 6.8	4.0 – 8.5 (dSm^{-1})		7 – 230
Wang *et al.* 2014a,b	Qi'Ao mangrove forest, China	6.6 – 7.9	0.5 – 1.7 (dSm^{-1})	33.3 – 63.7	3.0 – 27.3
Hu. *et al.* 2015	Mangrove forest, Southern China	5.2 – 6.4	2.4 – 7.0	0.3 – 36.5	54 – 206.8
Gupta 2016 *et al.*	Bhitarkanika, Orissa, India	6.1 – 6.3	1.5 – 2.3 (mScm^{-1})	18.5 – 73.3	
Gopinathan. 2017 *et al*	Muthupet mangrove area, Tamil Nadu, India	7.3 – 8.2	3.8 – 4.2 (dSm^{-1})	22.0 – 40.4	140 – 216
Fernandes & Rodrigues, 2017	Pernem, Goa	7.0	11.4 (dSm^{-1})	3.0 – 67.9	9 – 137
Gaonkar & Rodrigues, 2020	Chorao Island, Goa	5.7 – 5.9	0.9 – 8.9 (dSm^{-1})	20.0 – 97.5	20 – 138
Gaonkar & Rodrigues, 2021	Pichavaram Forest, Tamil Nadu	6.9 – 7.6	4.3 – 6.7 (mScm^{-1})	22.0 – 93.6	8 – 270
Akaji 2022 *et al.*	Iriomote Island, Japan	-	0.5 – 3.8 (Sm^{-1})	0 – 22	-

GLOMALIN-RELATED SOIL PROTEINS (GRSPS) IN MANGROVES

Arbuscular mycorrhizal fungi are also known to produce a glycoprotein in their hyphae called 'Glomalin'. Following the senescence of hyphae, glomalin gets accumulated in the soil contributing to 5% of soil C (Rillig *et al*. 2003). Glomalin glues soil particles together forming soil aggregates which increase water retaining ability and decrease soil erosion (Wang *et al*. 2018). Plant roots assist AM fungi in producing stable soil aggregates by forming an association with their extraradical hyphae which gets benefited by glomalin. The ability of AM fungi to sequester C by the production of glomalin protein improves in organic farming, intercropping, and crop rotation practices (Sharma 2021).

Glomalin-related soil proteins (GRSPs) show a high capability to bind some of the heavy metals like Pb, Cd, and Cu (Rillig 2004). The secretion of certain levels of glomalin by AM fungi during stress conditions is considered to function as a stress-induced protein to protect their host plants (Chi *et al*. 2018).

Although extracted from diverse soils, this glycoprotein is biochemically undefined but operationally quantified and labeled as a GRSP (Rillig, 2004). Based on the ease of extraction using

Table 3: Glomalin-related soil proteins (GRSPs) studies in the mangrove ecosystem

