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Arbuscular mycorrhizal fungi enhance nutrient uptake and ionic balance in *Ricinus communis* under saline stress

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Soil salinity is a major constraint on agricultural productivity, particularly for *Ricinus communis* L., an economically important oilseed crop sensitive to salt stress. This study evaluated the effects of arbuscular mycorrhizal fungi (AMF) on nutrient uptake and salt tolerance in two *R. communis* accessions under 0, 50, and 100 mM NaCl. Five *Glomus* species and a mixed inoculum were tested in a greenhouse experiment using a factorial design with 504 plants. Mycorrhizal colonization, phosphorus (P), potassium (K^+), and sodium (Na^+) contents, and K^+/Na^+ selectivity were assessed. Salinity reduced colonization, but *Glomus fasciculatum* and the mixed inoculum maintained 5 to 20% colonization at 100 mM NaCl. AMF significantly enhanced P and K^+ uptake while reducing Na^+ accumulation, particularly in accession 1. *G. fasciculatum* increased leaf P by up to 36.63 mg/g and root K^+ by 4.45 mg/g under saline conditions. Genotype-specific responses highlight the need for tailored AMF inoculants. These findings demonstrate AMF's potential to mitigate salinity stress in *R. communis*, offering a sustainable strategy for cultivation in saline regions. Future field trials and molecular studies are recommended to optimize AMF applications.

Key words: Genotypic variation, mycorrhizal colonization, phosphorus uptake, potassium selectivity, sodium exclusion, sustainable agriculture.

INTRODUCTION

Soil salinity is a major abiotic stress that affects agricultural productivity, particularly in arid and semi-arid regions, impacting over one billion hectares worldwide (Corwin, 2021). The expansion of salinized lands, estimated at 1 to 2 million ha annually, is largely driven by inappropriate irrigation practices, excessive fertilization, and intensive land use (Haj-Amor et al., 2021; Beltran-Peña et al., 2020; Wu et al., 2020). Salinity reduces soil osmotic potential, disrupts nutrient uptake, particularly potassium (K^+) and calcium (Ca^{2+}), and promotes toxic sodium (Na^+) accumulation, leading to growth inhibition and cellular damage in plants (Adejumobi et al., 2016; Zheng et al., 2021). Arbuscular mycorrhizal fungi (AMF), a group of obligate symbionts, form associations with plant roots and are known to enhance host plant tolerance to salinity by improving mineral nutrition, maintaining ionic balance, and supporting physiological resilience (Evelin et al., 2022;

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Zhang et al., 2023). In saline environments, AMF can enhance phosphorus (P) and K^+ uptake while minimizing Na^+ accumulation in host plants (Floc'h et al., 2022). These benefits are well documented in several crops, including maize, tomato, and soybean (Balliu et al., 2015; Rahman et al., 2019). However, limited studies have focused on the role of AMF in *Ricinus communis* L., a non-food industrial crop valued for its oil, which is used in biofuels, pharmaceuticals, and lubricants. In 2019, global seed production reached approximately 1.4 million tons (Food and Agriculture Organization [FAO], 2020). Although *R. communis* L. has demonstrated potential for adaptation under stress conditions, including salinity and drought, its physiological and nutritional responses in association with AMF are still not fully understood. Previous studies have shown that AMF can enhance the growth and physiological performance of *R. communis* by improving photosynthetic activity and pigment content under drought and salt stress (Zhang et al., 2018). Other studies have reported that AMF inoculation, either alone or in combination with other beneficial microbes, can enhance nutrient uptake and rhizosphere enzymatic activity under salinity conditions (Zhang et al., 2014). Moreover, the species has been highlighted as a suitable candidate for phytoremediation due to its physiological flexibility and responsiveness to microbial symbionts (Kiran and Prasad, 2017). However, there remains limited research specifically addressing how AMF influences mineral nutrition (P, K^+, Na^+), ion selectivity (K^+/Na^+ ratio), and symbiotic efficiency across different *R. communis* genotypes under saline stress. This study aims to fill this gap by evaluating the effects of five AMF species and a mixed inoculum on nutrient uptake and ionic balance in two genetically distinct *R. communis* accessions exposed to varying salinity levels. By analyzing genotype-specific responses, this work provides new insights into AMF-mediated mechanisms of salt tolerance and contributes to the development of sustainable strategies for saline agriculture.

MATERIALS AND METHODS

Plant material

Seeds of *R. communis* L. accessions 1 and 7, selected for salt tolerance via *in vitro* screening (Diallo et al., 2015), were collected from the Niayes zone, Dakar, Senegal, and stored in the gene bank of the In Vitro Culture Research Unit, Senegalese Institute of Agricultural Research (ISRA). Table 1 shows the details of the castor bean (*R. communis*) accession numbers from the gene bank of the Unité de Recherche en Culture In Vitro (URCI). These accessions were selected based on prior *in vitro* salinity screening (Diallo et al., 2016).

