

Full Length Research Paper

Synergic effect of Arbuscular mycorrhizal fungi (AMF) and rhizobia on *Vachellia nilotica* subsp. *adansonii* (Guill. & Perr.) Kuntze's symbiotic properties and growth under salinity conditions

Ramatoulaye Thiaba Samba^{1,2*}, Mariama Sagne Faye¹, Diégane Diouf^{2,3}, Cheikh Ndiaye^{1,2}, Paul Tendeng² and Samba Ndao Sylla^{1,2}

¹Département de Biologie végétale, Faculté des Sciences et Techniques, Université Cheikh Anta Diop Dakar (UCAD), Dakar-Fann, Sénégal.

²Laboratoire Commun de Microbiologie, Institut de Recherche pour le Développement (IRD)/Institut Sénégalais de Recherches Agricoles (ISRA), Université Cheikh Anta Diop de Dakar (UCAD), Dakar, Sénégal.

³Département Environnement, Biodiversité et Développement durable, UFR Sciences, Sociales et Environnementales, Université du Sine Saloum El Hadj Ibrahima Niass de Kaolack (USSEIN), Kaolack, Sénégal.

Received 18 September, 2025; Accepted 16 January, 2026

The use of salinity-tolerant symbiotic plants to rehabilitate salt-affected lands is practiced in many areas in the world, but is often faced with the survival of introduced plants in their new environments. However, plant vitality could be improved by inoculation with symbiotic rhizobia and arbuscular mycorrhizal fungi (AMF), known to make available essential plant nutrients such as nitrogen and phosphorus. *Vachellia nilotica* subspecies *Adansonii*, a symbiotic legume and excellent candidate for the rehabilitation of degraded soils. The present study aimed to assess the effect of rhizobia and AMF inoculation on *V. nilotica* species *adansonii* plants' growth improvement and salinity tolerance. A greenhouse experiment was carried out with inoculated treatments with AMF (*Rhizoglossum* and *Gigaspora* species) combined or not with rhizobia (*Mesorhizobium*, *Rhizobiun* and *Sinorhizobium*). Three levels of salinity were considered (0.250, and 500 mM). Nodulation, mycorrhization, plant growth parameters, and shoot mineral content were assessed. Results showed that salinity negatively affected these parameters. However, combined AMF/rhizobia improved them in inoculated plants under salinity. Globally, inoculation with *Rhizoglossum* and *Mesorhizobium* improves mycorrhization, nodulation, and biomass. Also, inoculated plants showed more nitrogen (N), Phosphorus (P) and Sodium (Na) content at high salinity. Sodium-potassium (K/Na) ratio decreases with salinity and was higher in *Rhizoglossum/Mesorhobium* treatment at 500 mM

Key words: *Vachellia nilotica*, arbuscular mycorrhizal fungi (AMF), salt tolerant rhizobia, inoculation, symbiotic parameters, salinity.

INTRODUCTION

Land degradation as salinization is a major constraint on the development of affected regions and constitutes both a global and a local challenge, sustainable development

goal 6 (SDG6). In many areas around the world as in Africa, this phenomenon is often due to the presence of salt (NaCl) in the soil and is exacerbated by high

temperatures related to global climate change. Salinization is the result of both natural process (intrusion of seawater into the land, etc) and human activities such as irrigation and salt farming. The consequences of this abiotic constraint include loss of fertility and degradation of the physical and chemical properties of the soil, leading to the loss of arable lands, reduced plant biodiversity, and finally to desertification. The rehabilitation and recovery of salt-affected soils are of vital importance and are becoming a necessity to increase land productivity. The outcome of these actions is to stabilize the soil, protect against weathering, conserve and develop natural plant resources, sequester carbon, and improve soil fertility.

In Senegal, soil rehabilitation involves several aspects: desalination through drainage (construction of anti-salt dams and bunds, drainage systems, etc.), liming, amendments with phosphogypsum or organic, and/or agrobiological methods such as revegetation of affected areas with tolerant plant species. This latter method is economically more affordable and more sustainable. The best plant species used in revegetation programs are plants able to survive on nutrient-poor, degraded land and tolerant to salinity. Some leguminous trees, such as *V. nilotica*, have this ability to regenerate, stabilize and improve soil fertility (Bouhnik et al., 2019). Salt-affected soils contain a very low rate of nitrogen (Heng et al., 2024; Elsiddig et al., 2023), which is a limiting factor for plant development.

Using plant species able to symbiotically fix nitrogen for reforestation is an alternative to rehabilitate salt affected soil. Egamberdieva et al. (2019) showed that leguminous trees had better growth rate and survival in saline conditions when inoculated with salt-tolerant rhizobia. However, most leguminous spp. and their associated microorganisms are sensitive to salinity; hence, the choice of tolerant symbiotic strains like those associated to *Acacia* s.l. It has also been shown that some rhizobia symbiotic to leguminous trees are also tolerant to soil salinity (Fall et al., 2008; Thrall et al., 2009).

Thus, *V. nilotica*, a multipurpose legume, has been used in many reforestation programs in Senegal and several other tropical regions around the world because of its ability to grow in salt affected soils.

This ability is thought to be linked to its capacity to form a tripartite symbiosis with both soil rhizobia and arbuscular mycorrhizal fungi (AMF) (Samba-Mbaye et al., 2020). These two symbiosis interactions play an important role in plant vitality, improving fertility and the stability of soil aggregates. Rhizobia are soil bacteria that are symbiotic to leguminous plants and can fix molecular nitrogen (N_2),

which is abundant in the atmosphere. These bacteria live in the nodules formed by the plants to fix the nitrogen and transform it into a form available for the plant's use. Because of this microbial symbiosis, plants can grow in nitrogen-deficient soils. So, using halo-tolerant rhizobia to alleviate salt stress in plants is a natural restorative strategy to change plant salt tolerance (Li et al., 2025).

Moreover, AMF are natural root symbionts providing water and essential mineral nutrients to host plants, improving plant growth and yield under both stressed and unstressed conditions (Begum et al., 2019). The greatest benefit of AMF in mycorrhized plants is phosphorus acquisition. According to Evelin et al. (2019), AMF deploy several biochemical and physiological mechanisms that act synergistically to enhance higher salinity tolerance of the host plant. Improving the phosphorus content of plants is the best salinity tolerance strategy for plants colonized by fungi. AMF are considered as biofertilizers and often as bio-protectors, because in addition to improving the hydromineral nutrition of plants, AMF assist them in fighting pathogens. According to Wang et al. (2018), AMF are also considered to be bioenhancers of plant tolerance to soil salinity.

However, in tropical soils, populations of native rhizobia and AMF strains are often quantitatively and qualitatively reduced because of increasing temperatures or inefficiency to optimize the beneficial effects of symbiosis. In this context of climate change with increasing temperatures, inoculation with effective strains becomes an imperative to improve plant symbiosis and plant growth in the nursery before transplanting to the field for more successful establishment. Inoculation with AMF to improve plant growth and productivity has been widely studied on several plant species (Smith and Smith, 2011) using either a single or several species, native or selected (Quiñones-Aguilar et al., 2016) associated or not with rhizobia. However, previous studies (Sène et al., 2010; Soliman et al., 2012; Fall et al., 2017; Klinsukon et al., 2021) have shown that double inoculation rhizobia/AMF had a more beneficial effect on the symbiotic properties and productivity of *Acacia* plants due to the synergistic effect of the two symbioses on the plant. It was shown that the efficiency of nitrogen fixation depended on phosphorus availability, which can be supplied by the mycorrhizal symbiosis. However, for each species, it will be necessary to determine the most effective microorganisms, especially because their effectiveness can vary depending on the associated plant spp.

Moreover, previous studies identified more *Glomus* spores in the rhizosphere of *V. nilotica* growing in non-

*Corresponding author. E-mail: ramatoulaye.mbaye@ucad.edu.sn.

Table 1. Description of experimental treatments

Treatment name	Description of applied type of inoculum
CM1	<i>Rhizoglossus aggregatum</i> + <i>Rhizoglossus intraradices</i>
CM2	<i>Gigaspora rosea</i> + <i>Gigaspora margarita</i>
R1CM1	<i>Rhizobium</i> spp. (LCM4934) + CM1
R1CM2	<i>Rhizobium</i> spp. (LCM4934) + CM2
R2CM1	<i>Ensifer</i> spp. (LCM4917) + CM1
R2CM2	<i>Ensifer</i> spp. (LCM4917) + CM2
R3CM1	<i>Mesorhizobium</i> spp. (LCM4942) + CM1
R3CM2	<i>Mesorhizobium</i> spp. (LCM4942) + CM2
TCM1	Control 1: non sterilised soil + CM1 inoculum sterilised at 120°C
TCM2	Control 2: non sterilised soil + CM2 inoculum sterilised at 120°C

saline soils, with *Rhizoglossus aggregatum* predominating, and slightly less frequently with *Rhizophagus intraradices* (Sène et al., 2012). This study also showed a predominance of these two AMF species in the rhizosphere of some tree species, and that the infectious potential is higher under cover. Also, Samba-Mbaye et al. (2020) identified the AMF genera in association with *V. nilotica*; and thus, efficient rhizobia strains have been isolated from nodules to improve plant development under salinity conditions. These bacteria and fungi, identified as naturally associated with *V. nilotica*, could constitute biological inputs to support the development of these plants in saline conditions. However, the inoculation of *V. nilotica* mainly with their true natural symbionts is not well studied, particularly in Senegal. To fill this gap, the present study aims to assess the effect of inoculation with rhizobia and/or AMF on the symbiotic and growth parameters of *V. nilotica* under salinity conditions. Ultimately, the results should enable us to identify the performed strains for inoculation, and those that are able to optimize plant growth in the nursery.

