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Original Article

Arbuscular Mycorrhizal Fungi Improve the Antioxidative Response and the Seed Production of Suaedoideae Species *Suaeda physophora* Pall under Salt Stress

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Abstract

Arbuscular mycorrhizal fungi (AMF) play a key role in plant growth and survival; however, the influence of AMF on the growth and production of Suaedoideae species is still not well understood. The object of this study was to understand the mechanism of AMF that affects the growth of Suaedoideae species under different saline conditions. The result showed that the Suaedoideae species *Suaeda physophora* was colonized by the AMF species *Glomus etunicatum* (*Ge*) and *Glomus mosseae* (*Gm*). AMF significantly increased the activities of superoxide dismutase (SOD) and peroxidase (POD) in *S. physophora* and reduced the concentrations of malondialdehyde (MDA) and H_2O_2 in the leaves of *S. physophora* under salt stress. AMF also improved the aboveground biomass of *S. physophora* and significantly increased its seed numbers. Moreover, AMF increased the aboveground phosphorus (P) content of *S. physophora*. No significant difference between the effect of AMF species *Ge* and *Gm* on *S. physophora* growth was observed. These results suggest that AMF can increase the salt resistance of the Suaedoideae species *S. physophora* by increasing SOD and POD activities, reducing MDA and H_2O_2 concentrations and increasing P uptake. The results highlight that AMF might play an important role in *S. physophora* growth and population survival under harsh salt conditions.

Keywords: arbuscular mycorrhizal fungi, antioxidants, population succession, restoration, salinization

Introduction

Suaedoideae is one of the most important plant subfamilies belonging to Amaranthaceae, which is often used for vegetation recovery because many of them are high-drought tolerance, salinity resistance and tolerant to nutrient deficiency (Zhang *et al*., 2012), especially in some regions with saline soils. *Suaeda physophora* Pall belonging to the Suaedoideae subfamily is a pioneer plant in the colonization and inhabitation of saline soils and therefore plays a key role in rehabilitation and utilization of vegetation in saline-alkali land. *S. physophora* is an oil-seed halophyte, which produces large amounts of biomass and seeds that can be added in fodder. The seed of *S. physophora* is considered a new source of grains or vegetable oils (Wang *et al*., 2013). Additionally, *S. physophora* has high nutritional value as forage or fodder crop; therefore, it has important economic value and ecological value and is a good choice for saline agriculture in northwest China. However, the growth of *S. physophora* in field conditions is frequently not optimal and is often suppressed by salt, drought, nutrient deficiency, and so on (Song *et al*., 2005, 2006; Zhang *et al*., 2015).

Arbuscular mycorrhizal fungi (AMF), the most important functional group of the phylum *Glomeromycota*, is organized by their special structures, such as arbuscules and vesicles (Zhang *et al*., 2012). These species structures can form mutualistic associations with most land plant species and obtain carbon (C) from their plant partners in exchange for mineral nutrients (Zheng *et al*., 2014). AMF can not only improve plant growth but also protect their host plants from drought stress, salt stress and nutrient depletions (Morte *et al*., 2001; Alqarawi *et al*., 2014). Some plant species are unable to live without AMF in some extreme environments (Pennisi, 2004) and thus play a key role in maintaining the functionality and stability of ecosystem (Aliasgharzadeh *et al*., 2001; Rodriguez and Redman, 2008).

Suaedoideae species (Amaranthaceae) were typically thought of as non-AMF plant species in early studies, which had low or no infection by its unique structures, such as

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arbuscules or vesicles (Hirrel *et al*., 1978; Brundrett, 2002; Smith and Read, 2008). However, a growing number of studies have now found that many Amaranthaceae species can be colonized by AMF in Port Wakefield, South Australia (Aleman and Tiver, 2010), in Simpson Desert, Australia (O'Connor *et al*., 2001), and in Junggar Basin, China (Shi *et al*., 2006; Zhang *et al*., 2012), meanwhile, AMF can improve their growth. For instance, Williams *et al*. (1974) first observed that the growth of *Atriplex canescens* inoculated with *Glomus mosseae* increased in sterilized soil. Recently, Zhang *et al*. (2012) found that both in the field and in the greenhouse inoculation trials, the growth of *Ceratocarpus arenarius* was stimulated by the indigenous AMF community and the inoculated AMF isolates, respectively. However, the symbiotic relationship between *S. physophora* and AMF and the growth response of *S. physophora* to AMF remains unclear. The object of this study was to verify the effects of AMF on plant growth of *S. physophora* by altering the antioxidative activities and improving the phosphorus (P) uptake under a salt concentration gradient.