Fungal material

Five species of AMF from the genus *Glomus* were obtained from the Laboratoire Commun de Microbiologie (LCM), Institut de Recherche pour le Développement [IRD]/Institut Sénégalais de Recherches Agricoles [ISRA]/Université Cheikh Anta Diop de Dakar [UCAD], Dakar, Senegal. These included *Glomus aggregatum*, *Glomus fasciculatum*, *Glomus intraradices*, *Glomus mosseae*, and *Glomus verriculosum*, along with a mixed inoculum comprising equal proportions of all five strains. Details of origin, references, and accession numbers are shown in Table 2.

Experimental design and growing conditions

The experiment was conducted in a controlled greenhouse at ISRA-Bel Air (Dakar, Senegal) using a completely randomized factorial design. The three factors tested were: (i) AMF treatment (control + six AMF inoculations: *G. aggregatum* (Ga), *G. fasciculatum* (Gf), *G. intraradices* (Gi), *G. mosseae* (Gmo), *G. verriculosum* (Gv), mixed inoculum of all five strains (Gssp), (ii) Accession (acc1 and acc7), and (iii) Salinity levels (0, 50, and 100 mM NaCl).

Each of the 42 treatment combinations had 12 replicates, totaling 504 plants. Seeds were surface-sterilized using 1% NaOCl for 5 min, rinsed thoroughly, and germinated on water agar in sterile jars. After five days, seedlings were transferred to sterile tubes with ¼-strength Murashige and Skoog (MS) medium (Murashige and Skoog, 1962) for 15 days to acclimate. Plants were then transplanted into 30 cm × 20 cm plastic pots containing 3 kg of autoclaved sandy soil, characterized by low organic matter (Table 3). AMF inoculant (10 g per pot) was applied directly into planting holes at the time of transplanting. Soil salinity treatments were applied weekly using NaCl solutions of the specified concentrations. Environmental conditions were maintained at 25 ± 2°C during the day, 20 ± 2°C at night, with 60 ± 5% relative humidity and a 14 h photoperiod (400 µmol m^{-2} s^{-1}).

Mycorrhizal colonization assessment

At 20 days after transplanting, root systems were carefully harvested and washed. Subsamples were cut into 1 cm segments and subjected to clearing in 10% KOH at 90°C for 30 min, followed by acidification in 1% HCl, and staining with 0.05% trypan blue in lactophenol (Phillips and Hayman, 1970). Mycorrhizal colonization frequency and intensity were quantified under a light microscope using the Trouvelot method (Trouvelot et al., 1986), as recommended.

Mineral nutrient analysis

Nutrient concentrations were analyzed at the Central Analysis Laboratory, ISRA/Bambey, Senegal. Leaf and root tissues were collected separately from each plant at the flowering stage (90 to 100 days after transplanting). The samples were rinsed, oven-dried at 70°C for 48 h, ground to a fine powder, and stored in airtight containers. P was determined using the molybdate blue method (Olsen and Dean, 1965). K^+ and Na^+ were quantified using atomic absorption spectrophotometry (AAS BK-AA320N) at 766 and 589 nm, respectively (Wolf, 1982). The K^+/Na^+ selectivity ratio was calculated as per Jeschke (1983):

$$R = \frac{K^+ content}{Na^+ content}$$

Statistical analysis

All data were subjected to three-way ANOVA using XLSTAT (version 2023) to assess effects of AMF inoculum, accession, and

Table 1. Origin and metadata of *R. communis* accessions.

Accession number	Collection date	Collection location	Coordinates	Notes
acc1 acc7	April 2007	Hann-Maristes, Petites Niayes, Dakar, Senegal	14°44'12" N, 17°25'57" W	Collected from natural castor bean populations. Specific genetic or phenotypic traits are not provided. Stored in URCI/LNRPV gene bank.

Table 2. Origin and references of *Glomus* species.

Species	Origin	Reference	Accession	Abbreviation
G. aggregatum	Djignaki, Senegal	Diop et al. (1994)	DAOM 227128	Ga
G. fasciculatum	Louga, Senegal	Diop et al. (1994)	DAOM 227130	Gf
G. intraradices	Ottawa, Canada	Agricultural Herbarium	DAOM 227133	Gi
G. mosseae	Diokoul, Senegal	Diop et al. (1994)	DAOM 227131	Gmo
G. verriculosum	Kabrousse, Senegal	Diop et al. (1994)	DAOM 227132	Gv

salinity, with repeated measures for temporal data. Normality was verified using the Shapiro-Wilk test, and log transformations were applied where necessary. Means were separated using the Tukey test ($P < 0.05$). Effect sizes (eta-squared) were calculated to evaluate treatment impacts.