MATERIALS AND METHODS

Plant and substrate of cultivation

The seeds of *V. nilotica* var. *adansonii* collected from Dahra locality were supplied by the "Centre National de Ressources Forestières (CNRFF)" of ISRA. Its current name is *V. nilotica* ssp. *adansonii* (Guill. and Perr.) Kuntze [syn. *Acacia nilotica* (L.) Willd. ex Del. subsp. *adstringens* (Schumm. and Thonn.) Roberty] (Kyalangalilwa et al., 2013). The cultivation substrate was sandy soil from Sangalkam with the following physical and chemical properties: sand 88.8%, silt 5.8%, clay 5.4%, organic matter 0.6%, total carbon 0.3%, total nitrogen 0.02%, C/N ratio 14%, total potassium 333.5 ppm, total phosphorus 41.4 ppm, assimilable phosphorus 2.1 ppm, total calcium 1.03 ppm, total magnesium 0.30 ppm, pH (soil/water ratio 1:2) 6.0; pH (soil/KCl ratio 1:2) 4.6.

AMF inoculum

The fungal strains were from the AM fungi collection of the "Laboratoire Commun de Microbiologie (LCM)". These inocula were produced by trapping with maize plants grown on sandy soil sterilized at 120 °C for 2 h. Two inocula (CM1 and CM2) were each composed of a mixture of two AMF strains in equal proportions. The CM1 inoculum is a mixture of *R. aggregatum* (syn. *Glomus aggregatum*, N.C. Schenck and G.S. Sm.) Sieverd, G.A. Silva and Oehl (Sieverding et al., 2014) and *R. intraradices* (syn. *Glomus intraradices*, N.C. Schenck and G.S. Sm.) Sieverd, G.A. Silva and Oehl (Sieverding et al., 2014), while the CM2 inoculum consisted of a mixture of *Gigaspora rosea* and *Gigaspora margarita*. The choice of AMF species was based on previously identified species in *V. nilotica*, but also on availability in the LCM collection. The inoculum was supplied to the soil as a sandy substrate containing spores and fragments of mycorrhized roots.

Rhizobial inoculum

Bacterial inocula were prepared using strains isolated from *V. nilotica* nodules grown in salt-affected soil. They were selected based on their symbiotic performance and salinity tolerance according to a previous study. Three strains of bacteria were used: *Rhizobium* sp. (LCM4934) or R1, *Ensifer* spp. (LCM4917) or R2 and *Mesorhizobium* spp. (LCM4942) or R3. These strains were chosen from the groups previously identified as nodulating *V. nilotica*.

The inoculum was a liquid bacterial culture prepared with YM medium. Pure strains were first grown aseptically in Petri dishes containing YMA. Isolated colonies were used to inoculate a flask contained YM medium which was then kept in a culture chamber at 30°C for 48 h. When the strains have reached their exponential growth, the optical density (OD) is measured at 600 for adjustments to ensure similar ODs for all the strains before inoculation.

Experimental design

The experiment was carried out in the greenhouse, and the design was a randomized block with two factors: the inoculation factor with 10 treatments (Table 1): 6 rhizobia/AMF double-inoculation, two AMF inoculation alone, and 2 controls without inoculum TCM1 and TCM2 (Table 1); and the salinity factor with three levels (0, 250, and

500 mM). For each treatment 10 replicates were considered.

Soil preparation and plant cultivation

The soil was first sieved to remove coarse debris, then moistened before being placed in plastic bags. The seeds of *V. nilotica*, which had a hard coat, were scarified with 96% sulphuric acid (H_2SO_4) for 2 h to remove the seed coat inhibition. Then they are removed from the acid and rinsed thoroughly with demineralized water to remove all traces of acid. They were then soaked in sterile demineralized water overnight. Finally, they were germinated in Petri dishes containing agar (0.9%) and placed in an oven at 37°C. After, the pre-germinated seeds were transplanted into plastic sheaths containing 1.5 kg of non-sterile soil with two germinated plants per tube. The plants were watered daily with tap water at field capacity. Before inoculation, the least vigorous plant was removed to obtain plants with uniform growth.

Plant inoculation

The fungal inoculum was added before transplanting. Twenty grams of fungal inoculum from each AMF cocktail were buried in the middle of the sheath. Then, the absolute control was inoculated with a sample of fungal inoculum sterilized at 120°C for 2h. Inoculation with rhizobia was carried out five days after transplanting. The seedlings were inoculated with 5 ml of bacterial inoculum of each rhizobium strain at the root collar of each plant.

Salinity application

Salinity levels for treatments were identified based on previous studies showing that greenhouse-cultivated *V. nilotica* plants could grow at sodium chloride (NaCl) concentrations up to 600 mM (Soumaré et al., 2008); and the salinity tolerance tests we carried out on the strains showed that they could grow at over 500 mM NaCl. Thus, 3 levels of salinity were chosen: 0 mM as the control, 250 mM as the moderate, and 500 mM as the high salinity. Fifteen days after inoculation, the saline solution was added. Salt stress was applied progressively by first watering the plants with a 50 mM saline solution until the soil salinity was closer to the level we wanted to apply, to avoid osmotic shock to the plants. To achieve this, the salinity of the soil solution was measured with a salinometer after each watering. Control plants (0 mM of NaCl) were watered with tap water and frequency of watering was every two days until the end of the experiment.

Parameters assessed

To assess the effect of inoculation on plant development and symbiosis under salinity conditions, growth, mycorrhization and nodulation parameters were estimated. The shoot mineral content of the plants was also analysed.

Plant growth and nodulation

The growth parameters measured were plant height, shoot biomass and root biomass. Thus, after four months of cultivation, the height of the plants was measured before harvest. To assess plant biomass, the shoots and roots parts were separated and dried in a 70°C oven for 48 h. The dry samples were then weighed. The number of nodules

per plant was counted at harvest.

Analysis of the shoot mineral content of plants

The analysis of mineral content (C, N, P, Na, K) in plant shoot was carried out by the LAMA laboratory (Laboratoire des Moyens Analytiques) certified ISO 9001 version 2000 (Institut de Recherche pour le Développement, IRD-Bel Air, Dakar-Senegal).

Roots mycorrhization

Before staining, root samples taken from inoculated and control plants and rinsed with tap water were preserved in 70°C alcohol.

Root staining

Root samples were stained using the method of Phillips and Hayman (1970). The roots were first rinsed in tap water, placed in test tubes containing a 10% KOH solution and boiled in a water bath at 90°C for 1 h. This operation emptied the cytoplasmic content of the root cells. The roots were rinsed (to remove the KOH) and soaked in bleach diluted 1:10 for 3 min to lighten them further. After rinsing under tap water and draining, they were soaked in a 0.05% trypan blue solution, and the tubes were placed in a water bath at 90°C for 30 min. At the end of this operation, the dye was drained and the roots soaked in tap water.

Evaluation of mycorrhization

The stained roots were cut into fragments of approximately 1 cm, mounted between a slide and a coverslip and coated with 20% glycerol for preservation. Each slide had 15 fragments and for each treatment there were 5 replicates. Each slide was observed under a microscope ($\times 20$) fragment by fragment. The presence of hyphae, vesicles or arbuscules in the roots was used to estimate the level of root colonization. The mycorrhization rate was assessed using the method described by Trouvelot et al. (1986). Microscopic observation was used to record the level of root colonization of each fragment rated on a scale from 0 to 5. The mycorrhization parameters were calculated according to the following formulae: Frequency of mycorrhization of the root system (F%) and intensity of mycorrhizal colonization of the root system (I%).

$F\% = (\text{Number of mycorrhized fragments} / \text{Total number of root fragments per slide}) \times 100$

$I\% = (95n_5 + 70n_4 + 30n_3 + 5n_2 + n_1) / (\text{Total number of fragments per slide})$

where, n_5 , n_4 , n_3 , n_2 and n_1 are, respectively, the number of fragments scored as 5 (90 to 100%), 4 (50 to 90%), 3 (10 to 50%), 2 (1 to 10%) and 1(0 to 1%) (number of mycorrhizal sections).

Statistical data analysis

Data were analysed using two-factor analysis of variance (ANOVA) model using XLSTAT version 2019 software with a 95% confidence interval. Pearson correlations between dependent variables were performed by the same software Means were compared using the Newman and Keul's test with a probability of $P < 0.05$.

