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Research Article

Mycorrhizal symbiosis and mineral nutrition of halophytic and halotolerant plants in saline and heavy metal contaminated wetlands

Warda SIDHOUM[1,2*], Chahrazed AIBECHE[3], Zohra FORTAS[1]

[1] *Université Oran 1 Ahmed Ben Bella, Département de Biotechnologie, Laboratoire de Biologie des Microorganismes et Biotechnologie, Algérie; sidhoumwarda@yahoo.fr (*corresponding author); zohra_fortas@yahoo.com*
[2] *Université de Mostaganem Abdel Hamid Ibn Badis, Algérie*
[3] *Université des Sciences et de la Technologie d'Oran Mohamed Boudiaf (USTO-MB), Laboratoire de Production et Valorisation Végétale et Microbienne (LP2VM), B.P. 1505, El-Mn'aour, Oran 31000, Algérie; chahrazed.aibeche@univ-usto.dz*

Abstract

High salinity and heavy metal concentrations pose a serious threat to wetland biodiversity. The aim of this study was to investigate whether or not these fungi are related to metal and nutrient uptake in autochthonous wetland flora. Five halophyte and halotolerant plants, from two polluted wetlands in northwestern Algeria were studied to assess their arbuscular mycorrhizal fungal (AMF) diversity and colonization, and to determine their foliar content of metallic trace elements (MTEs) and mineral nutrients. Arbuscular mycorrhizal associations were observed in all plant species. In soil rhizospheres of *Atriplex halimus*, *Marrubium vulgare* and *Suaeda fruticosa*, high concentrations of Cd and Pb were detected. According to nutrient leaf concentrations in the analyzed plants, *S. fruticosa* and *A. halimus* accumulate Na, Cu, Cd and Zn and *M. vulgare* accumulates P, Pb, Ni, Cr and Cd. Meanwhile, Pearson correlation showed that Cd, Cu and Na accumulation were inhibited by AMF infection. The phytoextraction and phytodesalination by the studied species seem to be good methods for the phytoremediation of the soil.

Keywords: arbuscular mycorrhizal fungi (AMF), autochthonous flora, macronutrients, metallic elements, phytoremediation, wetlands

Introduction

Arbuscular mycorrhiza (AM) is an obligate mutualistic symbiotic association between arbuscular mycorrhizal fungi (AMF) and 80% of plant species (Van Der Heijden *et al.,* 2015). Mycorrhizal associations are naturally abundant in mineral-poor soils, with plants enhancing their nitrogen and phosphorus nutrition through the mycorrhizosphere (Azcón-Aguilar and Barea, 2015). The extraradical fungal network of AMs explores a large volume of soil and allows the plant to obtain inorganic phosphate from the same pool of soluble ions as the roots, so the mycelium can be considered an extension of the root system (Azcón-Aguilar and Barea, 2015). AMs also enhance the uptake of other nutrients, S, Cu, Ca, Zn, Mn, Fe and K, depending on their availability in the soil and the presence of AM symbiosis-specific nutrient transporters (Giovannetti *et al.*, 2014).

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Several abiotic factors influence the abundance and distribution of AM fungi in aquatic ecosystems, in particular soil flooding, nutrient depletion, oxygen availability, salinity and pollution levels (Deepika and Kothamasi, 2015; Boorboori and Lackóová, 2025; Kralj and Chen, 2025). Several studies on AMF associated with wetland plants have focused on the diversity and colonization potential of these fungi according to hydrological gradient (de Marins *et al.*, 2009), salinity (Roda *et al.*, 2008) and metallic element content (Ban *et al.*, 2017).

The accumulation of high concentrations of heavy metals in soils adversely affects microbial diversity and the activity of AMF, which play an important role in plant growth (Atakan *et al.*, 2018), and leads to soil degradation and loss of plant biodiversity, hence the need to remediate these ecologically and socio-economically important areas. The removal of heavy metals by physical and chemical methods is very costly and unreliable (Benavides *et al.*, 2005). On the other hand, phytoremediation using plants associated with AMF is currently the most effective method for remediating soils contaminated with heavy metals (Meier *et al.*, 2015). In order to implement this technology, it is necessary to first select the plant-AMF pair best suited to salinity and metal stress with a high remediation capacity. In Algeria, few studies have been carried out on the simultaneous effects of salinity and heavy metals on the distribution of AMF in wetland soils (Sidhoum and Fortas, 2019; Sidhoum *et al.*, 2020), and it is in this context that our work aims to evaluate the root colonization by AMF of certain plants growing on saline wetland soils contaminated by heavy metals, to determine the concentrations of Cu, Zn, Pb, Cd, Ni, Cr, Na, P, and K in the leaves, and to identify the main factors associated with the plant rhizosphere that influence the accumulation of mineral elements and metals.