Materials and Methods

Plant and soil conditions

The seeds of *S. physophora*, which is considered a typical chenopod species, were collected from the salt desert in northwest China (44°32.207′ N, 87°16.509′ E) and stored in a refrigerator at 4 °C before being used. The *S. physophora* seeds were surface disinfested in 10% (v/v) hydrogen peroxide for 10 min, rinsed three times with deionized water, and then germinated at 20 °C. After 48 h, 10 germinated seeds were sown in pots. The seedlings were thinned to four per pot. Top soil was collected from the same site where the *S. physophora* seeds were collected. The soil was sterilized with 10 k $GyCo^{60}$ γ-ray. The soil after sterilization had the following properties (dry matter basis): pH (in H_2O) 8.55; Kjeldahl-N 55.6 mg kg^{-1}; organic matter 0.25%; Olsen-P (0.5 mol $L^{-1}NaHCO_3$-extractable) 4.22 mg kg^{-1}; and exchangeable K (1 mol $L^{-1}NH_4OAc$) 175 mg kg^{-1}.

AMF inoculums preparation

Glomus etunicatum (*Ge*) and *Glomus mosseae* (*Gm*) were previously isolated from the rhizosphere soil of the chenopod plant *S. physophora*. The fungal isolates were cultured on white clover growing in pots in the greenhouse for 5 months by using the same soil which was collected from the field where *S. physophora* is distributed. The mycorrhizal inoculum consisted of spores, mycelium, root segments and soil. There were about 200 spores in 5 g soil. For the mycorrhizal treatment, 50 g of combined inoculums of *Ge* and *Gm* was placed into the soil, and 50 g of sterilized inoculum was placed into the soil for the non-mycorrhizal treatment (control). To minimize differences in the rhizosphere microbial communities of the mycorrhizal and non-mycorrhizal treatments, 10 ml filtrates from the inoculum that were free of mycorrhizal propagules were added to the central compartment of each replicate of the non-mycorrhizal treatment, and 10 ml deionized water was added to each of the replicates in the mycorrhizal treatments. All treatments were replicated 6 times.

Experimental design

This experiment had a completely randomized design. The main treatments included five salt concentrations: 0, 50, 100, 200 and 400 mM. The salt concentrations were set according to a field survey and the results from a previous experiment (Song *et al*., 2005). Each salt treatment had three AMF treatments: control (C), *Ge* inoculation and *Gm* inoculation. The soil was watered to maintain soil water content at a level of 10% by weight. The plants were harvested after growing for four months.

Mycorrhizal colonization and phosphorus content

The shoots and roots were removed from soil and washed with deionized water. Roots were cut into 1 cm segments and mixed thoroughly for measuring the mycorrhizal colonization. A sub-sample of 0.5 g was cleared with 10% (w/v) KOH at 90 °C in a water bath for 20-30 min and stained with 0.5% (w/v) trypan blue. Mycorrhizal colonization was measured according to the method described by Zhang *et al*. (2011). The hyphal length density was measured according to the method described by Jakobsen *et al*. 1992. The shoots were ground and heated to dry ash in a muffle furnace at 300 °C for 3 h and at 550 °C for 5 h. The ash was dissolved in 2% (v/v) HCl. The P content was determined using inductively coupled plasma-atomic emission spectroscopy (ICP-AES; Perkin Elmer Optima 3300DV). Aboveground biomasses were weighed after oven dried at 65 °C for 48 h in an electric constant temperature drying oven.