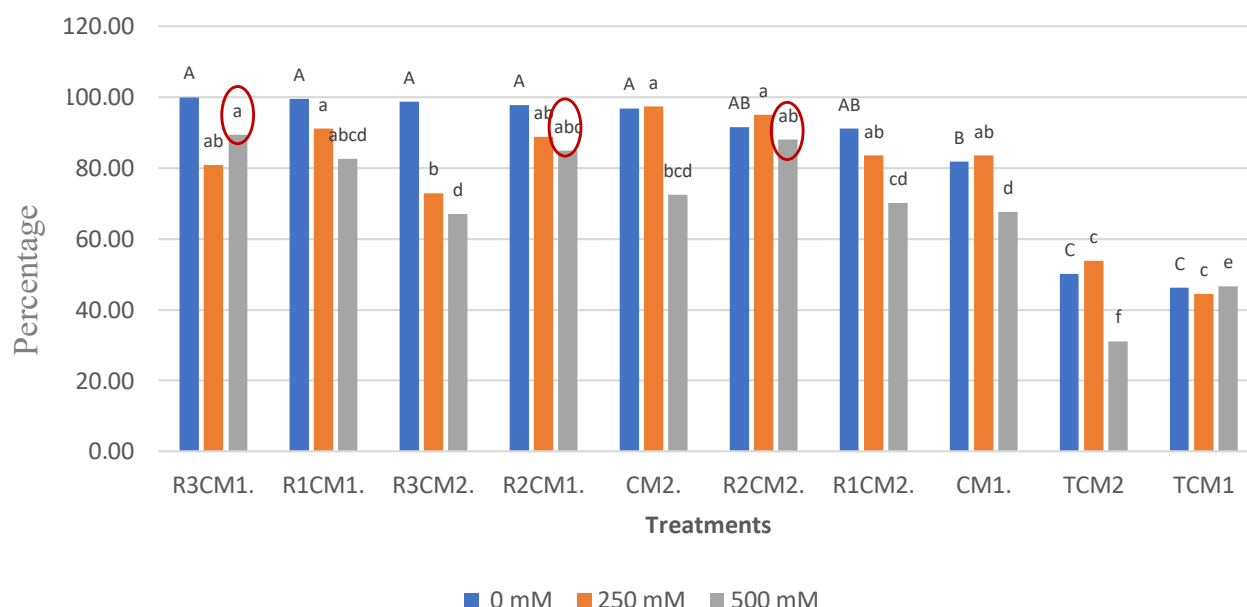


Figure 1. Effect of inoculation on mycorrhization frequency of *V. nilotica* plants under different salinity levels; Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

RESULTS

Effect of inoculation on plant mycorrhization under salinity

Effect of inoculation on mycorrhization frequency

The effect of inoculation on the mycorrhization frequency of *V. nilotica* (Figure 1) showed that in no salinity (0mM NaCl), all inoculated treatments had higher mycorrhization frequencies than non-inoculated (controls), thus demonstrating the positive impact of inoculation on mycorrhization. However, the double-inoculated treatments R3CM1 (100%), R1CM1, R3CM2 and R2CM1 had the highest frequencies. At moderate salinity (250 mM NaCl), all inoculated treatments had significantly higher mycorrhization frequencies than controls, indicating the positive effect of inoculation at moderate salinity level and the exogenous addition of AMF had a positive effect on mycorrhization frequency. Treatments R3CM1 (80.9%), and R2CM2, R2CM1 and R1CM1 had the highest absolute values, but were not significantly different than the other inoculated treatments. At high salinity (500 mM NaCl), all inoculated treatments had significantly higher mycorrhization frequencies than the non-inoculated controls. However, the values of frequencies varied with treatments. The highest frequencies were observed with the R3CM1 treatments first (89.33%), followed by R2CM2, R2CM1 and R1CM1.

These results showed that rhizobia associated with CM1 would be more effective at high salinity. Globally, it can be noted that whatever the salinity level, the rhizobia combined to AMF treatments (CM1, CM2) show better mycorrhization, particularly when associated with CM1 (*Rhizoglossus* spp.).

Effect on mycorrhization intensity

Results on mycorrhization intensity of *V. nilotica* plants under salinity (Figure 2) showed that in no salinity, all the inoculated treatments had significantly higher mycorrhization intensities than the controls. However, there was a significant difference between the inoculated treatments, as R3CM1 (74.93%) was far higher than the others. However, at moderate salinity, all inoculated treatments had significantly higher mycorrhization intensities than controls. At this level of salinity, the R3CM1 (40.67%), R3CM2 and CM2 treatments had the highest intensity values, and the remaining inoculated treatments were not significantly different. At high salinity, all inoculated treatments had significantly higher mycorrhization intensities than controls. However, there is a difference in mycorrhization between the inoculated treatments. The significantly highest intensity is R3CM1 treatments (16.73%) followed by R2CM2 and CM1. Overall, the main observation is whatever the salinity level, inoculated treatments had the highest mycorrhization

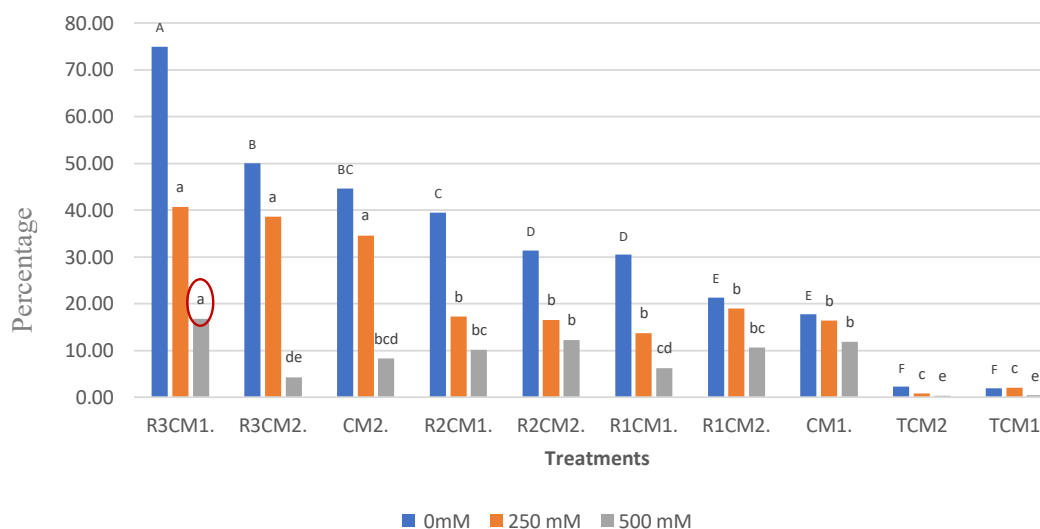


Figure 2. Effect of inoculation on mycorrhization intensity of *V. nilotica* plants under different salinity levels, Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

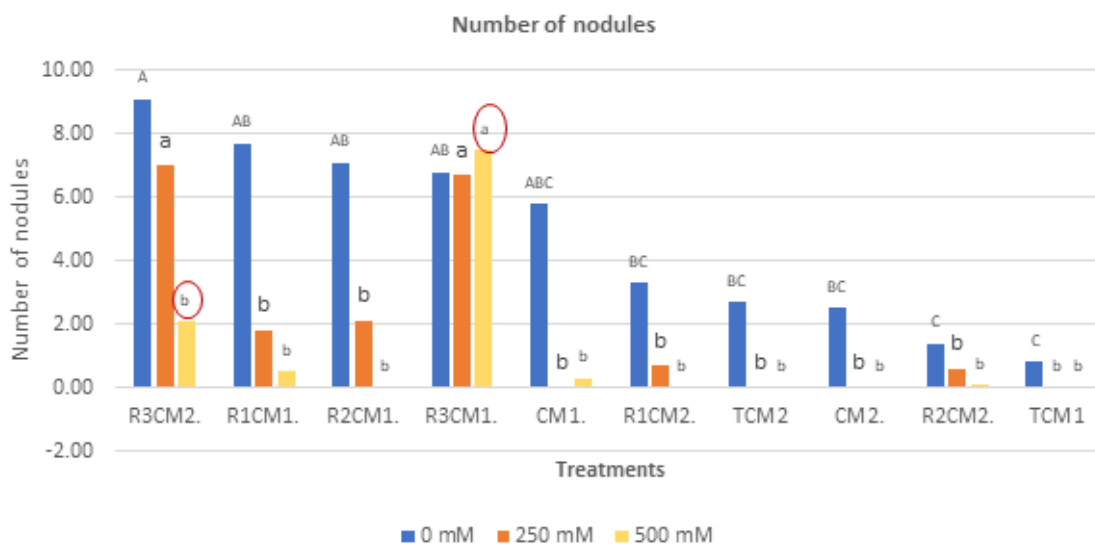


Figure 3. Effect of inoculation on nodulation of *V. nilotica* plants under different salinity levels, Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

intensity; and moreover, the R3CM1 treatment (*Mesorhizobium/Rhizoglosum spp.*) still was the highest.

Effect of inoculation on plant nodulation

Figure 3 shows the effect of inoculation with AMF alone, or in association with rhizobia, on nodulation of *V. nilotica* plants under different salinity levels. It was noted that

globally, there is an overall decrease in the number of nodules in the two salinity levels. However, in salinity zero, the double-inoculation AMF/rhizobium treatments significantly increased the number of nodules, except for R1CM2 and R2CM2 treatments, which showed the same results as the non-inoculated and CM1. The R3CM2 treatment was the highest because it induced more nodules, indicating that in no salinity *Mesorhizobium spp.* (R3) combined with *Gigaspora spp.* Is the most effective

treatment for nodulation. In moderate salinity, it was still the double-inoculation treatments that induced significantly more nodules, with R3CM2 and R3CM1 first, showing that the R3 strain (*Mesorhizobium* spp.) is the most infective at this salinity level.

At high salinity, the number of nodules was considerably reduced for all treatments, indicating the negative effect of salt on nodulation, except for the R3CM1 treatment (*Mesorhizobium/Rhizoglomus*) first, and R3CM2 secondly. This result agrees with result in moderate salinity, showing that R3 strain (*Mesorhizobium* spp.) is the most infective regardless of the type of AMF associated.