Materials and Methods

Study area and site selection

The study sites are two wetlands in Oran (northwest Algeria): Lac Télamine (a Ramsar site since 2004) and Daya Morsli (Figure 1). Lac Télamine (LT) (35°43'50"N 0°23'30"W) is located 7 km from the Hassi Amer II industrial zone, and Daya Morsli (DM) (35 39'58" N, 0°36'27" W) is located 2 km north of the Es-Senia III industrial zone; their altitude varies between 50 and 87 m above sea level. This region is characterized by a semi-arid Mediterranean climate. Winters are typically cold and rainy, giving way to dry summers that extend for about 4 to 6 months. Rainfall varies between 250 mm and 400 mm, while temperatures fluctuate between 9 °C and 32 °C. These habitats are subject to urban and industrial effluents, which cause their degradation (Sidhoum *et al.*, 2020).

Sampling procedure

Rhizospheric soil and plant organs samples from five species *Dittrichia viscosa* (L.) Greuter (Asteraceae) from Dayet Morsli, and *Atriplex halimus* L., *Atriplex canescens* (Pursh) Nutt, *Suaeda fruticosa* (Amaranthaceae), and *Marrubium vulgare* L. (Lamiaceae) from Telamine Lake were collected in March (LT) and September (DM) of 2015. The number of collected plant specimens was adjusted according to the size of the natural populations from 5 to 9 specimens in order to avoid drastic depletion of plant populations.

Measuring soil pH and electrical conductivity

Soil samples, previously dried at room temperature, were sieved (2 mm diameter) in accordance with NF ISO 11464, December 1994. Electrical conductivity and pH were determined using a conductivity meter and a pH meter at a temperature of 25 °C with a ratio of 1/5 and 2/5 (soil/solution), respectively.

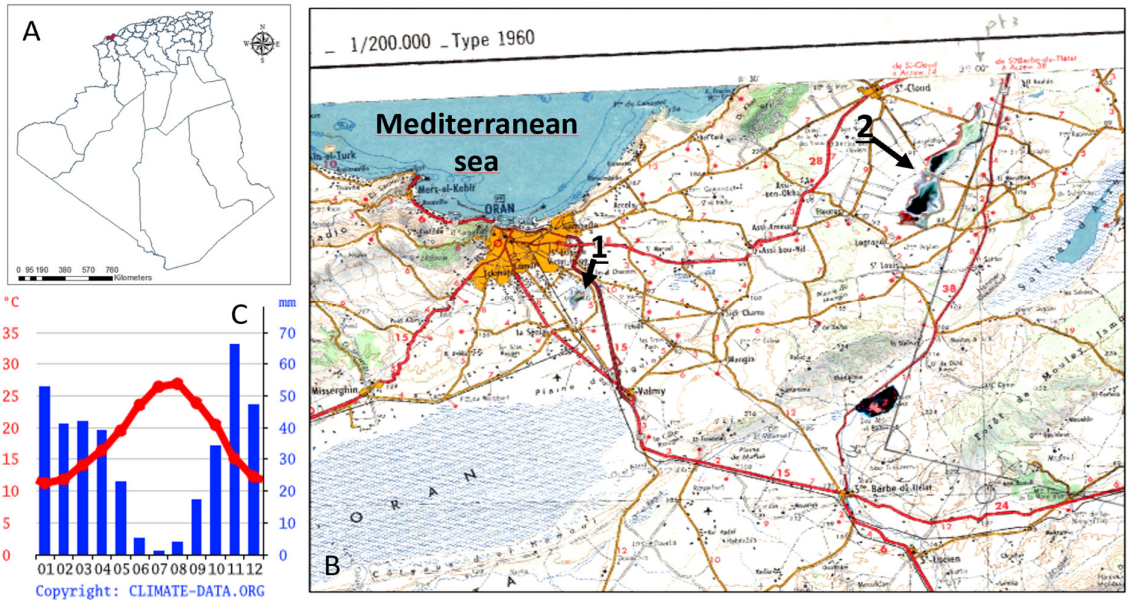


Figure 1. Map of Algeria (**A**), with a red dot marking the city of Oran; The map of Oran (**B**) highlights the studied locations, with arrows indicating the specific sites: Location 1 for Dayet Morsli and Location 2 for Telamine Lake; Bagnouls and Gaussen embrothermic diagram of Oran (**C**)

Mycorrhizal colonization statue

Root colonization rates by AMF were determined using the method of Phillips and Hayman (1970). Arbuscular mycorrhizal infection parameters were calculated using Trouvelot's method (Trouvelot *et al.,* 1986).

Total contents of major and trace metal elements in plants

Whole plants are collected and transported in plastic bags. Plant tips and damaged leaves are removed. Seined plant leaves are washed twice in tap water and then in distilled water for two minutes, before being dried at 60 °C for 48 hours (Vile *et al.*, 2005). All samples are ground in a tungsten carbide ring mill and sieved to 250-500 µm. Mineralization of soil and plant samples was conducted in accordance with the aqua regia method (Bradl, 2005), in accordance with AFNOR standards NF X31-151 (1993) (NF ISO 11466) and NF ISO 14 869-1 for soil and plants, respectively.

