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Reclamation of Saline Soil under Association between *Atriplex nummularia* L. and Glycophytes Plants

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Abstract: Phytoremediation is an efficient technique for the reclamation of salt-affected soils by growing plants. The present study aims to evaluate the intercropping of halophyte *Atriplex nummularia* Lindl. with naturally occurring species (*Mimosa caesalpiniifolia* Benth, *Leucaena leucocephala* (Lam.) de Wit and *Azadirachta indica* A. Juss.) adapted to semiarid regions as a management capable of enhancing the phytoremediation capacity of these species. A field experiment was conducted in a randomized block and contained four replicates. Species were cultivated alone and in association with *A. nummularia* to evaluate their potential uses in the reclamation of soils. Exchangeable Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, as well as salinity and sodicity variables, were evaluated. The evaluations were performed at 9 and 18 months of plant growth. The results indicated that *A. nummularia* individualized was the treatment most efficient; with reductions of 80%, 63%, and 84% in electrical conductivity, sodium adsorption ratio, and exchangeable sodium percentage values, respectively at 18 months compared to starting of the experiment. However, the use of *A. nummularia* and species adapted to the semiarid in association, or even alone, promoted beneficial effects on the soil quality after the establishment of the plants.

Keywords: phytoremediation; *Azadirachta indica*; *Leucaena leucocephala*; *Mimosa caesalpiniifolia*; salt-affected soils; soil reclaim

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1. Introduction

Salinization is one of the main processes of soil degradation in the world, besides being one of the environmental factors limiting the productivity of agricultural crops [1,2]. Its occurrence is mainly associated with arid and semiarid regions around the world, occurring in practically all the continents and corresponds to 7% of the total world's surface area [3,4].

Salts in excess can lead to drastic changes in some soil's physical and chemical properties resulting in the development of an environment unsuitable for the growth of most crops [5,6]. The increase in the extent of degraded areas by salts is in the opposite direction of the necessary increase in food production (71%) between 2005 and 2050 [7,8]. In addition to agricultural impacts, the increase in soil degradation directly affects the maintenance of the hydrological cycle, the health of the terrestrial biosphere, favors pollution and eutrophication of water bodies, consequently, affecting the global and local economy [9].

On the other hand, the tendency of a given area to deteriorate can be reversed by restoring land use or by using appropriate management practices [7]. The reclamation of degraded areas by salinity stands out as an effective way of alleviating population pressure and contributing to food security for future generations [10,11].

Phytoremediation is an alternative and efficient technique that consists of the cultivation of tolerant vegetable species, with the capacity to extract expressive amounts of salts from the soil and to store them in their tissues throughout their life cycle [12,13]. This technique is presented as a low-cost technique and is more consistent with the socioeconomic and edaphoclimatic conditions of these regions [14,15].

Areas undergoing reclaim tend to have improved physical, chemical, and microbiological properties as the revegetation process evolves [16,17]. Among the main changes are the increase in soil fertility, organic matter accumulation in the soil, reduction of erodibility, increase in water retention in the soil, and reduction of salinity [5].

Studies with plants with proven effectiveness in reclamation saline soils are still scarce and have been carried out with halophytes, especially plants of the Atriplex genus. However, these plants are not known by some rural populations and, therefore, are not well accepted. Other species, such as Sabiá (*Mimosa caesalpiniifolia* Benth) and Leucaena (*Leucaena leucocephala* (Lam.) de Wit), already quite adapted to the semiarid region could be tested for adaptability to saline and sodic soils. Or even less known ones, but which have been highlighted recently, such as Neem (*Azadirachta indica* A. Juss.) which has the capacity to adapt to numerous climatic and edaphic factors.

The adaptation of these plants to salinity in field conditions is not well understood and their cultivation in association with a halophyte could improve their establishment. The use of plant species with different root systems can promote a more effective action of these in the reclamation, leading to improvements in the quality of the soils under revegetation, and increasing the extraction of salts from the soil. Moreover, *Atriplex nummularia* Lindl. may improve soil properties so that other plant species can develop on degraded soils, protecting soil and water in semiarid environments, and contributing to environmental quality. The objective of this study was to evaluate the use of tree species alone and in association with *Atriplex nummularia* L. in the revegetation of degraded soil in the semi-arid region, increasing reclamation.

2. Materials and Methods

2.1. Study Area

The experiment was conducted in Cachoeira II Irrigated Perimeter, Municipality of Serra Talhada, Pernambuco, semiarid region of Brazil (7°58′54′′ to 8°01′36′′ S and 38°18′24′′ to 38°21′21′′ W) (Figure 1). The soil in the area is Fluvisol [18], which has flat relief, with small gradients and serious problems of water infiltration. For a long time (around 30 years), the area was used for banana cropping under furrow irrigation. Thereafter, due to soil degradation, the area was left without agricultural use for eight years.

The climate in the area is BSh type (semiarid of low latitude and altitude), with a dry period of nine months and rainfall concentrated from February to April [19]. Temperature ranges from 64.4 to 98.6 °F (average 80.6 °F) and 720 mm of average annual rainfall.