Effect of inoculation with rhizobia and AMF on biomass production, plant growth of *V. nilotica* under salinity levels

Effect of inoculation on shoot biomass

The effect of inoculation on shoot biomass of *V. nilotica* plants under salinity conditions (Figure 4A) showed that in no salinity all treatments had significantly higher biomass, with the double-inoculation treatments R1CM1, R2CM1 and R3CM1 first, suggesting that treatment with CM1 induced more biomass; whereas those associated with CM2 had a weaker effect. Also, at moderate salinity, the CM1 treatment produced more shoot biomass, followed by the R2CM2, R1CM2 and R1CM1 double-inoculation treatments and CM2 treatment was the less effective. The TCM1 and TCM2 controls were not significantly different from the R3CM2, R3CM1 and R2CM1 treatments.

This result, therefore, shows that the infectivity of R3 was not reflected in the biomass. However, the indigenous strains (controls) had a weaker effect than the exogenous strains. At high salinity, the R3CM1 treatment was the better, followed by R3CM2. This result also corroborated the observed number of nodules in this treatment, suggesting that R3 associated with AMF is effective at high salinity, whereas the indigenous strains have a weaker effect at this salt concentration. Overall, it appears that in the presence or absence of salinity, double-inoculation treatments often induced more shoot biomass. Treatments combining rhizobia and CM1 were more effective, while at higher salinities, *Mesorhizobium* spp. R3 combined with the two types of AMF best performed.

Effect on root biomass

Figure 4B shows the results of the effect of inoculation on root biomass of *V. nilotica* under salinity.

The CM1 treatments and the R1CM2, R2CM2, R3CM1, R3CM2 double-inoculated treatments significantly

increased root biomass production in no salinity. However, R1CM1 and CM2 treatments were not significantly different from the controls. At moderate salinity, treatment R1CM2 was not significantly different from treatments R2CM2, R2CM1, CM1, R1CM1 and TCM2. It was noted that at this salinity level, treatments with R2 or R1 increase root production, regardless of the type of associated AMF. TCM2 treatment also showed that there have indigenous strains that were effective in producing roots. At a higher salinity, the treatments that developed more roots were R3CM1, followed by R2CM1 and CM1. This result suggested that CM1 is effective in root development. The weaker treatments R3CM2, R1CM2 and R2CM2 show that CM2 does not stimulate root development at high salinity. Regardless of the salinity level, inoculated treatments induced more root biomass. However, at high salinity it was the *Rhizoglomus* spp. treatments that produced more root biomass, particularly when combined with *Mesorhizobium* spp.

Effect on plant total biomass

The results show that, overall total biomass varies according to salinity level (Figure 5). Biomass decreased with increasing salinity. The type of inoculum also influenced biomass production. In the absence of NaCl, all the double-inoculation treatments produced a higher biomass than the controls.

The R1CM1 treatment was the most effective, followed by R2CM1, R3CM1 and R3CM2, which were not significantly different, meaning that inoculation improved biomass production both in AMF alone and in rhizobia/AMF associations. However, at moderate salinity CM1 was not significantly different from the double-inoculation treatments. However, the TCM2 was also in the same group, indicating that there are indigenous strains with the same potential in terms of salinity tolerance and efficacy as the inoculated strains. Thus, CM2 alone was less effective than the inoculated strains. Similarly, at high salinity, the R3CM1 and R2CM1 double-inoculation treatments produced a higher biomass, which may indicate that these treatments contribute to the plant's salt tolerance. The low response noted for R1CM2 and R2CM2, could be meaning a depressive effect of CM2 in association with rhizobia. Globally, total biomass is generally higher in inoculated plants, and treatments with *Rhizoglomus* spp are often the most effective.

Effect on plant height

The effect of inoculation on plant height under salinity (Figure 6) showed a decrease in plant height with increasing salinity. In no salinity, all rhizobia associated

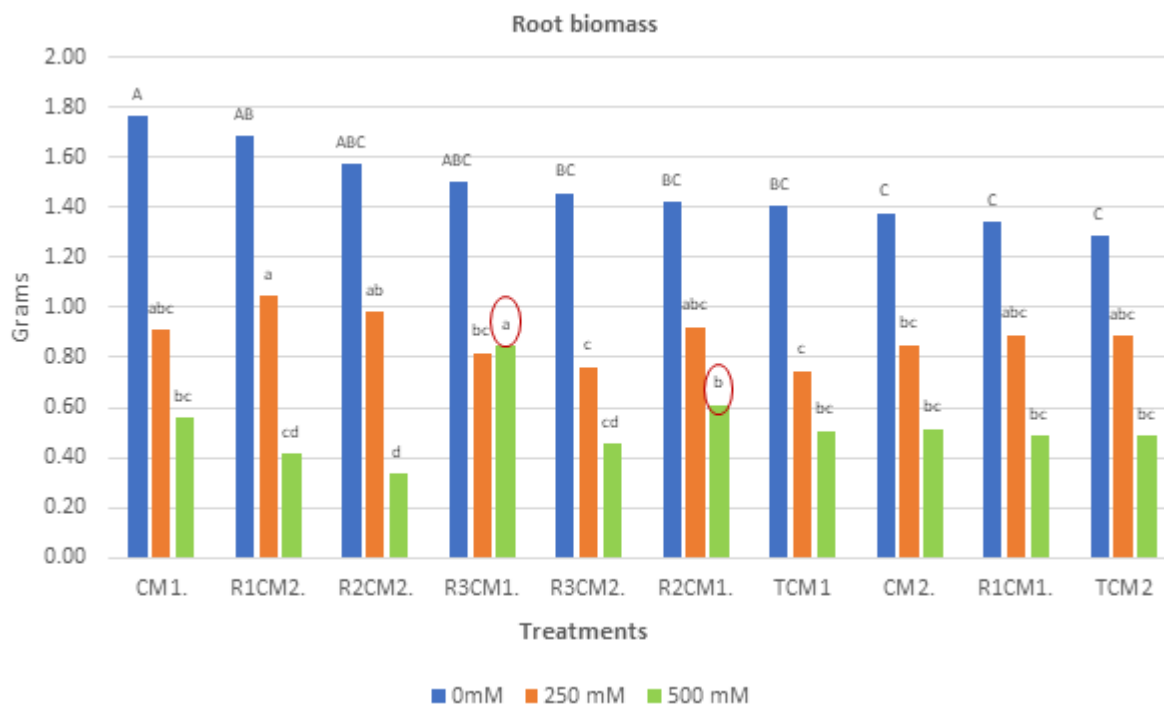


Figure 4. Effect of inoculation on shoot (a) and root (b) biomass of *V. nilotica* plants under different salinity levels, Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

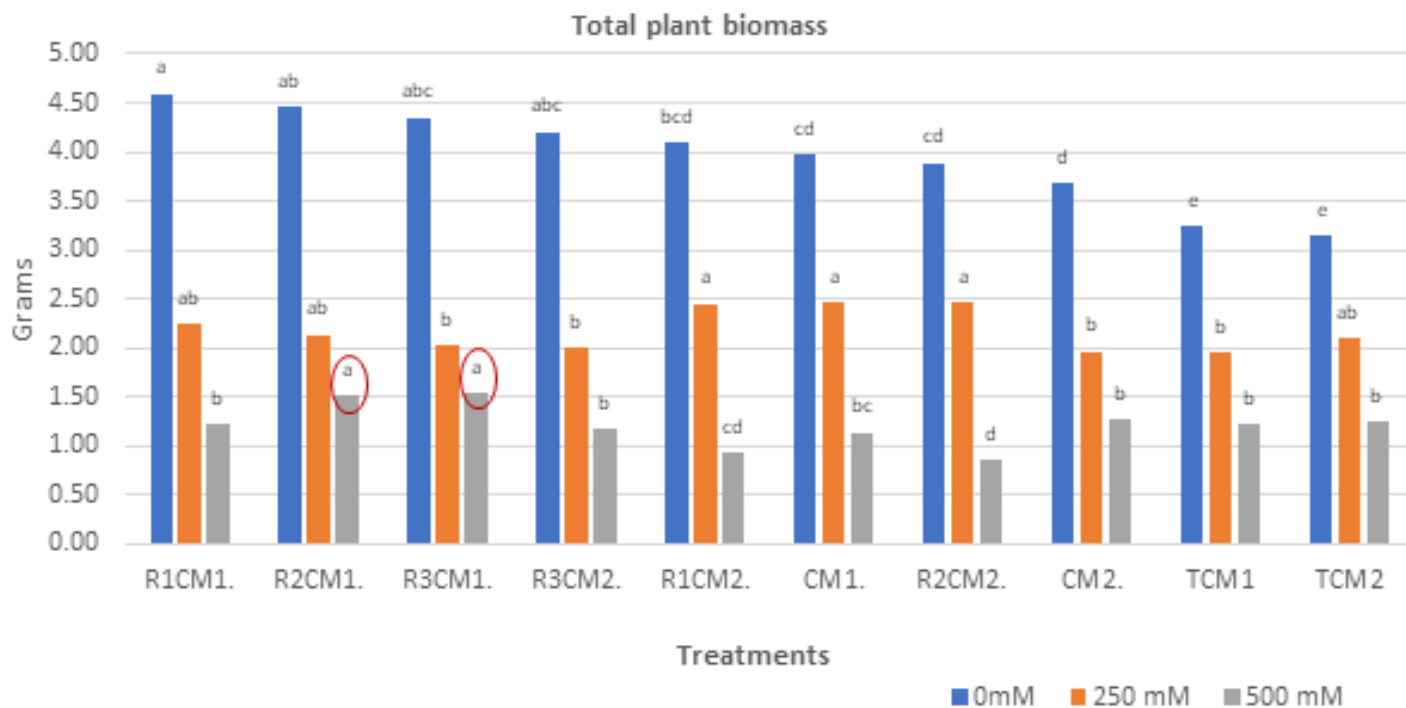


Figure 5. Effect of inoculation on total plant biomass of *V. nilotica* plants under different salinity levels, Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