Determination of Na+ and K+ Levels

Following mineralization, the levels of K^+ and Na^+ in the plants were determined using a flame photometer (JENWAY PFP7).

Phosphorus determination

The quantification of phosphorus in plant parts was conducted in accordance with the protocol described by (Pinta, 1968). A total of 10 mL of plant mineralizate (as previously described) was combined with 5 mL of nitro-vanado-molybdic reagent. The resulting solution was then made up to 25 mL with distilled water and subsequently measured with a spectrophotometer (Multi-Cell Changer JENWAY) at 430 nm. Readings are compared with a range of P standards treated under the same conditions, including 0, 2, 4, 6, 8, and 10 µg/mL.

Determination of metallic trace elements MTE

The mineralizates are measured by SAA Shimadzu AA-7000 flame atomic absorption spectrophotometer. Results are expressed in mg/kg of dry matter (Ms).

Statistical analysis

The data obtained were subjected to an analysis of variance at the 5% significance level ($P < 0.05$) using the statistical software SPSS (SPSS 23.0), with the ANOVA test performed. Pearson's correlation coefficient was also employed to determine the relationship between accumulated metals and minerals and mycorrhization rate (F%) in the species under study.

Results

The results of physicochemical analyses of the rhizospheric soils of five species (*A. halimus, A. canescens, S. fruticosa, M. vulgare, D. viscosa*) (Table 1) indicate that the soils are slightly alkaline, with a pH of 7. The pH values of the soils were found to be between 41 and 8.14, with high salinity levels (6.61 to 7.98 dS/m) observed in the soils of *A. halimus* and *S. fruticosa*, respectively. The salinity levels were found to be medium in the soils of *A. canescens* and *M. vulgare* (3.83 and 1.75 dS/m), and low in the soils of *D. viscosa* (0.36 dS/m). Although some soil samples exhibited elevated concentrations of elements exceeding the soil quality thresholds corresponding to the AFNOR standard NFU 44-041, such as cadmium in the rhizosphere of *A. halimus* (3.24 mg/kg) and lead (473.60 and 114.52 mg/kg) in *M. vulgare* and *S. fruticosa*, respectively.

Table 1. The chemical composition of rhizospheric soils of investigated plant species

Species	pH	EC (dS/m)	Cu (ppm)	Zn (ppm)	Pb (ppm)	Cr (ppm)	Ni (ppm)	Cd (ppm)
A. halimus	7.49± 0.37ac	6.61± 0.00a	6.52± 5.08ab	135.76± 40.27ab	17.31± 3.46ba	24.08± 8.86a	11.05± 2.25a	0.02± 0.02ac
A. canescens	7.54± 0.17ac	3.83± 0.00b	14.09± 5.18ab	188.16± 31.50a	37.22± 24.64ac	27.19± 7.81a	14.51± 6.63a	0.46± 0.59ab
M. vulgare	8.12± 0.06b	1.75± 0.56c	4.80± 0.25b	84.5± 19.91b	494.05± 61.35b	17.52± 0.00a	15.05± 0.93a	0.82± 0.09b
S. fruticosa	7.41± 0.00a	7.98± 0.00d	16.15± 1.94a	162.50± 42.56ab	114.52± 18.75c	65.22± 17.27b	20.15± 2.13a	0.33± 0.05bc
D. viscosa	7.97± 0.1bc	0.36± 0.15e	9.1± 2.97ab	164.50± 2.78ab	91.13± 8.75a	59.03± 2.76b	17.62± 3.71a	0.52± 0.23bc
One-way ANOVA	8.20**	593.77****	5.44*	4.42*	119.56****	16.08***	2.61^{ns}	3.03^{ns}

Values followed by the same letter in the same column are not significantly different according to the Tukey test at $P < 0.05$. Meaning levels: *: The statistical significance of the results was determined using the following levels of significance: ns indicates no significant *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$, ****: $P < 0.0001$.

Endomycorrhizal infection in five plant species

The arbuscular mycorrhizal association is observed in all five plant species, while infection by fungal endophytes with septate and melanized DSE mycelium is detected in 80% (Figure 2).

A study of the mycorrhizal status of the various species reveals that mycorrhization frequencies (F%) are variable, ranging from 24% in *S. fruticosa* to 98% in *M. vulgare*. The average mycorrhization intensity (M%) is low in the Amaranthaceae (5.44-16.82%) and average in the root systems of *M. vulgare* (49.85%) and *D. viscosa* (59.19%). Arbuscular contents (A%) are low in Amaranthaceae, particularly in *A. halimus* (1.04%), and high in *D. viscosa* (57.9%) (Figure 2).