RESULTS

Mycorrhizal colonization under saline conditions

Salinity significantly affected root colonization by AMF in both *R. communis* accessions ($P < 0.05$). Colonization rates declined as salinity increased, with pronounced differences among AMF species (Figures 1 to 2). Under non-saline conditions (0 mM NaCl), the mixed inoculum achieved the highest colonization rates (40% in accession 1, 24% in accession 7), followed by *G. intraradices* (34 and 14%) and *G. fasciculatum* (24 and 19%). At 50 mM NaCl, colonization moderately declined, with the mixed inoculum maintaining 15 to 20% colonization. At 100 mM NaCl, colonization dropped sharply; however, *G. fasciculatum* and *G. intraradices* still exhibited low but detectable colonization (5 to 10%). Accession 1 generally exhibited higher colonization rates than accession 7 across treatments, indicating potential genotypic variation in AMF compatibility. Microscopic examination confirmed the presence of typical mycorrhizal structures, including hyphae, arbuscules, and vesicles (Figure 3), supporting effective root colonization under all AMF treatments.

Phosphorus uptake

AMF inoculation significantly enhanced P uptake in both accessions under all salinity levels ($P < 0.05$). Under non-saline conditions (0 mM NaCl), the mixed inoculum and *G. intraradices* produced the highest P content in leaves (up to 36.63 mg/g in accession 1 and 36.60 mg/g in accession 7), compared to non-inoculated controls (18.70 mg/g and 23.12 mg/g, respectively) (Table 4). At 50 mM NaCl, P content decreased in all treatments, but AMF-inoculated plants, particularly those with *G. fasciculatum* or the mixed inoculum, maintained significantly higher levels than controls (Table 5). Even at 100 mM NaCl, P content remained above 15 mg/g in inoculated plants, while dropping below 10 mg/g in controls (Table 6).

Potassium and sodium dynamics under salt stress

AMF inoculation modulated K^+ and Na^+ uptake, improving ionic balance under saline conditions (Tables 4 to 6). At 50 mM NaCl, *G. fasciculatum* increased leaf Na^+ in Accession 1 (24.36 mg/g vs. 10.86 mg/g control) but reduced root Na^+ (0.228 mg/g vs. 0.40 mg/g; Table 5). The mixed inoculum enhanced root K^+ (4.34 mg/g in accession 1, 3.06 mg/g in accession 7) and reduced root Na^+ (0.29 and 0.20 mg/g). Gf and Gssp treatments showed significantly higher K^+ in roots and leaves, with a

Table 3. Physico-chemical characteristics of the soil substrate.

Component	Content (per 100 g soil)
Fine sand	66.5%
Coarse sand	24.5%
Fine silt	1.8%
Coarse silt	2.0%
Clay	5.2%
Organic matter	0.62%
Total carbon	0.36%
Total nitrogen	0.44%
C/N ratio	8.18
Assimilable phosphorus	39.55 ppm
pH (soil/water 1:2)	8.20

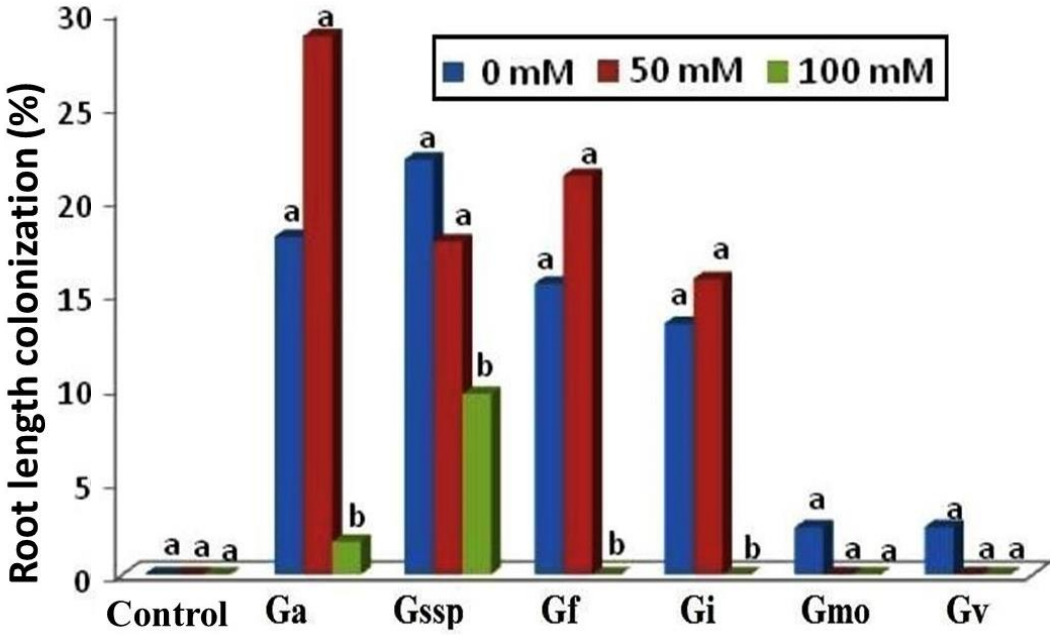

Figure 1. Mycorrhizal colonization (%) in *R. communis* accession 1 under 0, 50, and 100 mM NaCl with six AMF treatments. Bars represent means ± SE (n=12). Different letters indicate significant differences (Tukey, P < 0.05). Ga: *G. aggregatum*, Gf: *G. fasciculatum*, Gi: *G. intraradices*, Gmo: *G. mosseae*, Gv: *G. verriculosum*, Gssp: mixed inoculum of all five strains.