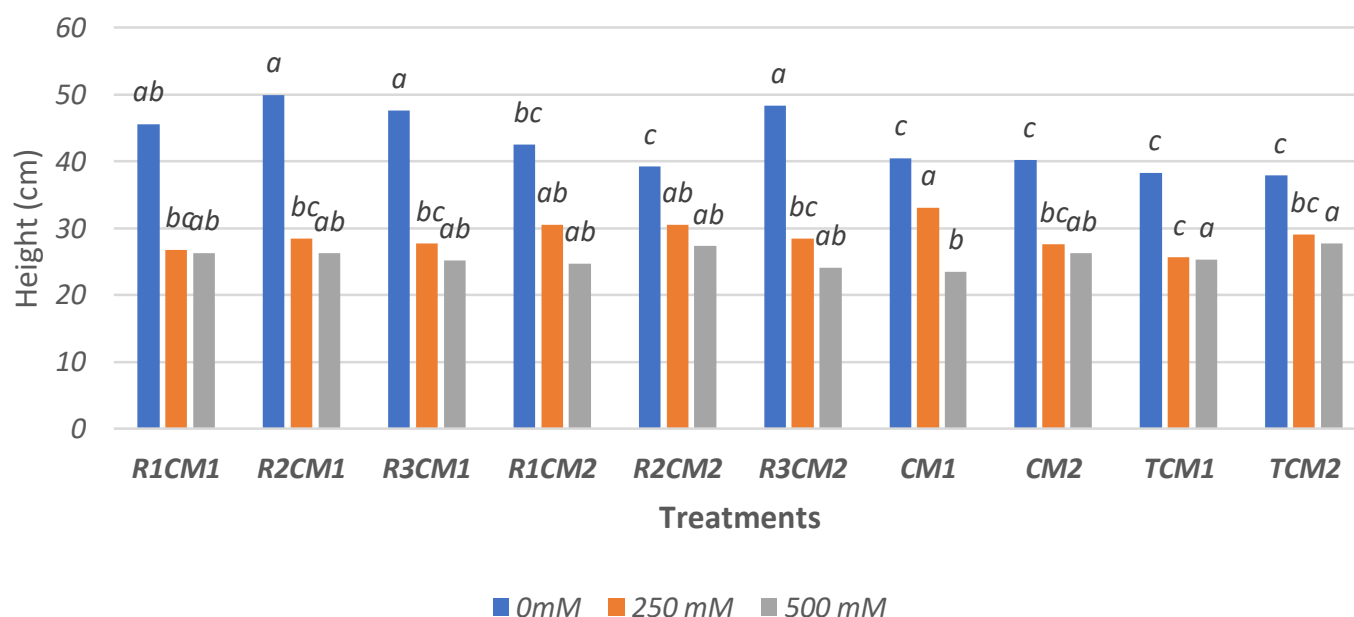


Figure 6. Effect of inoculation on plant height of *V. nilotica* plants under different salinity levels. Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

with CM1 and R3CM2 have greater plant height. In moderate salinity, plants of the CM1, R1CM2 and R2CM2 treatments grew taller, while at high salinity there was no significant difference between treatments, indicating a decrease of plant growth. Observation of plants at high salinity showed that, often they lose their leaves (Figure 7) and then regenerate smaller, fewer leaves.

Effect of inoculation on the shoot mineral content of *V. nilotica* plants inoculated under different levels of salinity

Table 2 shows the results for the effect of inoculation on the total nitrogen (N), phosphorus (P), sodium (Na) and potassium (K) content on the shoots of *V. nilotica* plants.

Effect on shoot nitrogen content

The total nitrogen content was significantly higher in all the inoculated treatments in 0 mM of NaCl, except for treatment R1CM2, which was not significantly different from the controls. The highest levels were observed in treatments R3CM2 and R1CM1, although R2CM1, R3CM1, R2CM2 and CM1 alone were not significantly different, indicating that these were the most effective treatments for nitrogen supply. At moderate salinity, nitrogen content was significantly higher in the inoculated

treatments R3CM1, R3CM2, CM1, CM2 and controls while the lowest nitrogen content was observed in the treatments R1CM1, R2CM1, R2CM2. At high salinity the nitrogen content was significantly higher in the inoculated treatments R1CM2, R3CM1, R3CM2, CM1, CM2. However, the inoculated treatments R1CM1, R2CM1, R2CM2 are not significantly different from controls. It can be noted that R3 (*Mesorhizobium*) associated to any type of AMF gives a high nitrogen content at moderate or high salinity.

Effect on shoot phosphorus content

The phosphorus content (total P) of plants in no salinity showed that the CM1, R1CM1, R2CM1 and R3CM1 treatments are significantly higher, indicating that inocula with CM1 (*R.spp.*) are more effective at supplying phosphorus to the plant, alone or in association with rhizobia. At moderate salinity, the highest total P content was observed with the R3CM1 treatment, with the CM1, CM2, TCM1 and R1CM1 treatments having lower values, which could be interpreted as *Rhizoglossus* efficiency. The lowest P content was observed with the inoculated treatments R3CM2, R2CM2, R1CM2 and TCM2.

At high salinity all the double-inoculated treatments have more total P than controls. The inoculated treatments R2CM2, R3CM1 and R3CM2 had the highest levels. Treatments R1CM2, R2CM1, R1CM1, CM2 had slightly

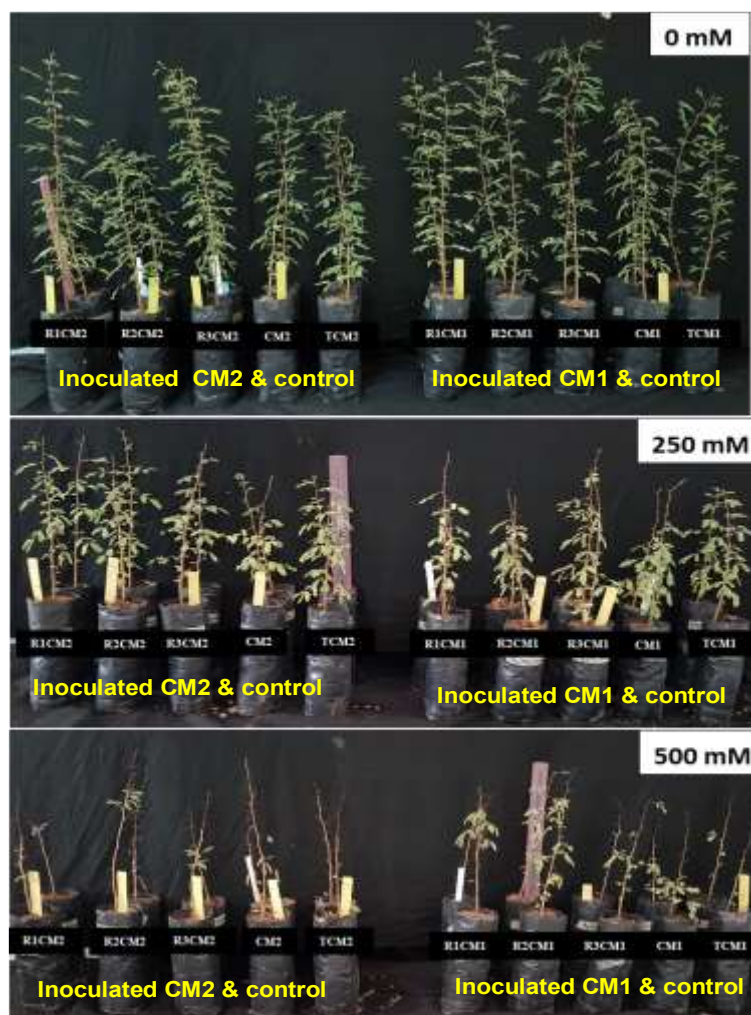


Figure 7. Status of *V. nilotica* plants inoculated and under different salinity levels (0mM NaCl, 250mM, 500 mM) after 3 months in greenhouse.

lower levels. The CM1 treatment, which is not significantly different from the controls, has the lowest content, and this corroborates the level of mycorrhization.

Effect on shoot sodium (Na) content

Sodium (Na) content was higher in treatments R1CM1, R2CM1 and R3CM1 in no salinity. Therefore, the CM1/rhizobia associations would be more effective in removing sodium from the soil and transferring it to the aerial parts of the plants. On the other hand, CM1 alone, CM2 alone, CM2/rhizobia associations and non-inoculated controls contain less Na.

At moderate salinity, all treatments had significantly high Na levels except R2CM2 and R3CM2. The inoculated treatments R3CM1, CM1 and R1CM2 had the highest

levels. At high salinity, the Na content was higher in the R2CM2 and R1CM2 treatments. The R2M1, R3CM1, R3CM2, R1CM1, CM1 and CM2 treatments had lower levels, and the lowest levels were observed in the non-inoculated controls.

Effect on shoot potassium (K) content

Potassium (K) content is higher for treatments CM1, R1CM1, R2CM1, R3CM1 in no salinity, but is not significantly different for almost all other treatments except control (TCM2). This means that the treatments associated with *Rhizoglossus* (CM1) have a higher K content.