Arbuscular mycorrhizae are of the Arum type in all plant species, exept some *D. viscosa* roots which are of the Paris type. In the roots of *D. viscosa* and *M. vulgare*, AMF hyphae form numerous coils, arbuscules, and abundant globular vesicles, which are typical of the Glomeraceae 20-50% in *M. vulgare* and *D. viscosa*, respectively. In contrast, in those of the Amaranthaceae, there is a spread of intercellular hyphae and rarely arbuscules.

Statistical analysis revealed significant differences in mycorrhization frequency (F%), mycorrhizal intensity (M%), and mycorrhizal intensity of colonized root fragments (m%). These differences were statistically significant. i.e.: F = 161.96; P <0.0001; F = 65.99; P <0.0001, and F = 9.03; P <0.01, respectively. Additionally, the analysis revealed significant differences in arbuscular content (A%), (a%), and septate endophytes (DSE%). The results indicated significant differences in the arbuscular content A% (F = 109.62; P <0.0001), the arbuscular content a% of colonized roots (F = 23.88; P <0.001), and the septate endophytes (DSE%) (F = 3.56; P <0.05).

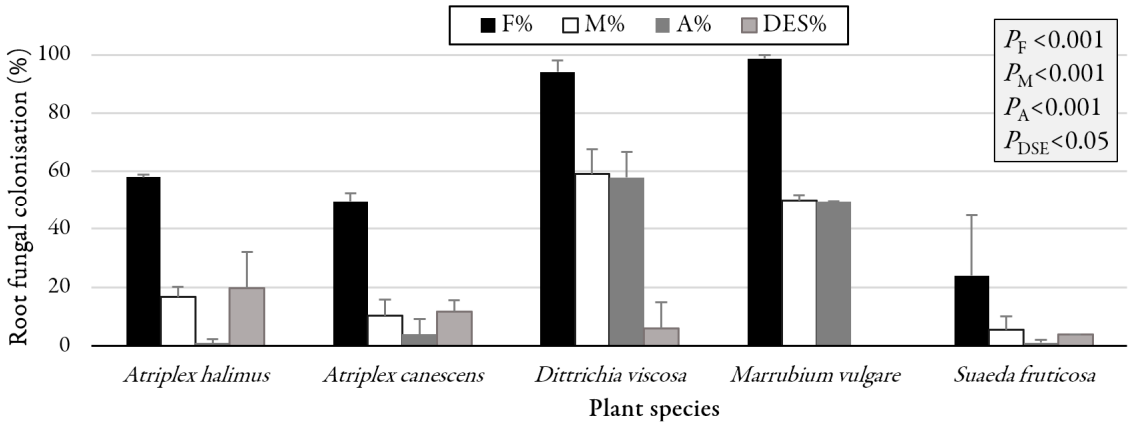


Figure 2. The estimated root fungal colonisation of five species by fungal endophytes: mycorrhizal fungi and dark septate fungi. F: Frequency of mycorrhization; DSE: Frequency of dark septate endophytes; M: Mycorrhization intensity relative to total root system; A: Arbuscular content of root system. Results are expressed as mean ± standard deviation (n = 3)

Contents of some mineral elements in the plant species surveyed

Foliar sodium and potassium contents

The results of Na+ and K+ content determinations in the leaves of the five plant species revealed that *S. fruticosa* contain significantly more Na+ (F=64.04; P<0.000001) than the other species, while *A. canescens* accumulate significantly more K+ (Figure 3). The values of the Na+/K+ content ratio (F= 10.61; P<0.01) in plant species are highly significant (Figure 4). These values are notably low in *M. vulgare* and *D. viscosa* which are identified as hypermycotrophic species.