Enzyme analysis

For analyses of leaf superoxide dismutase (SOD), peroxidase (POD), malondialdehyde (MDA), and H_2O_2, fresh leaves from the middle of each plant were sampled after growing 8 weeks. For each replicate pot, 1 g of leaves was ground to a fine powder in liquid nitrogen and then homogenized in 5 ml of extraction buffer (50 mM phosphate buffered saline, pH 7.8; 0.1 mM EDTA; 0.3% Triton X-100; 4% polyvinylpolypyrrolidone). After centrifugation (10500×g, 4 °C, 20 min), the supernatant was used for antioxidant enzyme analysis. The activity of SOD in leaves was quantified according to Giannopolitis and Ries (1977), one unit of the enzyme activity was defined as the amount of enzyme required to result in a 50% inhibition of the rate of nitro blue tetrazolium reduction measured at 560 nm. POD activity in each plant was determined using the guaiacol oxidation method by Maehly and Chance (1954) in a 3 ml reaction mixture containing 100 mM phosphate buffer (pH 6.0), 8 mM guaiacol, 100 μL enzyme extract and 2.75 mM H_2O_2. The increase in absorbance was recorded at 470 nm within 3 min after enzyme extract was added. The MDA concentration was quantified according to the method described by de Azevedo Neto *et al*. (2006). The extract of leaves was mixed with the same volume of a thiobarbituric acid solution (0.5%, w/v) containing tricholoroacetic acid (20%, w/v). The mixture was heated at 95 °C for 30 min, and then cooled in an ice-bath quickly. The mixture was centrifuged at 3000 × g for 10 min, and the absorbance of the supernatant was monitored at 532 and 600 nm. The H_2O_2 concentration was determined by estimating the titanium-hydro-peroxide complex using the method described by Harinasut *et al*. (2003).