At moderate salinity the K content is higher in treatments R1CM1, R2CM1, CM2 alone, and all the other treatments

Table 2. Effect of inoculation on shoots mineral content of *V. nilotica* plants inoculated under different salinity levels.

Inoculated treatments	NaCl 0 mM				NaCl 250 mM				NaCl 500 mM		
	N total (%)	P total (mg/kg)	Na (mg/kg)	K (mg/kg)	N total (%)	P total (mg/kg)	Na (mg/kg)	K (mg/kg)	P total (mg/kg)	Na (mg/kg)	K (mg/kg)
RICM1	1.54 ^a	1277.25 ^a	962.00 ^{ab}	7438.25 ^a	0.89 ^c	1230.25 ^{bc}	6242.25 ^{abc}	7848.50 ^{ab}	1284.0 ^{bc}	12349.8 ^b	8571.0 ^b
R2CM1	1.2 ^{abc}	1145.00 ^{ab}	1405.25 ^a	7369.50 ^a	0.99 ^{bc}	1437.25 ^b	6520.0 ^{abc}	9276.75 ^a	1279.0 ^{bc}	10447.5 ^b	11055.3 ^a
R3CM1	1.34 ^{ab}	1072.00 ^{abc}	1159.00 ^a	7193.00 ^a	1.03 ^{bc}	2618.50 ^a	7898.5 ^a	6697.50 ^{cd}	1605.0 ^{ab}	9262.3 ^{bc}	8231.8 ^b
R1CM2	1.1 ^{bc}	819.25 ^{cd}	650.00 ^{bc}	5785.75 ^{ab}	0.99 ^{bc}	775.50 ^{de}	7705.0 ^{ab}	6031.75 ^d	1303.3 ^{bc}	19418.8 ^a	8778.3 ^b
R2CM2	1.38 ^{ab}	906.00 ^{bcd}	645.25 ^{bc}	6317.25 ^{ab}	0.97 ^{bc}	623.75 ^e	4500.75 ^c	6836.75 ^{cd}	1763.8 ^a	21813.0 ^a	8179.3 ^b
R3CM2	1.53 ^a	773.75 ^d	513.50 ^{bc}	6363.00 ^{ab}	1.15 ^{ab}	720.25 ^{de}	5641.50 ^{bc}	6622.25 ^{cd}	1409.0 ^{ab}	11464.0 ^{bc}	7959.0 ^b
CM1	1.26 ^{abc}	1179.50 ^a	484.75 ^{bc}	7535.25 ^a	1.19 ^{ab}	1220.00 ^{bc}	6862.75 ^{ab}	6454.25 ^{cd}	1139.5 ^{cd}	10799.3 ^{bc}	7019.0 ^b
CM2	1.14 ^{bc}	864.00 ^{cd}	308.25 ^c	6236.75 ^{ab}	1.27 ^a	1134.25 ^{bc}	6809.00 ^{ab}	8655.00 ^{ab}	1295.8 ^{bc}	9541.5 ^{bc}	8634.0 ^b
TCM1	1.26 ^{abc}	920.75 ^{bcd}	362.00 ^c	5851.50 ^{ab}	1.26 ^a	969.00 ^{cd}	7896.5 ^a	7250.0 ^{bcd}	1065.8 ^{cd}	7103.8 ^{bc}	8121.0 ^b
TCM2	0.97 ^c	877.00 ^{cd}	223.25 ^c	5599.00 ^b	1.08 ^{ab}	680.50 ^{de}	6316.25 ^{abc}	7126.00 ^{bcd}	752.5 ^d	5945.8 ^c	8222.5 ^b

are not significantly different from the non-inoculated controls. At high salinity, apart the R2CM1 treatment, which has the highest K content, all others are not significantly different, including non-inoculated.

Effect on Sodium-potassium (K/Na) ratio of *V. nilotica* plants shoots

The K/Na ratio of plants (Figure 8) decreases with salinity at both moderate and high salinity levels.

The K/Na ratio in no salinity varied between 5.42 and 26.19 and was significantly higher in treatments CM2, TCM2 firstly, followed by treatments CM1, R2CM2, R3CM2, TCM1. CM2. At moderate salinity, this ratio is between 0.81 and 1.56 and is higher in R1CM1, R2CM1, R2CM2, R3CM2 and CM2. At high salinity, the K/Na ratio ranged from 0.38 to 1.51, and was highest in

R3CM1, CM2 and controls, thus CM1, R1CM1, R3CM2. All the other treatments were not significantly different.

Correlation between the different mineral contents of shoots of *V. nilotica* (Table 3) shows positive correlation between P and nitrogen content. Thus, Na is positively correlated with P and N. A negative correlation between Na and K/Na ratio is also noted.

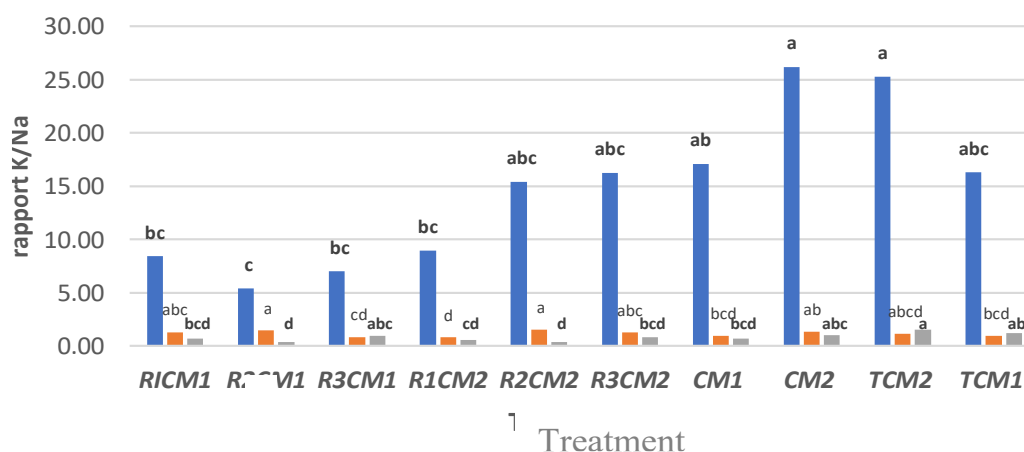
DISCUSSION

The effect of inoculation on plants tolerance to salinity was analysed for *V. nilotica* inoculated with AMF strains alone or combined with salt tolerant rhizobia in three levels of salinity. The inoculation in non-sterile soil was aimed to be closer to natural conditions and to analyse the behaviour of the inoculated strains in relation to soilborne strains.

Overall, the results showed a reduction in growth parameters (shoot and root biomass and height) and symbiotic parameters (nodulation, mycorrhization) with increasing NaCl concentration compared with no salinity treatments; this means that plant growth decreases with increased salinity. It has been reported that salinity is harmful to plants, because it causes osmotic stress and ionic stress; and osmotic stress reduces the water uptake and solutes (Lu and Fricke, 2023; Munns and Tester, 2008). However, these parameters were improved with inoculated treatments, particularly double-inoculated rhizobia/AMF treatments. *Rhizoglossus* spp. treatments are often the most effective, especially when combined with *Mesorhizobium* spp. In addition, it has been noted that there is a heterogeneity in the responses to inoculation, which could be due to the indigenous strains whose effects may converge with those of the inoculants. Similar results were showed by Abbas et al. (2013)

Table 3. Correlation between shoot minerals content parameters at high salinity (500 mM).

Correlation	Azote total	P total	Na	K	K/Na
Azote total	1	0,1235	0.2329	-0.0734	-0.3224
P total	0.1235	1	0.5129	-0.0006	-0.4189
Na	0.2329	0.5129	1	-0.0937	-0.8186
K	-0.0734	-0.0006	-0.0937	1	0.3867
K/Na	-0.3224	-0.4189	-0.8186	0.3867	1

**Figure 8.** Effect of inoculation on K/Na ratio of *V. nilotica* shoot plants biomass under different salinity levels, Numbers with the same letter are not significantly different according to Newman et Keul's test. $P < 0.0001$.

indicating that all growth parameters decrease with increasing salinity in *Acacia ampliceps* and *V. nilotica*. Similarly, Al-shaharani and Shetta (2011) reported that salinity affects growth, nodulation and nitrogen fixation parameters in *Acacia ehrenbergiana* and *Vachellia tortilis*. The inhibitory effect of salinity on nodulation is attributed to the decrease in colonization by a reduction in the proliferation of the rhizobial populations under saline conditions and to the lack of root hair formation (Abd-Alla et al., 2019; Thrall et al., 2008). According to these authors, salt stress also induces premature senescence of nodules, and nodule fixation activity is strongly inhibited when plants are under saline conditions. Indeed, salinity leads to the senescence of the first nodules formed and blocks the formation of new ones. However, the intensity of the adverse effects of salinity on nodule function depends on the plant species, the rhizobia strain, the duration of exposure to saline conditions and the nature and concentration of the salt. It should be noted that our strains improve plant development in non-saline conditions (0 mM NaCl), which means there is a plasticity of bacterial

strains which can develop and perform as well as in saline and non-saline soil.

Plant tolerance to salinity is often assessed in terms of biomass produced (Ruiz-Lozano et al., 2012; Evelin et al., 2019). The results showed a decrease in biomass with increasing salinity showing by a reduction in plant growth. However, total biomass is generally higher in inoculated plants, especially treatments with *Rhizoglossus* which is more effective. According to some authors (Nawaz et al., 2022; Dastogeer et al., 2020; Azooz et al., 2004) salinity can lead to a decrease in biomass production because increased soil salinity leads to a decrease in plant water potential, osmotic stress, ionic toxicities or nutrient imbalance. However, inoculation improves biomass production with salinity, leading to an improvement in plant tolerance. According to Talaat and Shawky (2011), higher biomass leads to a dilution of Na ions and manifests itself in higher plant productivity.