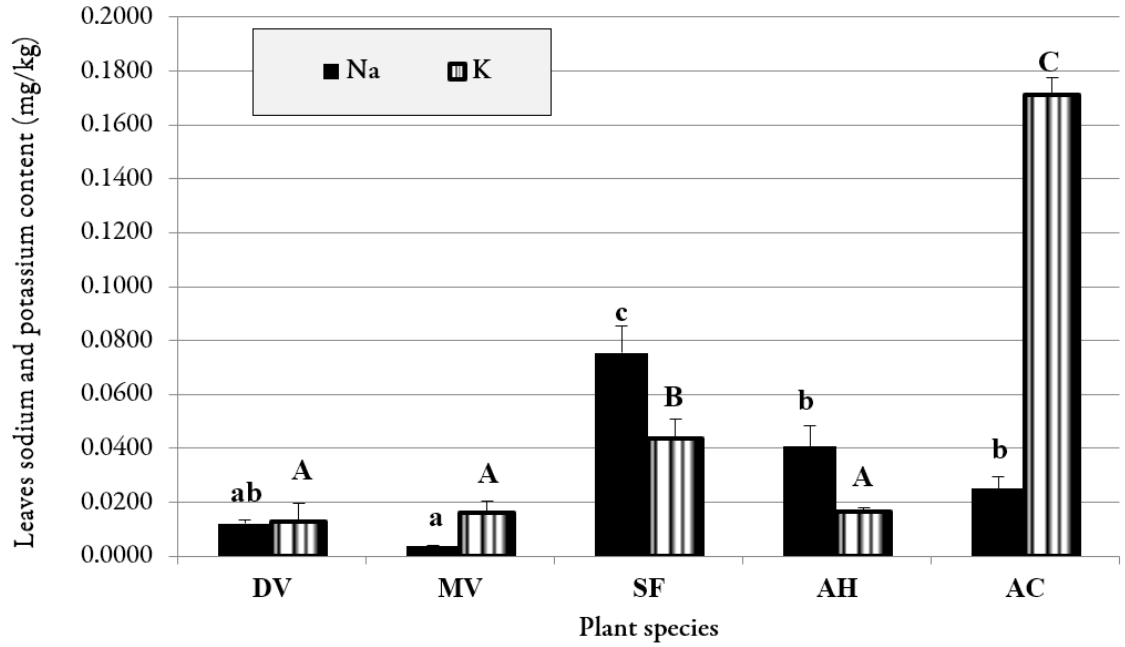


Figure 3. Leaf sodium and potassium levels in the five plant species studied (DV: *Dittrichia viscosa*; MV: *M arrubium vulgare*; SF: *Suaeda fruticosa*; AH: *Atriplex halimus*; AC: *Atriplex canescens*). Treatments with different letters show a significant difference according to Tukey's test

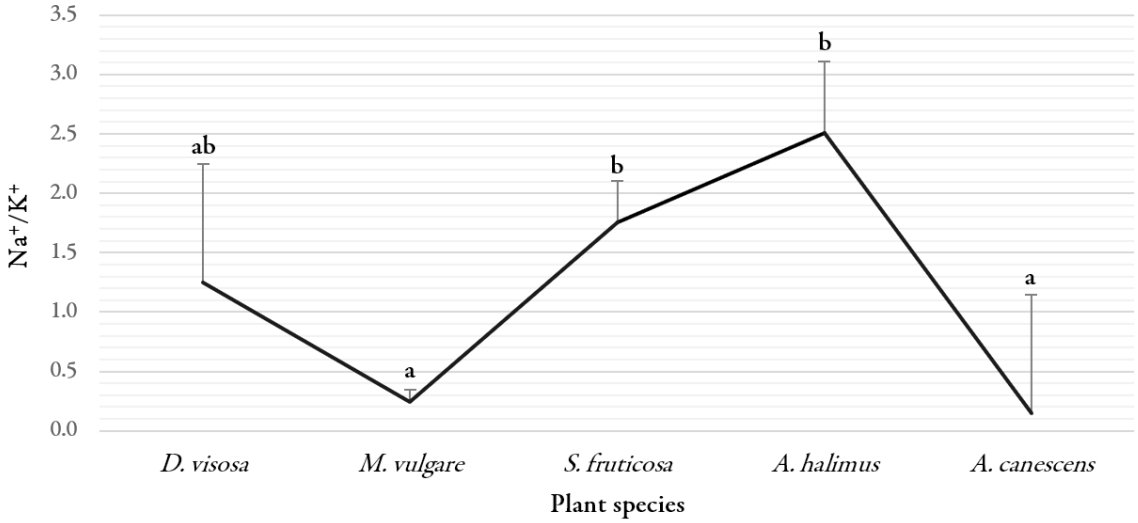


Figure 4. Study of the Na+/K+ ratio in the leaves of the five plant species studied (*Dittrichia viscosa*; *Marrubium vulgare*; *Suaeda fruticosa*; *Atriplex halimus*; *Atriplex canescens*). Different letters show a significant difference according to Tukey's test

Phosphorus content

The results of leaf P levels in the five plant species indicated that *M. vulgare* exhibited significantly higher levels (F=437.30; P<0.000001) than the other species, which exhibited relatively similar levels (Figure 5). Despite the low mycorrhizal colonization observed in Amaranthaceae, they accumulated significant quantities of P in comparison to *D. viscosa*, which exhibited high levels of AMF infection.

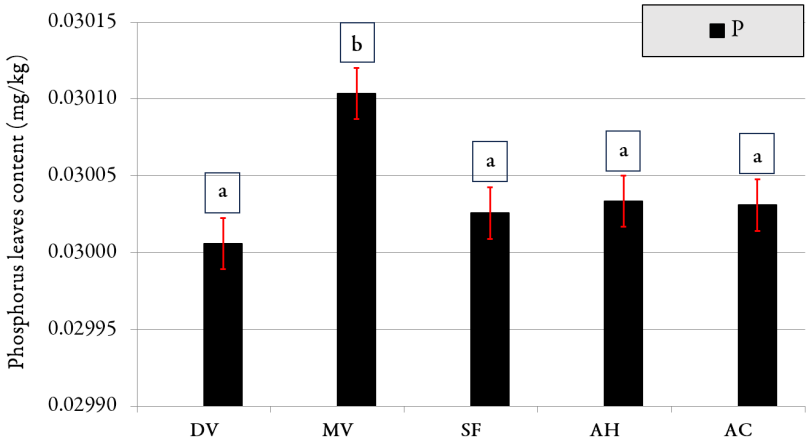


Figure 5. Foliar phosphorus content of wetland species (DV: *Dittrichia viscosa*; MV: *Marrubium vulgare*; SF: *Suaeda fruticosa*; AH: *Atriplex halimus*; AC: *Atriplex canescens*). Different letters show a significant difference according to Tukey's test