Authors	Site	Inference/major findings
Balachandran and Mishra, 2012	West coast, Maharashtra, India	Estimation of glomalin in heavy metal polluted mangrove areas was carried out. A positive correlation between GRSP and heavy metals was attained which implied the efficiency of AM fungi in reducing toxicity and facilitating the survival of plants under metal stress.
Wang *et al.* 2018a	Yellow River, China	In this study, the contribution of GRSP in the sequestration of terrigenous C, N, and Fe was investigated. They recorded 1.10 mg/g of total GRSP which accounted for 6.41% of total organic C and 3.75% of total N. Also, 1.46% of Fe was bound to GRSP.
Wang *et al*. 2018b	Zhangjiang River Estuary, China	This study presents a spatial distribution of GRSP and its contribution to sediment organic carbon (SOC) in the mangrove forest. The concentration of easily extractable GRSP (EE-GRSP) ranged from 1.20–2.22 mg/g whereas that of total GRSP (T-GRSP) ranged from 1.38–2.61 mg/g. GRSP accounted for 2.8 -5.9% of SOC. The data indicates that as the SOC content decreases, GRSP content increases.
Wang *et al*. 2019a	Zhangjiang River Estuary, China	The mangrove sediment samples were collected to analyze heavy metal content bound to GRSP's. The larger distribution of GRSPs increased the heavy metals (Fe, Mn, Cr, Cu, Zn, Ni, Cd, Pb) and metalloid Arsenic sequestration. Also, GRSP contributed to suspended solids that adsorb these heavy metals.
Wang *et al*. 2019b	Mangrove Natural Reserves of China	Microcosm experiments were carried out to determine the molecular structure of GRSP obtained from AM fungi *viz.,* R. *intraradices, G. versiforme*, and *A. laevis*. Also, GRSP analysis from mangrove natural reserves was investigated to discover the metal sequestration. They reported a positive correlation between total metals and GRSP bound metals. Several functional groups like hydroxyl, carboxyl, amide , and carbonyl were detected in the GRSP fractions.
Das *et al*. 2020	Sundarban Mangrove Biosphere Reserve, India	They observed seasonal trends in GRSP content and reported higher glomalin levels during post-monsoon than that of pre-monsoon and monsoon season. Soil redox potential influenced the amount of difficulty extractable GRSP (DE - GRSP). This indicates the effect of soil anoxic conditions in glomalin synthesis.
Tian *et al*. 2020a	Jiulong River, China	They examined the effect of shrimp pond effluent on GRSP-bound metals. Results revealed that the temporal increase in effluent discharge reduced the potential of GRSP-bound metals and altered the molecular composition of GRSP.
Tian *et al*. 2020b	Zhangjiang River Estuary, China	They compared GRSP based values of isotope (δ13C and δ15N) and C/N ratios with blue C sources in the mangrove ecosystem. Their results showed a novel blue carbon source of total GRSP.

different concentrations of citrate buffer and the duration of autoclaving, the GRSP fractions are divided into two categories *viz.,* easily extractable GRSP (EE-GRSP) and total GRSP (T-GRSP) (Zhang *et al*. 2015; Cornejo *et al.* 2008). The EE-GRSP is comparatively more labile while T-GRSP is relatively stable (Wu *et al*. 2014). Various Glomalin-related studies are listed below (Table 3).

AM FUNGI IN GROWTH STUDIES

AM fungi are anessential component of soil microbial flora forming asymbiotic relationship with terrestrial (Smith and Read 2008) and wetland plants (Tawaraya *et al.* 2003). Different growth studies carried out in different mangrove species and habitats are highlighted in Table 4.

They form a connection between the soil and their host plant to uptake soil nutrients and provide them to the plant. This symbiosis greatly promotes P uptake of plants and the enhancement of P nutrition can boost other functions (Cozzolino *et al.* 2010). Improved nutrient uptake results in a faster growth rate (D'souza and Rodrigues, 2016).

Table 4: Growth studies in mangrove species using AM fungi

Authors	Plant used	AM species used	Inference/major findings
Wang *et al*. 2010	*Sonneratia apetala*	*Rhizophagusintraradices, Funneliformismosseae, Glomus aggregatum, F. geosporum*	A greenhouse experiment was performed using *S. apetala* as a host plant. It was reported that AM inoculated plants had better growth and two folds increase in root, stem, and leaf biomass with improved levels of N, P, and K than those of non-mycorrhizal plants.
Wang *et al*. 2014b	*Kandeliaobovata*	Indigenous AM species and *Aegicerascorniculatum*	The effect of municipal sewage discharge on AM fungi and mangrove plant symbiosis was estimated .The inhibitory effect of sewage discharge was observed on the vesicles and arbuscules whereas hyphae were tolerant ofwastewater discharge.
Xie e*t al*. 2014	*Kandeliaobovata*	*F. geosporum, R. intraradices, Claroideoglomus claroideum, C. etunicatum*	The effect of AM fungi and P supply on plant growth biomass and nutrient uptake in *K. obovata* was evaluated . The plant height and biomass (358% higher than control) increased under combined treatment of P (60 mg kg^{-1}) and AM fungi.
D'Souza and Rodrigues, 2016	*Ceriops tagal*	*R. clarus, R. intraradices, Acaulosporalaevis*	An experiment was conducted to study the effect of three AM fungi on the growth of *C. tagal*. The study revealed that *R. clarus* is the most efficient AM fungi showing increased growth and biomass of the selected plant.