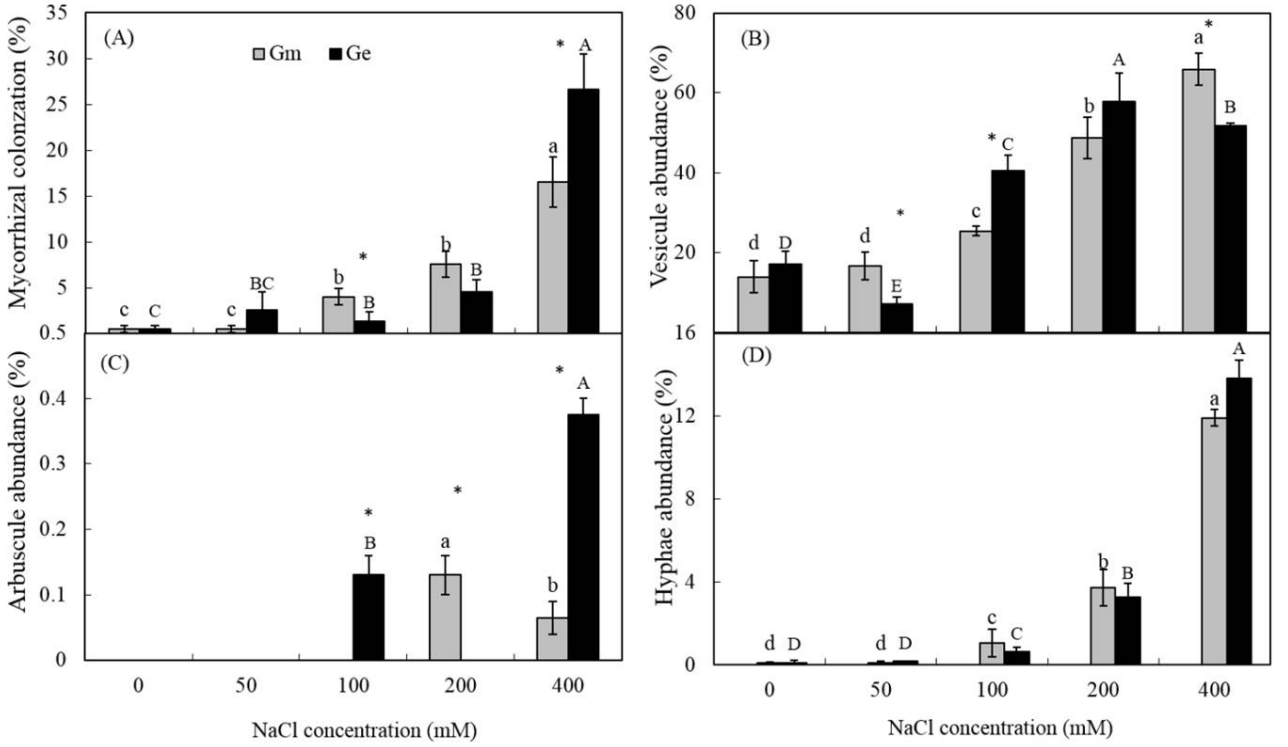

Fig. 1. Mycorrhizal colonization status in root system of *S. physophora* under different salt concentrations. Mycorrhizal colonization (A), vesicle abundance (B), arbuscule abundance (C) and hyphae abundance (D) of *Gm* or *Ge*. Different lowercase letters on grey columns and capital letters on black columns indicate significant differences among different salt concentration with the same kind of AMF at 0.05 level. Asterisk represents significant difference between different AMF treatments under the same salt concentration at 0.05 level

Statistical analyses

All data were analyzed with analysis of variance (ANOVA) using SPSS software (SPSS 16.0 for Windows, Chicago, IL, USA). Differences in the means were compared among treatments with Tukey's test and were considered significant at the 0.05 level.

Results

Mycorrhizal colonization

Mycorrhizal colonization was observed in the root of *S. physophora* at different salt concentrations when the AMF were inoculated (Fig. 1A). The mycorrhizal colonization significantly increased with an increase in the salt concentration (P<0.05). The mean colonization of these two AMF treatments *Gm* and *Ge* in the 400 mM salt concentration was 174.9% higher than that in the 50 mM salt concentration (P<0.05). Significant differences in mycorrhizal colonization between inoculations of *Gm* and *Ge* were observed at the concentrations of 100 and 400 Mm (all P<0.05), but no significant difference under other NaCl concentrations. The vesicule abundance in inoculation *Gm* treatment were lower than those in *Ge* treatment at concentrations of 0, 100 and 200 mM, but higher at concentrations of 50 and 400 mM (Fig. 1B). Both arbuscule and hyphae abundances were much higher in the mycorrhizae-treated samples than the abundance of the control samples (Fig. 1C, 1D). No significant difference in

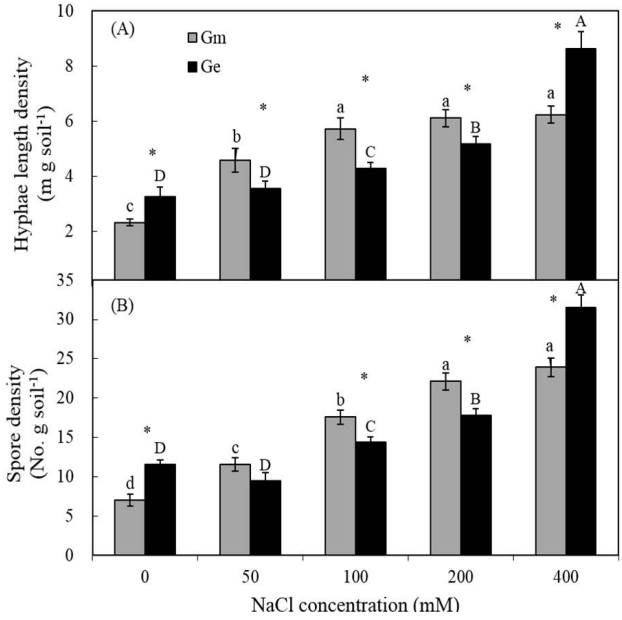

Fig. 2. The hyphae length density (A) and spore density (B) of AMF in different salt concentration. Different lowercase letters on grey columns and capital letters on black columns indicate significant differences among different salt treatment under the same inoculation AMF at 0.05 levels. Asterisk indicates significant differences between Gm and Ge treatments under same salt condition at 0.05 levels

Table 1. Effects of AMF on activities of POD and SOD, H_2O_2 concentration and MDA concentration of *S. physophora* under different NaCl concentrations