Metallic trace element content in the studied plant tissues

The five plant species exhibited no visible symptoms of metal toxicity in situ. The results of trace metal analysis in their leaves (Figure 6) reveal that metal concentrations in plant organs are lower or higher than in adjacent soils (Table 1). We also noted significant variations in leaf concentrations of Cu (9-94.84 ppm), Zn (121.33-156.66 ppm), Pb (12.19-30.94 ppm), Cr (9.27-49.30 ppm), Ni (4.70-15.26 ppm) and Cd (0.55-1.90 ppm).

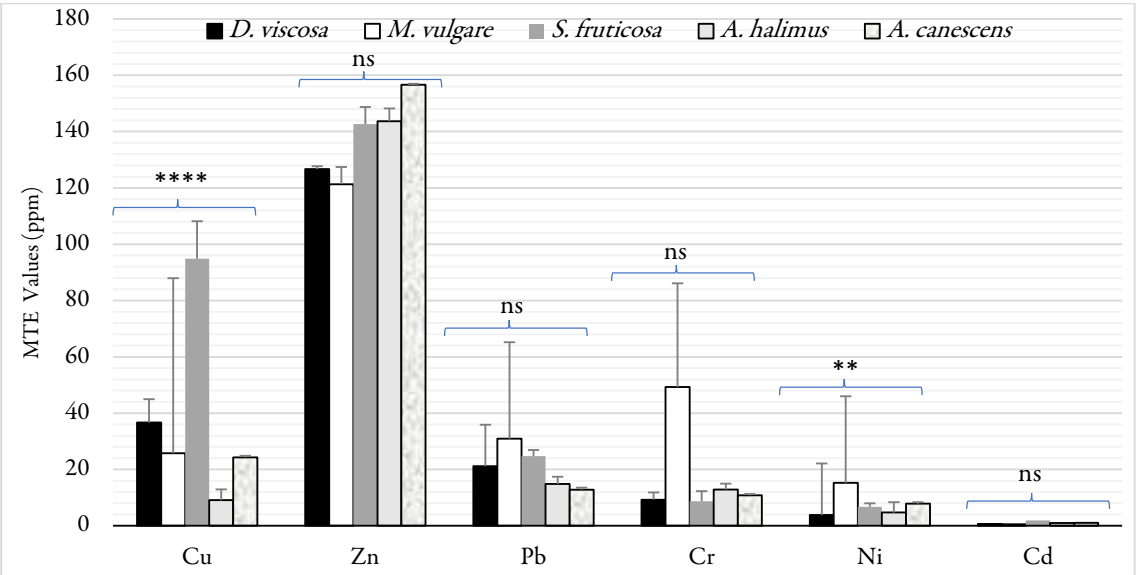


Figure 6. The concentrations of MTE in the leaves of the five plant species (n=3). The results are expressed as the mean ± standard deviation (n = 3). The significance levels are as follows: ns: not significant, **: P < 0.01, ****: P <0.0001

A decreasing accumulation of metals was observed in *S. fruticosa*, *A. canescens*, and *D. viscosa*, particularly in *M. vulgare* leaves, where the order of accumulation was [Zn]>[Cr]>[Pb]>[Cu]>[Ni]>[Cd], and in *A. halimus* leaves, where the order of accumulation was [Zn]>[Pb]>[Cr]>[Cu]>[Ni]>[Cd]. Furthermore, the concentrations of metals did not exceed 1.0 g/kg.

Effect of TME stress on the nutrition of some mineral elements in the plant species surveyed

To elucidate the relationship between minerals and metals accumulated in leaves, we subjected their corresponding values to a Pearson correlation test ($P < 0.05$). The results of this analysis are presented in Table 2. The results indicate that sodium uptake favors Cu and Cd, and P uptake favors Ni and Cr. In contrast, potassium was not correlated with any element. Conversely, mycorrhization rate (F%) was negatively correlated with leaf Na^+ levels ($r = -0.874$; $P = 0.00002$). Leaf P content was weakly correlated with mycorrhization rate ($r = 0.399$; $P = 0.14$).

Table 2. Pearson correlation coefficients between MTEs and some minerals in the surveyed plant species

	Na	K	P	F
Cu	**0.641****	-0.06	-0.16	**-0.49***
Zn	0.28	0.33	-0.27	-0.23
Pb	-0.06	-0.44	0.42	0.212
Cr	-0.38	-0.19	**0.635***	0.408
Ni	-0.35	0.013	**0.821****	0.320
Cd	**0.738****	0.15	0.40	**-0.667****
F	**-0.874****	-0,324	0.399	1
Species	0.34	**0.737****	-0.07	**-0.660****

The significance levels are as follows: ns: not significant, *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$.