Also, Soliman et al. (2012) showed that the main effect of salinity on *Acacia* plants is growth reduction, but inoculation improves the growth of inoculated plants.

Egamberdieva et al. (2019) noted that salt-tolerant rhizobia can improve legume productivity under salinity conditions. Ali et al. (2023) and Ilangumaran et al. (2021) found that legumes survived and grew better under salinity conditions when inoculated with salt-tolerant rhizobia. Thus, halotolerant strains improve plant growth under salt stress through the production of phytohormones, the biosynthesis of exopolysaccharides, ACC deaminase and volatile organic compounds (Mukhtar et al., 2019). These organic molecules act as chemical signals for plant metabolic pathways; help improve soil properties that reduce the adverse effects of salinity.

Nodulation and nitrogen fixation provide plants with nitrogen, while mycorrhization improves the hydromineral nutrition of plants, particularly their phosphorus content, due to hyphae that can draw water and minerals from very far away for the benefit of the plant (Smith and Read, 2008). It has been noted that inoculation increases mycorrhization parameters in non-sterile soils, whether with AMF alone or in double-inoculation. This positive effect is also noted in moderate salinity or high salinity soils, showing the importance to inoculate plants, particularly in tropical soils with low populations of symbiotic microorganisms. Indeed, symbiotic association with AMFs improves water uptake, nutrient acquisition and plant growth, among others.

According to Begum et al. (2019), AM fungi facilitate vigorous growth of host plants under stressful conditions by mediating a series of complex communication events between the plant and the fungus.

According to Zhang et al. (2016), inoculation with AMF could be a method of improving rice grain yield and quality because it significantly improves nitrogen accumulation and distribution in vegetative tissues at tillering and affects nitrogen distribution in the seeds. Thioye et al. (2017) showed the beneficial effect of *Rhizoglyphus irregularis* and *R. intraradices* on *Ziziphus* species.

According to Manga et al. (2017) inoculation with *R. intraradices* improved growth in *V. seyal* under salinity conditions, however the choice of fungal partner to inoculate is important in improving salinity tolerance.

Analysis of the minerals in the shoot biomass of plants has shown large responses of plants to inoculation, perhaps due to the unsterilized soil used. Thus, inoculated plants often contain more N, P and K. Na content increases in plant shoots with increasing salinity because, as described by Paganová et al. (2024), Na ions are stored in the plant organs (roots and shoots). The most tolerant species maintain a better K/Na balance in leaves as reported by Mateus et al. (2021). Indeed, Assaha et al. (2017) showed that one of the most important effects of salinity is the ionic stress caused by excessive accumulation of Na ions, particularly in the aerial parts of plants. Thus, ion regulation plays an important role in plant growth and stress tolerance, and potassium is a key

component.

The K/Na ratio is higher in the absence of salinity and decreases as salinity increases. Thus, with salinity the ratio increases in inoculated plants, particularly plants inoculated with rhizobia and AMF. In fact, the K/Na ratio is also important under stress conditions, as maintaining a high K/Na ratio prevents various K-regulated enzymatic processes from interfering (Rabiei et al., 2020). Several authors reported the importance of the K/Na ratio as an indicator of plant tolerance to salinity (Talwar et al., 2011; Wakeel, 2013; Gao et al., 2016; Klinsukon et al. 2021). A higher K/Na ratio gives plants better tolerance to salinity (Abbas et al., 2013). According to Assaha et al. (2017), a high K/Na ratio is generally maintained in onion through appropriate expression of the regulation of K and Na transporter activity and hydrogen pumps, thereby leading to better adaptation to stress.

Furthermore, it has been noted at high salinity (500 mM of NaCl), plants lose their leaves and then regenerate smaller, fewer leaves. According to Li et al. (2025) the continuous osmotic stress severely inhibits the growth of new leaves. The reduction in leaf size at 600 mM was also described by Munns (2005). According to this author, it is due to a hormonal control of cell division and differentiation that appears on the leaves, which become smaller but often thicker, indicating that the size and shape of the cells have changed (James et al., 2002). The leaves of salt-treated plants have a higher weight/surface area ratio. In addition, Yu et al. (2019) reported that salinity reduced leaf growth and shortened the leaf elongation period, resulting in shorter leaves. The same result was observed with *V. seyal* plants by Fall et al. (2017), and according to these authors when salinity increases the plant loses its leaves.

Finally, this study demonstrated that salinity decreases the *V. nilotica* plant's growth, marked by a decrease of shoot and root biomass as well as plant height. Symbiotic parameters were also affected, with a reduction in nodulation and mycorrhization. However, inoculation with combined rhizobia and AMF improves these parameters, enabling *V. nilotica* to be better developed in a salt affected lands.

Thus, inoculation of plants is important because microbial populations in saline soils are reduced. Results showed also that *Rhizoglyphus* spp. are often more effective, particularly when combined with the salt tolerant *Mesorhizobium*, indicating that these strains could be applied as biofertilizer to improve plant nurseries for the rehabilitation of salt affected soils. Variability in the response of inoculum to salinity may be due to the presence of indigenous strains that can express themselves in unsterilized soil.

The number of nodules was not correlated with efficiency in plant development, and this could be explained by the fact that nodules are often very large with a fewer number.

ACKNOWLEDGEMENTS

The authors thank O. S. Gueye (UCAD, Dakar), for its valuable technical assistance. This work was partially supported by PAPES funding program; we are grateful to the Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation (MESRI) of Senegal.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