reduction in root Na^+ to as low as 0.20 mg/g in accession 7 (Table 5). In accession 7, *G. fasciculatum* and *G. intraradices* increased leaf K^+ (15.27 mg/g and 14.22 mg/g vs. 10.17 mg/g control). At 100 mM NaCl, *G. fasciculatum* raised leaf Na^+ in accession 1 (11.10 mg/g vs. 7.22 mg/g control) but boosted root K^+ (3.98 mg/g; Table 6). The mixed inoculum reduced root Na^+ (0.182 mg/g in accession 1, 0.24 mg/g in accession 7) and increased root K^+ (4.45 and 4.08 mg/g). Accession 7 showed higher leaf K^+ with *G. intraradices* (8.60 mg/g vs. 6.52 mg/g control).

K^+/Na^+ selectivity ratio

AMF treatments improved K^+/Na^+ selectivity ratios, particularly under saline conditions (Table 7). In accession 1 leaves under non-saline conditions, *G. intraradices* maintained the highest ratio (58.8) under non-saline conditions, followed by *G. fasciculatum* (44.4). At 50 mM NaCl, *G. fasciculatum* and the mixed inoculum maintained higher ratios (18.9 and 17.9) compared to the control (8.5). In Accession 7 roots, *G. intraradices* showed a ratio of 35.7 without salt stress, while the mixed

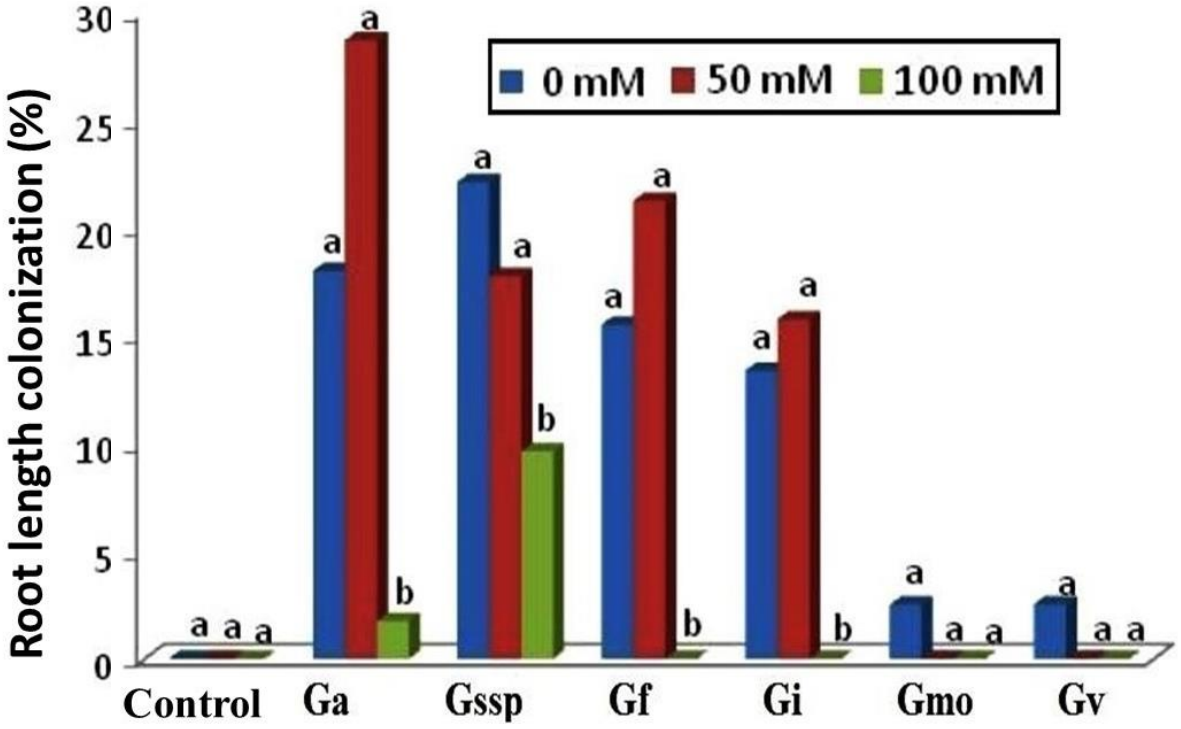

Figure 2. Mycorrhizal colonization (%) in *R. communis accession 7 under 0, 50, and 100* mM NaCl with six AMF treatments. Bars represent means ± SE (n=12). Different letters indicate significant differences (Tukey, $P < 0.05$). Ga: *G. aggregatum*, Gf: *G. fasciculatum*, Gi: *G. intraradices*, Gmo: *G. mosseae*, Gv: *G. verriculosum*, and Gssp: mixed inoculum of all five strains.