CONCLUSION

As in the case of terrestrial ecosystems, AM fungi show high density and diversity in the mangrove ecosystems as well. Their crucial roles in the composition, diversity, ecological succession, nutrition, and productivity of mangrove plants have been proven. However, their role in increasing photosynthesis, secondary metabolites, and crude oil-degradation in mangrove habitats has not been investigated. This review provides scope for future studies to be carried out on above mentioned unexplored areas of AM fungal applications in the mangrove ecosystem.

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REFERENCES

Abdel Latef, A.A., Chaoxing, H. 2014. Does the inoculation with *Glomus mosseae* improve salt tolerance in pepper plants? *J. Plant Growth Regulat.***33**: 644-653.

Abdel Latef, A.A., Miransari, M. 2014 .The role of arbuscular mycorrhizal fungi in alleviation of salt stress. In : *Use of microbes for the alleviation of soil stresses* (ed. M.Miransari) Springer Science Business Media, New York, USA, pp 23"38.

Aggarwal, A., Kadian, N., Karishma, N., Tanwar, A., Gupta, K.K. 2012. Arbuscular mycorrhizal symbiosis and alleviation of salinity stress. *J. Appl. Nat. Sci.* **4**:144–155.

Akaji,Y., Inoue ,T., Taniguchi, T., Baba, S. 2022. Arbuscular mycorrhizal fungal communities of a mangrove forest along a salinity gradient on Iriomote Island. *Plant Soil* **472**: 145-159.

Alongi, D.M. 2002. Present state and future of the world's mangrove forests. *Environ.Conserv*. **29**:331–349.

Alongi, D.M. 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast Shelf Sci.* **76**:1–13.

Alongi, D.M. 2012. Carbon sequestration in mangrove forests. *Carbon Manag.* **3**:313–322.

Alongi, D.M. 2014. Carbon cycling and storage in mangrove forests. *Annu. Rev. Mar. Sci.* **6**:195–219.

Artursson, V., Finlay, R.D., Jansson, J.K. 2006. Interactions between arbuscular mycorrhizal fungi and bacteria and their potential for stimulating plant growth. *Environ. Microbiol.* **8**:1–10.

Arunprasath, A., Gomathinayagam, M. 2014. Distribution and composition of true mangroves species in three major coastal regions of Tamilnadu, India. *Int. J. Adv. Res.* **2**:241–247.

Balachandran, S., Mishra, S. 2012. Assessment of arbuscular mycorrhizal fungi (AM fungi) and glomalin in the rhizosphere of heavy metal polluted mangrove forest. *Int. J. Environ. Sci.* **4**:392–401.

Bohrer, K.E., Friese, C.F., Amon, J.P. 2004. Seasonal dynamics of arbuscular mycorrhizal fungi in differing wetland habitats. *Mycorrhiza* **14**:329–337.

Bothe, H. 2012. Arbuscular mycorrhiza and salt tolerance of plants. *Symbiosis* **58**:7–16.

Bucher, M. 2007. Functional biology of plant phosphate uptake at root and mycorrhiza interfaces. *New Phytol.* **173**:11–26.

Buée, M, Rossignol, M., Jauneau, A., Ranjeva, R., Bécard, G. 2000. The pre-symbiotic growth of arbuscular mycorrhizal fungi is induced by a branching factor partially purified from plant root exudates. *Mol. Plant Microbe Interact*. **13**:693–698.

Chang, W., Sui, X., Fan, X.X., Jia, T.T., Song, F.Q. 2018. Arbuscular mycorrhizal symbiosis modulates antioxidant response and ion distribution in salt-stressed *Elaeagnus angustifolia* seedlings. *Front.Microbiol.* **9**:652.

Chi, G., Srivastava, A.K., Wu, Q. 2018. Exogenous easily extractable glomalin-related soil protein improves drought tolerance of trifoliate orange. *Arch.Agron. Soil Sci.* **64**:1341–1350.