NaCl (mM)	POD (U g^{-1} min^{-1})			SOD (U g^{-1} min^{-1})			H_2O_2(%)			MDA (μmolg^{-1} DW)		
	C	Gm	Ge	C	Gm	Ge	C	Gm	Ge	C	Gm	Ge
0	96.7 ±7.9cC	131.9 ±10.1bC	198.2 ±30.3aB	560 ±11.2bB	585 ±11.6aB	581 ±14.5abB	0.22 ±0.03aA	0.14 ±0.02bAB	0.11 ±0.02bB	0.72 ±0.03aC	0.30 ±0.02bC	0.20 ±0.07bB
50	132.6 ±8.8bB	192.6 ±19.5aAB	179.2 ±8.3aB	572 ±14.3bAB	615 ±13.4aA	605 ±12.1aAB	0.19 ±0.02aA	0.16 ±0.01bA	0.17 ±0.01abA	0.59 ±0.06aD	0.43 ±0.06bC	0.31 ±0.05cB
100	119.3 ±9.2bB	191.1 ±10.1aB	196.8 ±18.0aB	590 ±13.8bAB	627 ±12.6aA	610 ±10.3abAB	0.21 ±0.01aA	0.16 ±0.01bA	0.16 ±0.01bA	1.48 ±0.09aA	0.84 ±0.10bA	0.43 ±0.18cAB
200	166.4 ±9.9bA	219.5 ±9.3aAB	205.6 ±9.3aB	608 ±12.3bA	638 ±14.8aA	627 ±12.4abA	0.19 ±0.01aA	0.16 ±0.04bA	0.17 ±0.01abA	0.65 ±0.03aD	0.59 ±0.03bB	0.54 ±0.04cA
400	158.5 ±14.4bA	247.5 ±8.3aA	257.3 ±15.6aA	612 ±12.6bA	652 ±15.3aA	638 ±13.1aA	0.16 ±0.01aB	0.13 ±0.01bB	0.13 ±0.01bB	1.06 ±0.05aB	0.82 ±0.07bA	0.62 ±0.11bA

Note: Different lowercase letters in each row indicate significant differences among different AMF treatments under the same salt concentrations at 0.05 level. Different capital letters in each column indicate significant differences among different NaCl concentrations under same AMF treatment at 0.05 level

Table 2. Effects of AMF on aboveground biomass (A) and seed number (B) of *S. physophora* under different salt concentrations. Different lowercase letters indicate significant differences (P<0.05) among different AMF treatments under same salt level

NaCl (mM)	Aboveground biomass (g plant^{-1})			Seed number (No. plant^{-1})			Aboveground P concentration (%)		
	C	*Gm*	*Ge*	C	*Gm*	*Ge*	C	*Gm*	*Ge*
0	0.60±0.08cC	0.80±0.10bC	1.07±0.05aD	10.5±1.05bB	16.5±1.58aD	15.8±0.97aC	0.18±0.01cA	0.26±0.01aA	0.22±0.01bA
50	1.01±0.07bB	1.48±0.11aB	1.49±0.08aC	13.5±1.67bB	23.3±2.25aC	20.5±2.02aB	0.16±0.01cB	0.22±0.01aB	0.19±0.01bB
100	1.06±0.06cB	1.55±0.06aB	1.36±0.09bC	18.6±1.93cA	32.5±2.58aB	26.9±2.44aB	0.15±0.02bB	0.19±0.02aBC	0.18±0.01aB
200	1.23±0.28bAB	1.94±0.19aA	1.79±0.15aB	21.3±2.36bA	40.4±2.9aA	37.9±3.89aA	0.14±0.01bB	0.19±0.02aBC	0.18±0.01aB
400	1.63±0.08cA	2.03±0.07bA	2.38±0.05aA	20.5±2.02bA	46.2±4.31aA	42.4±4.11aA	0.13±0.01bB	0.18±0.01aC	0.16±0.01aC

hyphae abundance between *Gm* and *Ge* treatments under same salt concentration (P>0.05) was observed, but significant difference in arbuscule abundance between *Gm* and *Ge* treatments were detected.