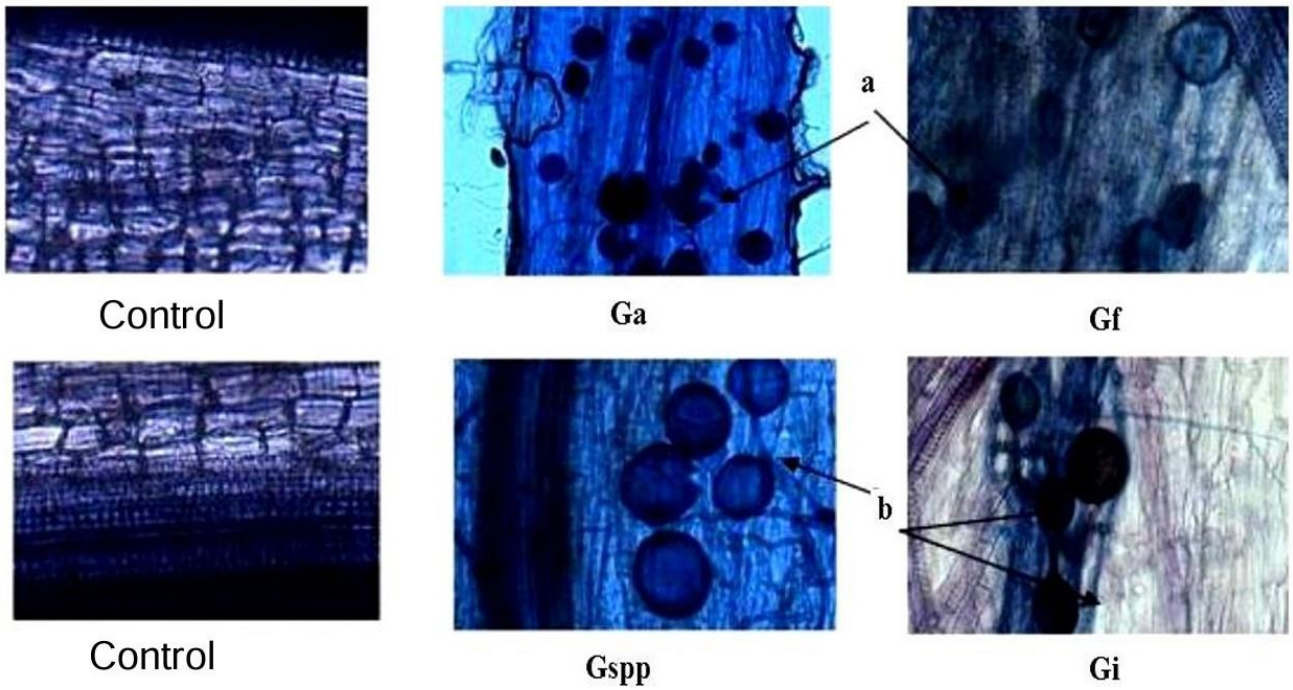

Figure 3. Microscopic structures of arbuscular mycorrhizal fungi observed in Ricinus communis roots accession 1 in the absence of NaCl (A) and in the presence of 50 mM NaCl: a) vesicle and (b) hypha. Roots were stained with trypan blue and observed under light microscopy (400× magnification). Control: non-inoculated, Ga: *G. aggregatum*, Gf: *G. fasciculatum*, Gspp: strain cocktail, and Gi: *G. intraradices*.

Table 4. Mineral content (mg/g dry matter) in *R. communis* under AMF treatments without salt stress.

Accession	Mineral	Control	Ga	Gssp	Gf	Gi	Gmo	Gv
Acc 1	P	18.70d*	19.10^{d}	36.63^{a}	31.51^{c}	33.69^{bc}	17.29^{d}	34.36^{b}
	Na^+	0.30^{a}	0.26^{a}	0.25^{a}	0.20^{a}	0.27^{a}	0.31^{a}	0.28^{a}
	K^+	7.86^{d}	8.70^{d}	10.01^{c}	11.10^{ab}	11.75^{a}	8.15^{d}	8.01^{d}
Acc 7	P	23.12^{e}	26.02^{cd}	29.10^{bc}	28.88^{c}	36.60^{a}	24.04^{d}	31.80^{b}
	Na^+	0.26^{a}	0.31^{a}	0.30^{a}	0.32^{a}	0.34^{a}	0.29^{a}	0.25^{a}
	K^+	7.70^{d}	7.15^{e}	8.70^{c}	9.35^{bc}	11.43^{a}	6.20^{f}	7.97^{d}

*Different lowercase letters indicate significant differences (Tukey, P < 0.05). Ga: *G. aggregatum,* Gf: *G. fasciculatum,* Gi*: G. intraradices,* Gmo*: G. mosseae,* Gv: *G. verriculosum*, and Gssp: mixed inoculum of all five strains.