Clark, R.B., Zeto, S.K. 2008. Mineral acquisition by arbuscular mycorrhizal plants. *J. Plant Nutr.* **23**: 867–902.

Cornejo, P.,Meier,S.,Borie, G.,Rillig, M.C., Borie, F. 2008. Glomalin-related soil protein in a Mediterranean ecosystem affected by a copper smelter and its contribution to Cu and Zn sequestration. *Sci. Total Environ*. **406**:154–160.

Cozzolino, V., Pigna, M., Meo, V., Caporale, A.G., Violante, A. 2010.Effects of arbuscular mycorrhizal inoculation and phosphorus supply on the growth of *Lactuca sativa* L. and arsenic and phosphorus availability in an arsenic polluted soil under non-sterile conditions. *Appl. Soil Ecol.* **45**:262–268.

D'souza, J., Rodrigues, B.F. 2013a. Biodiversity of arbuscular mycorrhizal (AM) fungi in mangroves of Goa in West India. *J. For. Res*. **24**:515–523.

D'souza, J., Rodrigues, B.F. 2013b. Seasonal diversity of arbuscular mycorrhizal fungi in mangroves of Goa, India. *Int. J.Biodivers*. **2013**:Article ID 196527.

D'souza, J., Rodrigues, B.F. 2016. Enhancement of growth in mangrove plant (*Ceriops tagal*) by *Rhizophagus clarus*. *J. Plant Nutr.* 40:365–371.

Das, S., Ganguly, D., Chakraborty, S., Mukherjee, A., Kumar, T. 2020. The first report of Glomalin from the Sundarban Mangrove Biosphere Reserve, India, a long-term sediment carbon storage. *Reg. Stu. Mar. Sci.* **39**:101398.

Dastager, S.G., Damare, S. 2013. Marine actinobacteria showing phosphate-solubilizing efficiency in Chorao Island, Goa, India. *Curr.Microbiol.* **66**:421–427.

Delvian, D., Rambey, R. 2019. IOP Conf. Ser.: Earth Environ. Sci. International Conference on Agriculture, Environment, and Food Security, Medan, Indonesia

Ellison, J.C., Zouh, I. 2012. Vulnerability to Climate Change of Mangroves: Assessment from Cameroon. *Cent. Afr. Biol.* **1**:617–638.

Entry, J.A., Rygiewicz, P.T., Watrud,L.S., Donnelly, P.K. 2002. Influence of adverse soil conditions on the formation and function of arbuscular mycorrhizas. *Adv. Environ. Res.* **7**:123–138.

Evelin, H., Giri, B., Kapoor, R. 2012. Contribution of *Glomus intraradices* inoculation to nutrient acquisition and mitigation of ionic imbalance in NaCl-stressed *Trigonella foenum-graecum*. *Mycorrhiza* **22**:203–217.

Fernandes, E., Rodrigues, B.F. 2017. Arbuscular mycorrhizal diversity in mangrove plant species from Agarwada (Pernem), Goa. M.Sc. Dissertation.

Ferrol, N., Barea, J.M., Aguilar, A.C. 2002a. Mechanisms of nutrient transport across interfaces in arbuscular mycorrhizas. *Plant Soil* **244**: 231–237.

Ferrol, N., Pozo, M.J., Antelo, M., Azcón-Aguilar, C. 2002b. Arbuscular mycorrhizal simbiosis regulates plasma membrane H+-ATPase gene expression in tomato plants. *J. Exp. Bot.* **53**:374.

Frey-Klett, P., Chavatte, M., Clausse, M-L., Courrier, S., Le Roux, C., Raaijmakers, J., Martinotti, M.G., Pierrat, J-C., Garbaye, J. 2005) Ectomycorrhizal symbiosis affects functional diversity of rhizosphere fluorescent pseudomonads. *New Phytol.* **165**:317–328.

Gaonkar, S., Rodrigues, B.F. 2020. Diversity of arbuscular mycorrhizal (AM) fungi in mangroves of Chorao Island, Goa, India. *Wetl. Ecol.Manag.***28**:765–778.