Spore density and hyphal length density both exhibited increased with the increase of the salt concentration (Fig. 2A, 2B). At salt concentrations of 50, 100 and 200 mM, the spore density and hyphal length density in the treatments that were inoculated with *Gm* were higher (all P<0.05) than the spore density and hyphal density in treatments that were inoculated with *Ge*, and significant differences in spore density and hyphal density were observed between *Gm* and *Ge* treatments. When exposed to a salt concentration of 400 mM, the spore density and hyphal length densities in the *Ge* treatment were much higher than those of the *Gm* treatment (all P<0.05).

SOD and POD activities and $H_2O_2$and MDA in leaves

The activities of POD and SOD in leaves significantly increased with the increase of salt concentration, both in the control and the AMF inoculation treatments (Table 1). Compared to the control, POD activities in the AMF treatments inoculated with *Gm* and *Ge* increased on average by 45.8% (P<0.01) and 53.9% (P<0.01), respectively. No significant differences were observed in POD and SOD activities between *Gm* and *Ge* treatments, except in the 0 mM salt concentration. The presence of *Gm* and *Ge* increased SOD activities by 11.9% (P<0.05) and 4.2% (P>0.05) higher than the control of SOD activities, respectively. Although no significant differences between the SOD activities of the *Gm* and *Ge* treatments were observed, the effects of *Gm* on SOD activity were higher than the effects of *Ge*.

Salinity at concentration 400 mM decreased H_2O_2 concentration (P<0.05, Table 1) in *S. physophora* by 32% but increased MDA concentration by 48% (P<0.05, Table 1), respectively, compared to control. AMF significantly decreased the H_2O_2 concentration and MDA concentration (Table 1) in plants. Compared to control, the inoculation of the AMF *Gm* and *Ge* decreased H_2O_2 concentrations in the plants by an average of 22.0% (P<0.05) and 24.3% (P<0.05), respectively; there were no significant differences between *Gm* and *Ge* treatments (P>0.05) exposed to the same salt concentration (Table 1). The mean MDA concentration in the AMF inoculated treatments decreased by 43.5% (P<0.05) more than the MDA concentration in the control treatment (Table 1). The concentration of leaf MDA in the treatment inoculated with *Ge* was 58.5% (P<0.05) lower than the MDA concentration in the leaves in the treatment inoculated with *Gm*; significant differences in the MDA concentration in leaves between the *Gm* and *Ge* treatments were detected in the same salt concentration (all P<0.05).

Aboveground biomass and seed production

Salt stress caused significant increase in aboveground biomass *of S. physophora*. Inoculation with AMF significantly caused more improvement of the aboveground biomass of *S. physophora* exposed to the five different salt concentrations (Table 2). After exposures to salt concentrations of 100 mM and 200 mM, the aboveground biomass of *S. physophora* in the treatments inoculated with *Gm* in both treatments was much higher than the biomass of *S. physophora* in the treatments inoculated with *Ge*; whereas after an exposure a to salt concentration of 400 mM, the *Ge*-inoculated plant biomass was higher than the *Gm*-inoculated *S. physophora* biomass (P<0.05). The mean aboveground biomass of AMF-inoculated *S. physophora* was 43.2% higher than the control biomass according to the two AMF treatments and five salt concentrations.

The inoculation of AMF also increased seed production of *S. physophora* (Table 2). Compared to the control, the mean seed numbers in plants in the AMF treatments increased by 79.2% (P<0.05); no significant difference between *Gm*-inoculated and *Ge*-inoculated treatments were observed (P>0.05).

P uptake

The inoculation of AMF significantly increased the P concentration in *S. physophora*; the mean P concentration in treatments with AMF was 31.5% higher than the P concentration in the control ($P<0.05$, Table 2). After an exposure to salt concentrations of 0 mM and 50 mM, the effect of *Gm* on the P concentration in *S. physophora* was higher than effect of *Ge* on the P concentration. Significant differences ($P<0.05$) were observed between *Gm*-inoculated and *Ge*-inoculated treatments on the P concentration at these salt concentrations, whereas no significant difference between *Gm*-inoculated and *Ge*-inoculated treatments were observed after exposure to the other salt concentrations.