Table 5. Mineral content (mg/g dry matter) in *R. communis* under AMF treatments at 50 mM NaCl.

Tissue	Accession	Mineral	Control	Ga	Gssp	Gf	Gi	Gmo	Gv
Leaves	Acc 1	P	12.50^{d}*	15.20^{c}	22.10^{a}	20.30^{b}	18.40^{bc}	11.80^{d}	17.60^{c}
		Na^+	10.86^{f}	16.88^{e}	22.24^{ab}	24.36^{a}	21.72^{c}	17.96^{e}	20.20^{de}
		K^+	2.16^{ab}	2.05^{bc}	1.11^{e}	1.02^{e}	1.05^{e}	2.34^{a}	1.33^{d}
	Acc 7	P	14.20^{e}	16.50^{d}	20.80^{b}	19.40^{c}	22.10^{a}	13.90^{e}	18.30^{c}
		Na^+	1.65^{a}	1.55^{a}	0.82^{c}	0.70^{d}	1.13^{b}	1.90^{a}	1.45^{a}
		K^+	10.17^{de}	12.45^{c}	15.27^{a}	14.22^{ab}	12.03^{c}	10.50^{de}	11.00^{d}
Roots	Acc 1	Na^+	0.40^{a}	0.35^{a}	0.29^{ab}	0.23^{b}	0.25^{ab}	0.375^{a}	0.27^{ab}
		K^+	2.32^{d}	3.22^{bc}	4.34^{a}	3.52^{b}	3.13^{bc}	2.37^{d}	3.32^{bc}
	Acc 7	Na^+	0.472^{a}	0.403^{a}	0.20^{d}	0.342^{b}	0.34^{b}	0.438^{a}	0.289^{c}
		K^+	2.23^{c}	2.12^{c}	3.06^{b}	4.33^{a}	4.15^{a}	2.21^{c}	3.01^{b}

*Different lowercase letters indicate significant differences (Tukey, P < 0.05). Ga: *G. aggregatum,* Gf: *G. fasciculatum,* Gi*: G. intraradices,* Gmo*: G. mosseae,* Gv: *G. verriculosum*, and Gssp: mixed inoculum of all five strains.

Table 6. Mineral content (mg/g dry matter) in *R. communis* under AMF treatments at 100 mM NaCl.

Tissue	Accession	Mineral	Control	Ga	Mixed	Gf	Gi	Gmo	Gv
Leaves	Acc 1	P	8.20^{d}	10.50^{c}	15.30^{a}	14.10^{b}	12.80^{bc}	7.90^{d}	11.40^{c}
		Na^+	7.22^{e}	8.42^{cd}	10.11^{b}	11.10^{a}	9.87^{b}	8.25^{cd}	8.00^{d}
		K^+	1.87^{a}	1.75^{a}	1.00^{d}	1.10^{cd}	1.25^{c}	1.89^{a}	1.44^{b}
	Acc 7	P	9.10^{e}*	11.20^{d}	14.50^{b}	13.80^{c}	**15.60^{a}**	9.50^{e}	12.70^{c}
		Na^+	1.80^{a}	1.95^{a}	1.30^{b}	1.22^{c}	1.20^{cd}	1.45^{b}	1.20^{cd}
		K^+	6.52^{c}	7.10^{bc}	8.35^{ab}	8.08^{b}	8.60^{a}	7.00^{bc}	6.86^{c}
Roots	Acc 1	Na^+	0.25^{a}	0.179^{c}	0.182^{c}	0.318^{a}	0.207^{b}	0.24^{a}	0.22^{b}
		K^+	2.36^{c}	4.02^{a}	4.45^{a}	3.98^{a}	4.05^{a}	3.17^{b}	3.23^{b}
	Acc 7	Na^+	0.41^{a}	0.34^{b}	0.24^{c}	0.25^{c}	0.27^{b}	0.38^{b}	0.31^{b}
		K^+	2.36^{c}	3.14^{b}	4.08^{a}	4.03^{a}	4.08^{a}	3.20^{b}	3.08^{b}

*Different lowercase letters indicate significant differences (Tukey, P < 0.05). Ga: *G. aggregatum,* Gf: *G. fasciculatum,* Gi*: G. intraradices,* Gmo*: G. mosseae,* Gv: *G. verriculosum*, and Gssp: mixed inoculum of all five strains.

Table 7. K^+/Na^+ selectivity ratios in *R. communis* under AMF treatments and saline conditions.