Gaonkar, S., Rodrigues, B.F. 2021. Arbuscular mycorrhizal fungal status in mangroves of Pichavaram Forest, Tamil Nadu, India. *Trop. Ecol.* **62**:538–548.

Genre, A., Chabaud, M., Timmers, T., Bonfante, P., Barker, D.G. 2005. Arbuscular mycorrhizal fungi elicit a novel intracellular apparatus in *Medicago truncatula* root epidermal cells before infection. *Plant Cell* **17**:3489–3499.

George, E. 2000. Nutrient uptake – Contributions of arbuscular mycorrhizal fungi to plant mineral nutrition. *In*: *Arbuscular Mycorrhizas: Physiology and Function.*(Eds. Y. Kapulnik, D.D. Douds), Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 307–343.

Goltapeh, E.M., Danesh, Y.R., Prasad, R., Varma, A. 2008. Mycorrhizal Fungi: what we know and what should we know? In: *Mycorrhiza*, (Ed. A. Verma), Springer-Verlag Berlin Heidelberg, pp 3–7.

Gopinathan, M., Mahesh, V., Durgadevi, R. 2017. Occurrence and distribution of AM fungi associated in *Avicennia marina* (Forssk) Vierh in Soils of South East Coastal area of Muthupet, India. *J. Glob.Biosci.* **6**:4741–4747.

Gupta, N., Bihari, K.M., Sengupta, I. 2016. Diversity of arbuscular mycorrhizal fungi in different salinity of mangrove ecosystem of Odisha, India. *Adv. Plants Agric. Res.* **3**:19–23.

Hackney, C.T., Padgett, D.E., Posey, M.H. 2000. Fungal and bacterial contributions to the decomposition of *Cladium* and *Typha* leaves in nutrient enriched and nutrient poor areas of the everglades, with a note on ergosterol concentrations in everglades soils. *Mycol. Res.* **104**:666–670.

Hajiboland, R. 2013. Role of arbuscular mycorrhiza in amelioration of salinity. In: *Salt stress in plants: signalling, omics and adaptations*. (Ed. P. Ahmad, M.M.Azooz, M.N.V. Prasad) Springer, New York, pp 301-354.

Harrison, M.J., Pumplin, N., Breuillin, F.J., Noar, R.D., Boyce, H.J.P. 2010. Phosphate transporters in arbuscular mycorrhizal symbiosis. In: *Arbuscular Mycorrhizas*: *Physiology and Function* (Eds.H.Koltai, Y. Kapulnik), Springer Dordrecht Heidelberg London New York, pp 117–135.

He,Z.Q., He, C.X., Zhang, Z.B., Zou, Z.R., Wang, H.S. 2007. Changes of antioxidative enzymes and cell membrane osmosis in tomato colonized by arbuscular mycorrhizae under NaCl stress. *Colloids Surf. B***59**:128–133.

Hogarth, J.P. 2015. The biology of mangroves and seagrasses. Oxford University Press, Oxford, *Nature*, pp 304.

Hu, W., Wu, Y., Xin, G., Wang, Y., Guo, J., Peng, X. 2015. Arbuscular mycorrhizal fungi and their influencing factors for *Aegicerascorniculatum*and *Acanthus ilicifolius*in southern China. *Pak. J. Bot.* **47**:158–1586.

Igulu, M.M., Nagelkerken, I., Dorenbosch, M., Grol, M.G., Harborne, A.R., Kimirei, I.A., Mumby, P.J., Olds, A.D., Mgaya, Y.D. 2014. Mangrove habitat use by juvenile reef fish: meta-analysis reveals that tidal regime matters more than biogeographic region. *PLoS ONE* **9**: e114715.

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

Jakobsen, I., Hammer, E.C. 2015. Nutrient dynamics in arbuscular mycorrhizal networks. In: *Mycorrhizal Networks*, (Ed.T.D.Horton), Springer Dordrecht Heidelberg London New York, pp. 91–131.