Discussion

POD and SOD are important for plants to tolerate the salinity of the soil; the former can remove intracellular oxides, and the latter can eliminate harmful substances produced by the organism during metabolic processes. Several studies found that there is a strong correlation between the enzymatic antioxidant defence system and the salt tolerance of plants (Misra *et al*., 2006; Tunc-Ozdemir *et al*., 2009). The present study found that the POD and SOD activities increased with an increase in the salt concentration. This implies that the enhancement of SOD and POD scavenge reactive oxygen species (ROS) to protect *S. physophora* from cellular oxidative damage, which is an important protective mechanism against cellular oxidative damage under salt stress (Ahmad *et al*., 2012). The inoculation of the AMF significantly improved the POD activity of *S. physophora,* which is consistent with previous studies on *Ephedra aphylla* (Alqarawi *et al*., 2014), tomatoes (He *et al*., 2007), wheat (Talaat and Shawky, 2014) and cowpeas (Abeer *et al*., 2015). Moreover, the AMF also increased the activity of SOD in the leaves of *S. physophora*, which corresponds with previous studies (Wu, 2011; Li *et al*., 2012). AMF might have some abilities to up-regulate stress to tolerance and decrease the accumulation of H_2O_2 because of the expression of various SOD genes, indicating lower oxidative damage in the colonized plants (Wu *et al*., 2010; Hajiboland *et al*., 2010). However, Wu (2011) found that the influence of AMF on plant salt tolerance was determined by the AMF species. In the current study, no significant differences were observed between the species *Gm* and *Ge* on the POD and SOD activities of *S. physophora*, which might be related to these two species of AMF both were collected from the rhizosphere soil of *S. physophora,* and they formed relatively stable associations with each other, therefore have similar effects on the POD and SOD activities of *S. physophora*.

MDA is a specific product of lipid peroxidation induced by ROS, and H_2O_2 is the product of cell membrane oxidation. The accumulation of MDA and H_2O_2 represents the aggravation of stress in plant and suppresses plant growth (Ahmad *et al*., 2010, 2012). In the present study, the MDA content increased at all NaCl concentrations but increased more at NaCl concentration of 100 mM (Table 1). This means that salt sensitive concentration of *S. physophora* showed more lipid peroxidation at 100 mM than other concentrations. MDA content is often used as indicators of NaCl stress to test the radical damage. The current results provided support for the weakest oxidative stress tolerance of *S. physophora* under salt concentration of 100 mM. H_2O_2 content decreased after salt treatment (Table 1), which is not accordance with the result from wheat (Zheng *et al*., 2009) and *Catharanthus roseus* (Jaleel *et al*., 2007), but which is consistent with results from *Brassica juncea* (Ahmad *et al*., 2012) and *Suaeda salsa* (Pang *et al*., 2005). These results revealed that salt-induced oxidative stress did not occur in the leaves of *S. physophora*. That means the activity of antioxidant enzymes (POD and SOD) increased at all NaCl concentrations and reduced the content of H_2O_2. H_2O_2 is harmful to growth of cells, while antioxidant enzyme catalase can decompose H_2O_2 to water and oxygen (van Breusegem *et al*., 2001; Ashraf, 2009), which is one of the adaptive strategy under saline stress. AMF significantly decreased the concentrations of MDA and H_2O_2 in leaves of *S. physophora* under saline conditions. These results agree with previous studies that found the AMF species *Gm* reduced the MDA concentration in *Suaeda salsa* leaves (Wu, 2011; Li *et al*., 2012) and reduced the concentration of H_2O_2 in plant leaves (Huang *et al*., 2008). The results suggest that the inoculation of AMF can improve plant growth via a reduction in the damage caused by MDA and H_2O_2 accumulation under salt stress. Besides that the changes of antioxidase can alter the salt tolerance of *S. physophora*, the osmotic adjustment and lateral root growth caused by inorganic ions concentration can influence the salt tolerance and improve growth (Song *et al*., 2006; Yuan *et al*., 2010). However, whether AMF can affect the osmotic and later root growth of *S. physophora* is still not clear under salt condition, which needs further studies.