Accession	Tissue	Treatment	Control	Ga	Gssp	Gf	Gi	Gmo	Gv
Acc 1	Leaves	0 mM NaCl	26.2*	34.8	38.5	44.4	58.8	30.2	24.3
		50 mM NaCl	8.5	13.4	17.9	18.9	15.7	14.0	17.7
Acc 7	Roots	0 mM NaCl	27.5	27.5	28.1	27.5	35.7	17.7	27.5
		50 mM NaCl	7.1	11.9	24.5	21.6	14.5	8.5	16.7

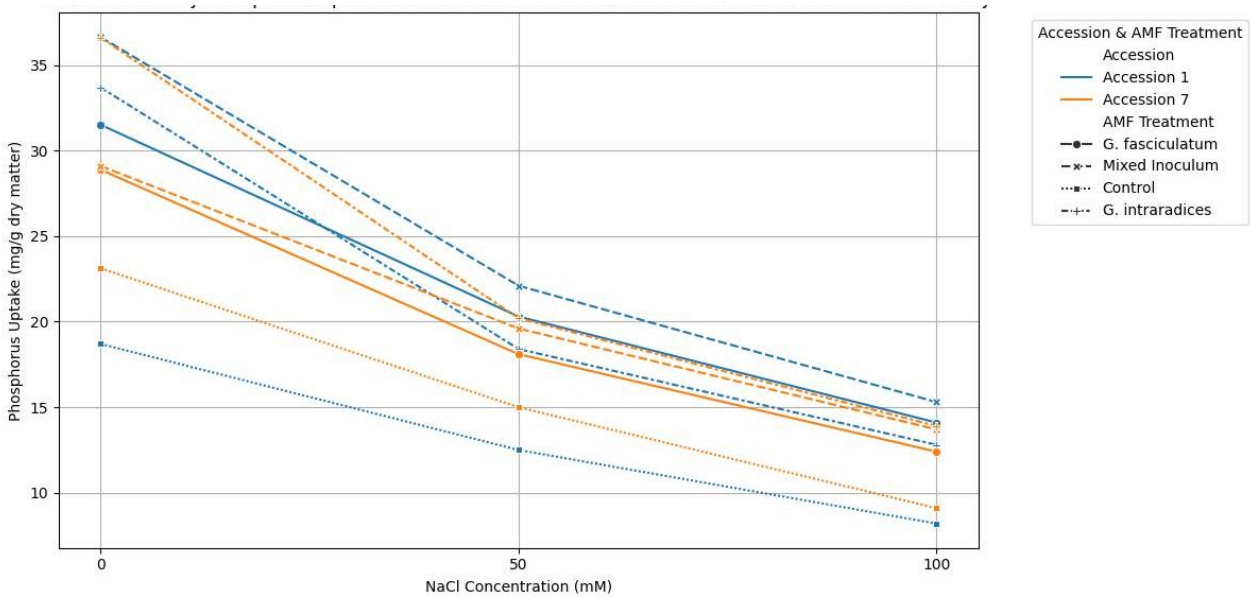

Figure 4. Summary of phosphorus uptake (mg/g dry matter) in *R. communis* accessions under varying salinity and AMF treatments. Data represent mean values from both leaf and root measurements. Gssp: mixed inoculum, *Gf: G. fasciculatum* and *Gi: G. intraradices.*

inoculum and *G. fasciculatum* achieved 24.5 and 21.6 at 50 mM NaCl (vs. 7.1 control). Values represent ratios calculated as:

$$R = \frac{K^+ content}{Na^+ content}$$

Genotypic variations

Accession 1 showed stronger overall responses to *G. fasciculatum* and Gssp, with higher colonization, P and K^+ uptake, and selectivity ratios. In contrast, accession 7 responded more favorably to *G. intraradices*, particularly under high salinity.

Overall response of accessions to AMF treatments

To provide a comprehensive comparison, Figure 4 shows the overall P uptake patterns in both *R. communis* accessions across AMF treatments and salinity levels. Accession 1 showed consistently higher uptake, particularly when inoculated with *G. fasciculatum* and the mixed AMF formulation. These treatments maintained superior P uptake even at 100 mM NaCl, whereas non-inoculated plants suffered substantial declines.

DISCUSSION

This study highlights the significant role of AMF in enhancing nutrient uptake and ionic homeostasis in *R. communis* under saline stress, with variations influenced by AMF strains and plant genotypes. These findings underscore the potential of AMF as bioinoculants for improving crop resilience in salt-affected environments, particularly in sustainable agricultural systems.

AMF colonization under saline conditions

Salinity generally reduces AMF colonization due to

osmotic stress and ionic toxicity, which impair spore germination and hyphal growth (Klinsukon et al., 2021; Evelin et al., 2022). Certain AMF strains, however, maintain colonization under high salinity, likely due to adaptive traits such as enhanced spore viability or hyphal plasticity (Boorboori and Lackóová, 2025). The observed differences in colonization between *R. communis* accessions suggest genotype-specific compatibility with AMF, potentially driven by variations in root exudates or architecture that influence fungal recruitment (Diatta, 2014; Manga, 2022). These findings emphasize the importance of selecting salt-tolerant AMF strains and compatible host genotypes to optimize symbiosis in saline conditions.