Javot, H., Pumplin, N., Harrison, M.J. 2006. Phosphate in the arbuscular mycorrhizal symbiosis: transport properties and regulatory roles. *Plant Cell Environ*. **30**:310–322.

Juniper, S., Abbott, L.K. 2006. Soil salinity delays germination and limits growth of hyphae from propagules of arbuscular mycorrhizal fungi. *Mycorrhiza* **16**:371–379.

Karandashov, V., Bucher, M. 2005. Symbiotic phosphate transport in arbuscular mycorrhizas. *Trends Plant Sci*. **10**:22–29.

Kathiresan, K. 2000. A review of studies on Pichavaram mangrove, southeast India. *Hydrobiologia* **430**:185–205.

Kothamasi, D., Kothamasi, S., Bhattacharyya, A., Kuhad, R.C., Babu, C.R. 2006. Arbuscular mycorrhizae and phosphate solubilising bacteria of the rhizosphere of the mangrove ecosystem of Great Nicobar Island, India. *Biol.Fertil. Soils* **42**:358–361.

Kumar, T., Ghose, M. 2008. Status of arbuscular mycorrhizal fungi (AMF) in the Sundarbans of India in relation to tidal inundation and chemical properties of soil. *Wetl. Ecol.Manag*. **16**:471–483.

Leifheit, E.F., Veresoglou, S.D., Lehmann, A., Morris, E.K., Rillig, M.C. 2014. Multiple factors influence the role of arbuscular mycorrhizal fungi in soil aggregation—a meta-analysis. *Plant Soil* **374**:523–537.

Leigh, J., Hodge, A., Fitter, A.H.2008. Arbuscular mycorrhizal fungi can transfer substantial amounts of nitrogen to their host plant from organic material. *New Phytol*. **181**:199–207.

Li,Y.F., Ju, L.H., Zhang, L.Y., Xu, G.H. 2013. Effects of AM fungi on plant growth and nitrogen and phosphorus utilization in rice/ mungbean intercropping under different phosphorus application levels. *Jiangsu Agric. Sci*. **41**:51–55.

Lin, C., Wang, Y., Liu, M., Li, Q., Xiao, W., Song, W. 2020. Effects of nitrogen deposition and phosphorus addition on arbuscular mycorrhizal fungi of Chinese fir (*Cunninghamia lanceolata*). *Scient. Rep.* **10**:12260.

Loccoz,M.Y., Mavingui, P., Combes, C., Normand, P., Steinberg, C. 2015. Microorganisms and biotic interactions. In: *Environmental Microbiology: fundamentals and applications: Microbial ecology* (Eds. J.C. Bertrand, P. Caumette, P.Lebaron, R. Matheron, P. Normand, T. Sime-Ngando T) Springer Science+Business Media Dordrecht, pp 395–444.

Miransari, M. 2011. Interactions between arbuscular mycorrhizal fungi and soil bacteria. Appl *Microbiol.Biotechnol*. **89**:917–930.

Mohammadi, K., Khalesro, S.,Sohrabi, Y., Heidari, G. 2011. A review: Beneficial effects of the mycorrhizal fungi for plant growth. *J. Appl. Environ. Biol. Sci.***1**:310–319.

Peng, J., Li, Y., Shi, P., Chen, X., Lin, H., Zhao, B. 2010. The differential behavior of arbuscular mycorrhizal fungi in interaction with *Astragalus sinicus*L. under salt stress. *Mycorrhiza* **21**:27–33.

Radhika, K.P., Rodrigues, B.F. 2007. Arbuscular mycorrhizae in association with aquatic and marshy plant species in Goa, India. *Aquat. Bot* .**86**:291–294.

Redecker, D., Morton, J.B., Bruns, T.D. 2000. Ancestral lineages of arbuscular mycorrhizal fungi (Glomales). *Mol.Phylogenet.Evol.***14**:276–284.

Reef, R., Feller, I.C., Lovelock, C.E. 2010. Nutrition of mangroves. *Tree Physiol.***30**:1148–1160.