Discussion

The present study found that the high foliar sodium content in *S. fruticosa* and *Atriplex halimus* is primarily linked to elevated sodium levels in their rhizospheric soils, characteristic of halophytes' ability to accumulate sodium in their leaves. Concurrently, there is a noted decrease in foliar potassium (K+) content as sodium concentrations (Na+) rise, with plants maintaining stable potassium levels in roots despite saline conditions, indicating a mechanism to manage ion homeostasis. A negative correlation between mycorrhization and Na+ levels was observed, confirming that mycorrhizal associations significantly inhibit the upward translocation of sodium, thereby enhancing phosphorus acquisition. Furthermore, the study revealed that sodium uptake favors the accumulation of heavy metals such as copper (Cu) and cadmium (Cd), while phosphorus uptake is associated with nickel (Ni) and chromium (Cr), yet potassium does not correlate with any heavy metals. The five species assessed, including *A. halimus*, exhibited the capacity to accumulate zinc (Zn) and Cd but were not hyperaccumulators of Cu, lead (Pb), or arsenic (As), as their concentrations remained below 1.0 g/kg. Lastly, a low to moderate mycorrhizal colonization frequency was noted in *S. fruticosa*, alongside the presence of dark septate endophytes (DSE) in *A. canescens*, *A. halimus*, and *D. viscosa*, providing insights into the ecological role of symbiotic fungi in saline environments and their relationship with plant metal uptake dynamics.

Arbuscular mycorrhizal fungi (AMF) are well-documented for their role in enhancing the root surface area by colonizing host plant roots and establishing extensive hyphal networks in the soil (Chandrasekaran, 2022). This increased root architecture improves nutrient uptake, while also limiting the uptake of toxic metals and sodium (Na+). By enhancing phosphorus absorption efficiency, plants can allocate less energy to root growth under stress, optimizing resource distribution (Debeljak *et al.*, 2018).

AMF in plant roots support ion homeostasis, enabling regulation of metal uptake while ensuring adequate nutrient levels, which is particularly critical under salinity stress, where excess Na+ can disrupt cellular function and hinder water uptake (Zhang *et al.*, 2023)Research indicates that AMF may reduce Na+ accumulation in plant tissues through mechanisms such as increased root exudation of organic acids, altering soil pH and facilitating cation exchange (Lu *et al.*, 2020), thereby helping to mitigate Na+ toxicity.

When examining heavy metals like cadmium (Cd) and copper (Cu), AMF play crucial roles in chelation and sequestration processes, enhancing the synthesis of phytochelatins and metallothioneins, which bind to heavy metals, making them less toxic (Zhang *et al.*, 2009; Krishnamoorthy *et al.*, 2019). AMF may also facilitate metal sequestration in vacuoles or root tissues, preventing their accumulation in shoot tissues and thereby protecting the plant from phytotoxicity (Anamika Agarwal *et al.*, 2017).

In addition, AMF colonization is associated with heightened antioxidant enzyme activity in plants facing heavy metal stress. This increased activity of enzymes such as superoxide dismutase, catalase, and peroxidase can alleviate oxidative stress induced by metal toxicity, supporting the negative correlations observed between AMF colonization and metal accumulation (Azizoglu *et al.*, 2025). Through the enhancement of antioxidative defense mechanisms, AMF contribute to reducing oxidative damage, which might otherwise increase metal uptake.

AMF also influence key physiological responses, such as stomatal conductance, which affects transpiration and nutrient uptake efficiency. Under metal and salt stress, they can induce changes in leaf turgor and osmotic regulation, fostering better water retention and nutrient assimilation (Wu *et al.*, 2020). These physiological adjustments help lower metal influx and improve P acquisition, thus alleviating the stress-induced negative impacts on plant growth.

The observation that the level of phosphorus in plants is not correlated with mycorrhizal frequency highlights the nuanced role of photosynthetic pathways in nutrient acquisition and plant resilience, particularly in species such as *A. halimus* and *A. canescens*, which utilize the C4 pathway. These C4 species demonstrate a remarkable ability to maintain effective mineral nutrition under stressful conditions, underscoring their evolutionary adaptation that allows for greater efficiency in phosphorus utilization independent of mycorrhizal associations (Chandrasekaran *et al.*, 2019). This contrasts with C3 plants, which often rely heavily on mycorrhizal fungi for optimal nutrient uptake, indicating a fundamental difference in nutrient strategies between these two groups (Frew, 2019).