Enhanced nutrient uptake and ion homeostasis

AMF significantly enhances P and K^+ uptake while reducing Na^+ accumulation, mitigating salinity-induced nutrient deficiencies and ionic imbalances. The improved P uptake likely results from AMF hyphae extending beyond the root depletion zone, increasing access to immobile P ions and upregulating phosphate transporter genes (Jia et al., 2019; Smith and Read, 2008). This supports critical physiological processes like ATP synthesis and membrane stability under stress (Zhang et al., 2023). Enhanced K^+ uptake, particularly in roots, suggests AMF-induced activation of K^+ transporters, which maintain turgor and stomatal function (Wang et al., 2022; Evelin et al., 2019). Reduced Na^+ accumulation indicates AMF-mediated regulation of ion transporters, such as SOS1 and NHX1, which exclude or compartmentalize Na^+ to reduce toxicity (Diao et al., 2021; Porcel et al., 2012). Improved K^+/Na^+ selectivity ratios further highlight AMF's role in ion discrimination, sustaining K^+-dependent processes under salinity (Abbaspour et al., 2021).

Genotypic variations in AMF responsiveness

The differential responses of *R. communis* accessions to AMF strains underscore the influence of plant genotype on symbiotic efficiency. Some accessions exhibit stronger compatibility with specific AMF, likely due to variations in root exudate composition or ion transporter gene expression (Chen et al., 2022; Tisarum et al., 2020). These genotypic differences suggest that matching AMF strains with specific plant genotypes can optimize nutrient uptake and stress tolerance, a critical consideration for crop improvement in saline environments.

Proposed mechanisms of AMF-mediated salinity tolerance

Although molecular data were not collected in this study, several mechanisms likely contribute to the salinity tolerance conferred by AMF in *R. communis*. The extraradical hyphae of AMF extend beyond the root depletion zone, significantly enhancing the plant's access to P and K^+, thereby improving nutrient acquisition under saline stress (Smith and Read, 2008). Additionally, AMF may regulate ion transport by upregulating genes such as HKT1 and SOS1, which promote K^+ retention while facilitating sodium exclusion, mitigating ionic toxicity (Abbaspour et al., 2021; Porcel et al., 2012). Osmotic adjustment is likely supported by AMF-induced accumulation of osmoprotectants, such as proline and soluble sugars, which aid in water retention under high salinity (Evelin et al., 2022; Talaat and Shawky, 2014). Furthermore, AMF may bolster antioxidant defenses by enhancing the activity of enzymes like superoxide dismutase, reducing oxidative stress caused by salinity-induced reactive oxygen species (Chang et al., 2018). These interconnected mechanisms collectively underpin the enhanced resilience of AMF-inoculated plants in saline environments.

Agronomic implications and future directions

The ability of certain AMF strains to maintain colonization and enhance nutrient uptake under salinity highlights their potential as bioinoculants for *R. communis* in salt-affected soils, such as Senegal's Niayes region. These findings align with efforts to develop sustainable agriculture by reducing reliance on chemical fertilizers and enhancing crop resilience to climate-induced stresses (Zhang et al., 2023; Floc'h et al., 2022). Genotypic variation emphasizes the need to select compatible plant–AMF combinations to maximize benefits, particularly for castor bean accessions from the URCI/LNRPV gene bank (e.g., acc1, acc3, acc4, acc7), which could support bioenergy production and stress resilience.

Future research should employ transcriptomic and metabolomic analyses to confirm the roles of ion transporters (e.g., HKT1, NHX1) and osmoprotectants (e.g., proline, sugars) in AMF-mediated salinity tolerance. Field trials are essential to validate these findings under real-world conditions, focusing on high-performing AMF strains and genotypes. Such studies could enhance the application of AMF in saline agriculture, supporting sustainable crop production and bioenergy systems.

Conclusion

This study demonstrates that AMF, particularly *G. fasciculatum* and a mixed inoculum, significantly enhance *R. communis* L. tolerance to salinity by improving P and K^+ uptake, reducing sodium accumulation, and maintaining higher K^+/Na^+ selectivity ratios. These findings highlight AMF's potential as a sustainable tool to

mitigate salinity stress in an economically important crop, addressing a critical challenge in arid and semi-arid regions. The genotype-specific responses of *R. communis* accessions underscore the importance of tailoring AMF inoculants to optimize benefits. Future research should focus on field-scale trials, transcriptomic analyses of ion transport mechanisms, and the development of commercial AMF inoculants to translate these findings into practical solutions for saline agriculture. By enhancing crop resilience and reducing reliance on chemical fertilizers, AMF inoculation offers a promising strategy for sustainable *Ricinus communis* cultivation and broader food security in salinity-affected regions.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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