- Abd-Alla MH, Nafady NA, Bashandy SR, Hassan AA (2019). Mitigation of effect of salt stress on the nodulation, nitrogen fixation and growth of chickpea (*Cicer arietinum* L.) by triple microbial inoculation. *Rhizosphere* 10:100148.
- Al-shaharani TS, Shetta ND (2011). Evaluation of growth, nodulation and nitrogen fixation of two *Acacia* species under salt stress. *World Applied Sciences Journal* 13:256-265.
- Ali Q, Shabaan M, Ashraf S, Kamran M, Zulfiqar U, Ahmad M, Zahir ZA, Sarwar MJ, Iqbal R, Ali B, Ali MA, Elshikh MS, Arslan M (2023). Comparative efficacy of different salt-tolerant rhizobial inoculants in improving growth and productivity of *Vigna radiata* L. under salt stress. *Scientific Reports* 13(1):17442.
- Abbas G, Saqib M, Akhtar J, Basra SMA (2013). Salinity tolerance potential of two acacia species at early seedling stage. *Pakistan Journal of Agricultural Sciences* 50(4):683-688.
- Assaha D, Ueda A, Saneoka H, Al-Yahyai R, Yaish MW (2017). The role of Na⁺ and K⁺ transporters in salt stress adaptation in Glycophytes. *Frontiers in physiology* 8:509.
- Azooz MM, Shaddad MA, Abdel-Latef AA (2004). Leaf growth and K⁺/Na⁺ ratio as an indication of the salt tolerance of three sorghum cultivars grown under salinity stress and IAA treatment. *Acta Agronomica Hungarica* 52:287-296.
- Begum N, Qin C, Anger MA, Raza S, Khan MI, Ashraf M, Ahmed N, Zhang L (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: Implications in abiotic stress tolerance. *Frontiers in Plant Science* 10:1068.
- Bouhnik O, ElFaik S, Alami S, Talbi C, Lamin H, Abdelmoumen H, Munoz GT, Bedmar EJ, Missbah El Idrissi M (2019). *Ensifer fredii* symbiovar *vachelliae* nodulates endemic *Vachellia gummifera* in semiarid Moroccan areas. *Systematic and Applied Microbiology* 42(5):125999.
- Dastogeer KMG, Zahan MI, Tahjib-Ul-Arif M, Akter MA, Okazaki S (2020). Plant salinity tolerance conferred by arbuscular mycorrhizal fungi and associated mechanisms: A meta-analysis. *Frontiers in Plant Science* 11:588550.
- Egamberdieva D, Wirth S, Bellingrath-Kimura SD, Mishra J, Arora NK (2019). Salt-Tolerant Plant Growth Promoting Rhizobacteria for Enhancing Crop Productivity of Saline Soils. *Frontiers in Microbiology* 10:2791.
- Elsiddiq AMI, Zhou G, Zhu G, Nimir NEA, Suliman MSE, Ibrahim MEH, Ali AYA (2023). Nitrogen fertilizer promoting salt tolerance of two sorghum varieties under different salt compositions. *Chilean Journal of Agricultural Research* 83(1):3-13.
- Evelin H, Devi TS, Gupta S, Kapoor R (2019). Mitigation of salinity stress in plants by arbuscular mycorrhizal symbiosis: Current understanding and new challenges. *Frontiers in Plant Science* 10:470.
- Fall D, Diouf D, Ourarhi M, Faye A, Abdelmoumen H, Neyra M, Sylla SN, Missbah El Idrissi M (2008). Phenotypic and genotypic characteristics of *Acacia senegal* (L.) Willd. root-nodulating bacteria isolated from soils in the dryland part of Senegal. *Letters Applied Microbiology* 47(2):85-97.
- Fall D, Bakhoun N, Fall F, Diouf F, Faye MN, Ndiaye C, Hochoer V, Diouf D (2017). Improvement of tree growth in salt-affected soils under greenhouse conditions using a combination of peanut shells and microbial inoculation. *Journal of Agricultural Biotechnology and Sustainable Development* 9(5):34-44.
- Gao Y, Lu Y, Wu M, Liang E, Li Y, Zhang D, Yin Z, Ren X, Dai Y, Deng D, Chen J (2016). Ability to remove Na⁺ and retain K⁺ correlates with salt tolerance in two maize inbred lines seedlings. *Frontiers in Plant Science* 7:1716.
- Heng T, Ma Y, Ai P, Liu Z, Wu M, Liu C (2024). The effects of soil salt stress on the nitrogen uptake, yield response and nitrogen use efficiency of cotton in arid areas. *Agronomy* 14(1):229.
- Ilangumaran G, Schwinghamer TD, Smith DL (2021). Rhizobacteria From Root Nodules of an Indigenous Legume Enhance Salinity Stress Tolerance in Soybean. *Frontiers in Sustainable Food Systems* 4:1-18.
- James RA, Rivelli AR, Munns R, Von Caemmerer S (2002). Factors affecting CO₂ assimilation, leaf injury and growth in salt-stressed durum wheat. *Functional Plant Biology* 29:1393-1403.
- Klinsukon C, Lumyong S, Kuyper TW, Boonlue S (2021). Colonization by arbuscular mycorrhizal fungi improves salinity tolerance of eucalyptus (*Eucalyptus camaldulensis*) seedlings. *Scientific Reports* 11:4362.
- Kyalangaliwa B, Boatwright JS, Daru BH, Maurin O, van der Bank M (2013). Phylogenetic position and revised classification of *Acacia* sl. (*Fabaceae: Mimosoideae*) in Africa, including new combinations in *Vachellia* and *Senegalia*. *Botanical Journal of the Linnean Society* 172(4):500-523.
- Li HP, Ma HB, Zhang JL (2025). Halo-tolerant plant growth-promoting bacteria-mediated plant salt resistance and microbiome-based solutions for sustainable agriculture in saline soils. *FEMS Microbiology Ecology* 101(5):fiae037.
- Lu Y, Fricke W (2023). Salt stress-regulation of root water uptake in a whole-plant and diurnal context. *International Journal of Molecular Sciences* 24(9):8070.
- Manga A, Ndiaye F, Diop, TA (2017). Le champignon arbusculaire *Glomus aggregatum* améliore la nutrition minérale d'*Acacia seyal* soumis au stress salin progressif. *International Journal of Biological and Chemical Sciences* 11(5):2352-2365.
- Mateus NS, Leite AF, Santos EF, Ferraz AV, Goncalves JLM, Lavres J (2021). Partial substitution of K by Na alleviates drought stress and increases water use efficiency in *Eucalyptus* Species seedlings. *Frontiers in Plant Science* 12:689963.
- Mukhtar S, Malik KA, Mehnaz S (2019). Microbiome of halophytes: Diversity and importance for plant health and productivity. *Microbiology and Biotechnology Letters* 47(1):1-10.
- Munns R (2005). Genes and salt tolerance: Bringing them together. *New Phytologist* 67(3):645-663.
- Munns R, Tester M (2008). Mechanisms of salinity tolerance. *Annual Review of Plant Biology* 59:651-681.
- Nawaz M, Hassan MU, Chattha MU, Mahmood A, Shah AN, Hashem M, Alamri S, Batool M, Rasheed A, Thabit MA, Alhaithloul HAS, Qari SH. (2022). Trehalose: A promising osmo-protectant against salinity stress-physiological and molecular mechanisms and future prospective. *Molecular Biology Reports* 49(12):11255-11271.
- Paganová V, Hus M, Lichtnerová H, Ziarovska J, Moravčíková D, KučkaM, Ražná K, Abbas A (2024). Physiological and molecular responses of *Pyrus pyraeaster* seedlings to salt treatment analyzed by miRNA and Cytochrome P450 gene-based markers. *Plants* 13:261.
- Phillips JM, Hayman DS (1970). Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. *Transactions of British Mycological Society* 55:158-161.
- Quiñones-Aguilar EE, Montoya-Martínez AC, Rincón-Enríquez G, Lobit P, López-Pérez L (2016). Effectiveness of native arbuscular mycorrhizal consortia on the growth of *Agave inaequidens*. *Journal of Soil Science and Plant Nutrition* 16: 1052-1064.
- Rabiei Z, Hosseini SJ, Pirdashti H, Hazrati S (2020). Physiological and biochemical traits in coriander affected by plant growth-promoting rhizobacteria under salt stress. *Heliyon* 6(10):e05321.
- Ruiz-Lozano JM, Porcel R, Bárcana G, Azcón R, Aroca R (2012).

- Contribution of arbuscular mycorrhizal symbiosis to plant drought tolerance: State of the art. In Plant responses to drought stress: From morphological to molecular features pp 335-362.
- Samba-Mbaye RT, Anoir CM, Diouf D, Kane A, Diop I, Assigbete K, Tendeng P, Sylla SN (2020). Diversity of arbuscular mycorrhizal fungi (AMF) and soils potential infectivity of *Vachellia nilotica* (L) PJH Hurter & Mabb rhizosphere in Senegalese salt-affected soils. African Journal of Biotechnology 19(7):487-499.
- Sène G, Thiao M, Samba Mbaye R, Ndoeye F, Kane A, Diouf D, Sylla S N (2010). Response of three peanut cultivars toward inoculation with two *Bradyrhizobium* strains and an Arbuscular mycorrhizal fungus in Senegal. African Journal of Microbiology Research 4(23):2520-2527.
- Sène G, Samba Mbaye R, Thiao M, Khasa D, Kane A, Manga A, Mbaye MS, Sylla SN (2012). The Abundance and Diversity of legume-nodulating rhizobia and arbuscular mycorrhizal fungal communities samples from deforested and man-made forest system in a semiarid sahel region in Senegal. European journal of Soil Biology 52:30-40.
- Sieverding E, da Silva GA, Berndt R, Oehl F (2014). *Rhizoglossum*, a new genus of the *Glomeraceae*. Mycotaxon 129(2): 373-386.
- Smith SE, Smith FA (2011). Roles of arbuscular mycorrhiza in plant nutrition and growth: New paradigms from cellular to ecosystem scales. Annual Review of Plant Biology 62:227-50.
- Smith SE, Read DJ (2008). Mycorrhizal symbiosis. 3rd edition Elsevier, Academic Press.
- Soliman AS, Shanan NT, Massoud ON, Swelim DM (2012). Improving salinity tolerance of *Acacia saligna* (Labill.) plant by arbuscular mycorrhizal fungi and *Rhizobium* inoculation. African Journal of Biotechnology 11(5):1259-1266.
- Soumaré A, Manga AGB, Thiao M, Ndoeye I, Diop TA (2008). Effet de l'inoculation des champignons mycorrhiziens arbusculaires sur le développement d'*Acacia nilotica* subsp. *Adstringens* soumis à différentes concentrations de sel. Journal des Sciences et Technologies 7(1):74-83.
- Talaat NB, Shawky BT (2011). Influence of arbuscular mycorrhizae on yield, nutrients, organic solutes, and antioxidant enzymes of two wheat cultivars under salt stress. Journal of Plant Nutrition and Soil Science 174:283-291.
- Talwar HS, Kumari A, Surwenshi A, Seetharama N (2011). Sodium: Potassium ratio in foliage as an indicator of tolerance to chloride-dominant soil salinity in oat (*Avena sativa*). The Indian Journal of Agricultural Sciences 81(5).
- Thioye B, Mania S, Kane A, Ndiaye C, Ould Soule A, Fall D, Duponnois R, Sylla SN, Bâ AM (2017). Growth response of different species of *Ziziphus* to inoculation with arbuscular mycorrhizal fungi. Fruits 72(3):174-181.
- Thrall PH, Bever JD, Slattery JF (2008). Rhizobial mediation of *Acacia* adaptation to soil salinity: Evidence of underlying trade-offs and tests of expected patterns. Journal of Ecology 96:746-755.
- Thrall PH, Broadhurst LM, Hoque MS, Bagnall DJ (2009). Diversity and salt tolerance of native *Acacia* rhizobia isolated from saline and non-saline soils. Austral Ecology 34:950-963.
- Trouvelot A, Kouh J, Gianinazzi-pearson V (1986). Mesure du taux de mycorrhization VA d'un système racinaire. Recherche des méthodes d'estimation ayant une signification fonctionnelle. Physiological and Genetical Aspects of Mycorrhizae 217-221.
- Wakeel A (2013). Potassium-sodium interactions in soil and plant under saline-sodic conditions. Journal of Plant Nutrition and Soil Science 176:344-354.
- Wang Y, Wang M, Li Y, Wu A, Huang J (2018). Effects of arbuscular mycorrhizal fungi on growth and nitrogen uptake of *Chrysanthemum morifolium* under salt stress. PLoS One 13(4):1-14.
- Yu X, Shi P, Hui C, Miao L, Liu C, Zhang Q, Feng C (2019). Effects of salt stress on the leaf shape and scaling of *Pyrus betulifolia* Bunge. Symmetry 11(8):991.
- Zhang X, Li W, Fang M, Jixian Y, Meng S (2016). Effects of arbuscular mycorrhizal fungi inoculation on carbon and nitrogen distribution and grain yield and nutritional quality in rice (*Oryza sativa* L). Journal of the Science of Food and Agriculture 97:2919-2925.