P is one of the most important elements for plant growth. Generally, the accumulation of P plays an important role in alleviating the adverse effect of P deficiency on plant growth and in regulating plant growth under salt-stress (Cantrell and Linderman 2001). Because phosphate ions precipitate with Ca^{+2}, Mg^{+2} and Zn^{+2} ions in saline soils and become unavailable to plants (Azcón-Aguilar *et al*., 1979). Therefore, P mineralization or fertilization is necessary for plant growth which may be helpful in mitigating salt stress by overcoming P-binding capacity of the soil (Cantrell and Lindermann, 2001). A previous study found that AMF did not increase the P content of *Amaranthaceae* species *Ceratocarpus arenarius* (Zhang *et al*., 2012). The present study found that AMF significantly improved the aboveground P concentrations of *S. physophora* under different salt concentrations; this is not consistent with above previous study. The results suggest that the increase in P uptake in *S. physophora* caused by the AMF might be an important adaptation strategy to resist salt stress. Arbuscules are the main structures for the carbon (C)-phosphorus trade-off between *S. physophora* and AMF, however, arbuscule abundance was not high in the root system of *S. physophora*, which appears to be detrimental to P uptake. The mechanism is responsible for the C-P trade-off between AMF and *S. physophora* need to be further studied.

AMF significantly increased aboveground biomass of *S. physophora* under different salt conditions (Table 2), which is consistent with some previous studies (Zhang *et al*., 2012; Alqarawi *et al*., 2014; Zhao *et al*., 2015). Moreover, the aboveground biomass of *S. physophora* increased with the increase of NaCl concentration in the control. The promotion of plant aboveground biomass under saline conditions may be

ascribed to the growth increase of the *S. physophora* root system and the improved water and nutrient uptake ability, which resulted in improving plant growth and increasing aboveground biomass. However, the contributions of AMF on biomass in high salt concentrations (200 mM and 400 mM) were higher than that in control. The result suggests that AMF might play a key role in improving salt resistance of *S. physophora* under high salt condition and maintaining productivity. The possible reasons are that AMF can help plants uptake water (Porcel *et al*., 2003) and nutrients (Kaya *et al*., 2009) from the soil and can decrease the concentration of toxic ions caused by high salt in the soil (Al-Karaki *et al*., 2001; Mohammad *et al*., 2003). Moreover, AMF have been shown to increase the activities of antioxidative enzymes (He *et al*., 2007) and produce plant growth hormones (Iqbal and Ashraf, 2013) that have beneficial effects on plant growth under salt stress.

It is well known that the seedlings of *Amaranthaceae* species in saline areas must resist the impact of the harsh environment, such as drought, waterlogging, and high salt (Song *et al*., 2005; Wang *et al*., 2008; Zhang *et al*., 2015). The number of seed germinated in the field is usually very high, but most of them cannot survive; therefore, a certain number of seeds is needed to ensure the reproduction of the next generation's population (Wang *et al*., 2008). In the present study, the seed number of *S. physophora*increased under salt treatment (Fig. 4B), which might be an adaptive strategy of salt stress. High salinity could suppress germination of *Amaranthaceae* species (Wang *et al*. 2015), more seeds can reduce the risk of inhibition of seed germination caused by salinity inhibiting and help species survive in high salt environments. AMF significantly increased the number of seeds produced by *S. physophora*, which indicates that AMF play an important role in seed production, which can ensure the reproduction of the *S. physophora* population in the future. Moreover, an increase in seed production will increase the amount of oil produced from *S. physophora* seeds.

Conclusions

The current result found that the Suaedoideae species *S. physophora* was colonized by AMF. AMF significantly reduced the negative effect of salt on the growth of *S. physophora* via increasing the activities of SOD and POD and reducing the contents of H_2O_2 and MDA. AMF significantly increased aboveground P content, biomass and seeds number. Moreover, the contributions of AMF on the aboveground biomass and seed number in high NaCl concentrations were much higher than in control or low NaCl concentration. These results suggest that AMF can reduce the negative effects of salt on the growth of Suaedoideae species and maintain the productivity and population reproduction, especially in high salt conditions. The present results highlight that AMF might be as a potential approach which can be used to restore Suaedoideae species in saline region.

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