Rillig, M.C. 2004. Arbuscular mycorrhizae, glomalin, and soil aggregation. *Can. J. Soil Sci.* **84**: 355–363.

Rillig, M.C., Ramsey, P.W., Morris, S., Paul, E.A.2003. Glomalin, an arbuscular-mycorrhizal fungal soil protein, responds to land-use change. *Plant Soil* **253**:293–299.

Roy-Bolduc, A., Hijri, M. 2011. The use of mycorrhizae to enhance phosphorus uptake: a way out the phosphorus crisis. *J.Biofertil.Biopestici.* **2**:104.

Sanon, A., Andrianjaka, Z., Prin, Y., Bally, R., Thioulouse, J., Comte, G., Duponnois, R. 2009. Rhizosphere microbiota interferes with plant-plant interactions. *Plant Soil* **321**:259–278.

Schüßler, A., Martin, H., Cohen, D., Fitz ,M., Wipf, D. 2007.Studies on the *Geosiphon* symbiosis led to the characterization of the first glomeromycotan sugar transporter. *Plant Signal.Behav*. **2**: 431–434.

Sengupta, A., Chaudhuri, S. 2002. Arbuscular mycorrhizal relations of mangrove plant community at the Ganges River estuary in India. *Mycorrhiza* **12**:169–174.

Sharma, M.P. 2021. Appraisal of native AM fungi in improving the plant productivity, soil health and sequestering soil carbon in agroecosystems. *Kavaka* **56**: 13–21.

Smith, S.E., Read, D.J.2008. Mycorrhizal symbiosis. 3rd ed. Elsevier, Amsterdam, 11–117 pp.

Smith, S.E., Smith, F.A., Jakobsen, I.2003. Mycorrhizal fungi can dominate phosphate supply to plants irrespective of growth responses. *Plant Physiol*. **133**:16–20.

Šraj-Kržič, N., Pongrac, P., Klemenc, M., Kladnik, A., Regvar, M., Gaberscik, A.2006. Mycorrhizal colonisation in plants from intermittent aquatic habitats. *Aquat. Bot.* **85**:331–336.

Sridhar, K.R., Roy, S., Sudheep, N.M. 2011. Assemblage and diversity of arbuscular mycorrhizal fungi in mangrove plant species of the southwest coast of India. In:*Mangroves ecology, biology and taxonomy*(Ed. J. Metras). Nova Science Publishers Inc, Hauppage, 257–274 pp.

Sun, X.W., Wang, X.J., Chen, M., Dou, C.Y., Gao, F.Z., Jin, L. 2011. Effects of eco-environmental factors on the production and distribution of arbuscular mycorrhizal fungal spores. *Acta Pratacult. Sin*. **20**:214–221.

Tarkka, M.T., Frey-Klett, P. 2008. Mycorrhiza helper bacteria. In:Mycorrhiza-State of the art, genetics and molecular biology, eco-function, biotechnology, eco-physiology, structure and systematics, 3rdEdn, (Ed. A. Varma) Springer-Verlag Berlin Heidelberg, pp 113–132.

Tawaraya,K., Takaya, Y., Turjaman, M., Tuah, S.J., Limin, S.H.,Tamai, Y., Cha, J.Y., Wagatsuma, T., Osaki, M. 2003. Arbuscular mycorrhizal colonization of tree species grown in peat swamp forests of Central Kalimantan, Indonesia. *Forr. Ecol.Manag.* **182**:381–386.

Tian, Y., Lu, H., Hong, H., Qian, L., Yuan, B., Liu, J., Yan, C. 2020a. Potential and mechanism of glomalin-related soil protein on metal sequestration in mangrove wetlands affected by aquaculture effluents. *J. Hazard. Mater.* **420**:126517.

Tian, Y., Yan, C., Wang, Q., Ma, W., Yang, D., Liu, J., Lu, H. 2020b. Glomalin-related soil protein enriched in δ13C and δ15N excels at storing blue carbon in mangrove wetlands. *Sci. Total Environ*. **732**:138327.