Additionally, some studies suggest that the elevated sodium content in the leaves of S. fruticosa might stem from halophytes' ability to accumulate sodium in their aerial portions while reducing potassium uptake as evidenced in various species, including *S. fruticosa* and *A. halimus* (Grouzis *et al.*, 1977; Sleimi *et al.*, 1999; Barakat *et al.*, 2014; Sleimi, 2018). Notably, *A. canescens* maintains a high potassium content in its leaves, which is crucial for controlling K^+/Na^+ selectivity to limit Na^+ rises and ensure adequate K^+ supply to aerial organs (Aouissat *et al.*, 2011; Pan *et al.*, 2016). Studies also indicate that potassium plays a pivotal role as an osmoticum, which enhances a plant's water status crucial for adapting to salt stress (Peng *et al.*, 2016).

Our findings show that the potassium levels in the leaf tissues of M. vulgare and D. viscosa were slightly higher than sodium, confirming findings from Al Hassan *et al.* (2016), where low NaCl concentrations were observed in *D. viscosa*. This potassium involvement extends to enzyme activation and the regulation of water and solute transport in plant tissues.

Moreover, mycorrhization significantly inhibits Na^+ translocation to aerial parts, promoting phosphorus acquisition through a connection to the total surface area of fine roots. *A. canescens*, with its extensive horizontally oriented root system, exemplifies this high phosphorus content in its roots (Lanfranco *et al.*, 2018). Although soil salinity significantly hampers phosphorus uptake—due to phosphate ions precipitating with other cations—AMF can enhance phosphorus absorption, mitigate the adverse effects of sodium and chloride ions, and maintain vacuolar membrane integrity (Shokri and Maadi, 2009).

Macroelements like potassium, sodium, and phosphorus, along with microelements including copper, zinc, and nickel, are fundamental for plant growth. Notably, nickel competes with similar nutrients during uptake (Mateos-Naranjo *et al.*, 2013; Nikalje and Suprasanna, 2018). Nonetheless, despite potential interferences from heavy metals like cadmium affecting mineral nutrition (Dong *et al.*, 2006), the observed results indicate that mineral nutrition is largely unaffected by these elements, affirming the phytoaccumulation potential of the studied species.

Finally, while the concentrations of Cu, Pb, As, and Zn did not exceed 1.0 g/kg, implying these species are not hyperaccumulators (Baker *et al.*, 1989), differences in metal accumulation exist among species, with high Zn and lower Cd accumulation observed. Considering zinc's role as a crucial micronutrient in plant metabolism (Kaur and Garg, 2021), ongoing research into the effectiveness of these species, in conjunction with AMF presence, could provide insights into their adaptive mechanisms to environmental stressors. Consistent with Morillo *et al.* (2004) and Chaudhry *et al.* (2005), our findings indicate low to moderate mycorrhizal frequency in *S. fruticosa*, with some studies reporting significantly higher frequencies under different conditions (Macia-Vicente *et al.* 2012; Mathur *et al.*, 2005). Additionally, dark septate endophytes were identified in the roots of *A. canescens*, *A. halimus*, and *D. viscosa*, supporting the potential role of AMF in enhancing phosphorus solubilization (Barrow and Osuna, 2002).

Conclusions

In conclusion, the research highlights the pivotal role of halophytic and halotolerant plant species in mitigating the adverse effects of saline and contaminated wetland soils. The moderate alkalinity and varying salinity levels of their rhizospheric soils, coupled with the presence of elevated trace metals, underscore the resilience and adaptive mechanisms of studied plants. Their ability to accumulate significant concentrations of heavy metals such as cadmium, lead, and copper positions them as valuable candidates for phytoextraction and phytodesalination strategies, which could facilitate the rehabilitation of polluted agricultural lands. Furthermore, the intriguing interplay between sodium accumulation and metal uptake, along with the beneficial effects of mycorrhization in regulating nutrient absorption, opens new avenues for enhancing the resilience of these species in challenging environments. Future research focused on the propagation of these species in greenhouse settings, combined with the investigation of their mycosymbionts, could unveil innovative approaches to effective phytoremediation and the sustainable management of saline and heavy metal-laden soils. Thus, these findings not only deepen our understanding of plant-soil interactions in extreme environments but also contribute valuable insights toward developing ecological solutions for soil remediation.

These findings significantly enhance our understanding of plant-soil interactions in extreme environments and provide valuable insights for developing ecological solutions for soil remediation; however, future research should include controlled experiments to isolate the effects of selected species on phytoremediation outcomes and explore the interactions and impacts of other soil microorganisms that play a vital role in soil health and plant dynamics. Additionally, acknowledging the limitations of our study in regard to seasonal variations underscores the need for longitudinal studies to capture fluctuations in plant growth and microbial activity over time, thereby enabling a more accurate evaluation of ecological responses and the effectiveness of the studied species in phytoremediation.

Authors' Contributions

Conceptualization: W.S., and Z.F. Methodology: W.S., Formal analysis: W.S., Writing original draft preparation: W.S., C.A. Writing review and editing W.S., C.A. and Z.F. Supervision: W.S. All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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