Van Der Heijden, Horton, T.R. 2009. Socialism in soil? The importance of mycorrhizal fungal networks for facilitation in natural ecosystems. *J. Ecol*. **97**:1139–1150.

Wang, Q., Li, J.W., Chen, J.Y., Hong, H.L., Lu, H.L., Liu, J.C., Dong, Y.W., Yan, C. 2018b. Glomalin-related soil protein deposition and carbon sequestration in the Old Yellow River delta. *Sci. Total Environ*. **625**:619–626.

Wang, Q., Lu, H., Chen, J., Jiang. Y., Williams, M.A., Wu, S., Li, J., Liu, J., Yang, G., Yan, C. 2019b. Interactions of soil metals with glomalin-related soil protein as soil pollution bioindicators in mangrove wetland ecosystems. *Sci. Total Environ*. **709**:136051.

Wang, Q., Lu, H.L., Chen, J.Y., Hong, H.L., Liu, J.C., Li, J.W., Yan, C.L. 2018a. Spatial distribution of glomalin-related soil protein and its relationship with sediment carbon sequestration across a mangrove forest. *Sci. Total Environ*. **613**:548–6556.

Wang, Q., Mei, D., Chen, J., Lin, Y., Liu, J., Lu, H., Yan,C .2019a. Sequestration of heavy metal by glomalin-related soil protein: Implication for water quality improvement in mangrove wetlands. *Water Res.* **148**:142–152.

Wang, Y, Huang, Y., Qiu, Q., Xin, G., Yang, Z., Shi, S.2011. Flooding greatly affects the diversity of arbuscular mycorrhizal fungi communities in the roots of wetland plants. *PLoS One* **6**:e24512.

Wang, Y., Li, T., Li, Y., Qiu,Q., Li, S., Xin, G.2014a. Distribution of arbuscular mycorrhizal fungi in four semi-mangrove plant communities. *Ann. Microbiol*. **65**:603–610.

Wang, Y., Qiu, Q., Li, S., Xin, G., Tam, N.F.2014b. Inhibitory effect of municipal sewage on symbiosis between mangrove plants and arbuscular mycorrhizal fungi. *Aquat. Biol.* **20**:119–127.

Wang, Y., Qui, Q., Yang, Z., Hu, Z., Tam, N.F., Xin, G. 2010. Arbuscular mycorrhizal fungi in two mangroves in South China. *Plant Soil* **331:**181–191.

Willis, A., Rodrigues, B.F., Harris, P.J.C.2013. The ecology of arbuscular mycorrhizal fungi. *Crit. Rev. Plant Sci*. **32**:1–20.

Wu, Q.S., Cao, M.Q., Zou, Y.N., He, X.H. 2014. Direct and indirect effects of glomalin, mycorrhizal hyphae, and roots on aggregate stability in rhizosphere of trifoliate orange. *Sci. Rep*. **4**:5823.

Xie, X., Weng, B., Cai, B., Dong, Y., Yan, C. 2014. Effects of arbuscular mycorrhizal inoculation and phosphorus supply on the growth and nutrient uptake of *Kandeliaobovata* (Sheue, Liu &Yong) seedlings in autoclaved soil. *Appl.Soil Ecol*. **75**:162–171.

Yamato, M., Ikeda, S., Iwase, K.2008 .Community of arbuscular mycorrhizal fungi in a coastal vegetation on Okinawa Island and effect of the isolated fungi on growth of sorghum under salt-treated conditions. *Mycorrhiza* **18**:241–249.

Yinan, Z., Hongqing, Y.U., Tao, Z., Jixun, G.2017. Mycorrhizal colonization of chenopods and its influencing factors in different saline habitats, China. *J. Arid Land*. **9**:143–152.

Zhang, J.,Tang, X., He, X.2015.Glomalin-related soil protein responses to elevated CO_2 and nitrogen addition in a subtropical forest: Potential consequences for soil carbon accumulation. *Soil Biol.Biochem*. **83**:142–149.

Zhang, X.H. 2003. Adaptability of arbuscular mycorrhizal fungi to different soil environmental factors. PhD Thesis, Agricultural University of Hebei.