2.2. Species Selection

To test the adaptability of species to saline-sodic soils, as well as to enable their cultivation as an alternative practice in the management of soil reclamation, we selected three plant species normally found in the semi-arid region of Brazil: Sabiá (*Mimosa caesalpiniifolia* Benth), Leucaena [*Leucaena leucocephala* (Lam.) de Wit] and Neem (*Azadirachta indica* A. Juss). These plants were compared to Atriplex (*Atriplex nummularia* Lindl.), which has already been used in other degraded areas and with proven effectiveness in the reclamation of salt-affected soils, given the characteristics of vegetative growth and the high concentration of salts in the tissues [14].

The *A. indica*, *M. caesalpiniifolia,* and *L. leucocephala* are plant species adapted to the semiarid region and could be tested regarding the potential of reclamation saline and sodic soils, for sustainable management and use of products from plants.

An additional consideration for the species selection deals with the root effect, which provides channels for the percolating soil solution. An added advantage relates to the better availability of some macro and micronutrients after soil amelioration that involves ions leaching.

Figure 1. Study area location, Irrigated Perimeter Cachoeira II, Serra Talhada, State of Pernambuco, Brazil.

2.3. Seedling Production

The seedlings of each species were cultivated in a greenhouse at the Federal Rural University of Pernambuco, on an organic substrate. It was cropped 85-day-old *A. nummularia* seedlings that were produced from the cuttings of a single mother plant to maintain genetic uniformity. The seedlings of *A. indica*, *L. leucocephala,* and *M. caesalpinifolia* were produced from the seeds and were cropped 90-day-old seedlings.

The seedlings were transplanted to the field when they were 30 cm long (Atriplex, Neem, and Sabiá) or 40 cm (Leucaena). Manually transplanting one plant per hole (0.3 × 0.3 × 0.3 m), without the addition of organic or chemical compost, only seedling substrate.

2.4. Treatments and Experimental Design

The experimental area was divided into four randomized blocks, with the eight tested treatments, totaling 32 experimental plots. Each plot was dimensioned in 8 × 8 m (64 m^2) and the useful plot was 4 × 4 m (16 m^2). These eight studied treatments were: four individualized treatments where the selected species were cultivated alone (Sabiá, Leucaena, Neem, Atriplex, one in each plot); three treatments associating Atriplex and one of the other species (Atriplex/Sabiá, Atriplex/Leucaena, and Atriplex/Neem); and one control treatment, without cultivation of any plant species.

The control plots were not cultivated and were kept without plants, by manual weeding the naturally occurring species (self-sown plants) once a month, using a hoe.

The planting spacing was 2 × 2 m, totaling 16 plants per plot and 4 plants in the useful plot. The seedlings were transplanted to the field in November 2013, with a height varying between 0.3–0.4 m. No addition of fertilizer, organic, or chemical was performed during the experiment. To ensure the establishment of seedlings, weekly irrigations were carried out for 60 days after transplanting. The water used for irrigation was pumped directly from the Pajeú River (Table 1).

Table 1. Water characteristics: pH, electrical conductivity (EC), soluble cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}), sodium adsorption ratio (SAR), and Pajeú river water classification for salinity and sodicity risk.

pH	EC	Na^+	K^+	Ca^{2+}	Mg^{2+}	SAR	Risk [1]
	dS m^{-1}	mmol$_c$ L^{-1}				(mmol$_c$ $L^{-1})^{0.5}$	
7.89	1.28	19.25	0.25	2.30	0.23	17.11	C3S2

[1] USSL Staff [19].

2.5. Soil Sampling

For the characterization and evaluation of soil chemical quality, four simple samples were collected at the center of each plot to constitute composite samples, one for each plot. The samples were taken at 0.5 m from the stem of the four central plants in the useful area. In the control treatment, the center of the useful area was used as a reference for sampling.

Three soil samplings were performed. In the sampling for chemical characterization of the soil in the experiment set up, thirty-two samples were collected in the 0–30 cm layer. Whereas in the two samplings to evaluate changes in soil chemical quality, performed at 9 and eighteen months after setting up the experiment, the samples were always collected at depths of 0–10, 10–30, and 30–60 cm layers.

After each sampling, the soil samples were air dried and sieved in a 2 mm mesh, and reserved for chemical analysis.

2.6. Soil Chemical Analyzes

Exchangeable cations Ca^{2+}, Mg^{2+}, Na^+ and K^+ were extracted by 1 mol L^{-1} ammonium acetate at pH 7.0 [20], in which Na^+ and K^+ were quantified by flame photometry, and Ca^{2+} and Mg^{2+} by atomic absorption spectrophotometry [21]. Cation exchangeable capacity was determined by the cation index method [19]. Sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP) were calculated according to USSL Staff [19].

Soluble cations were quantified in the saturation extract, obtained by the preparation of the saturated paste, and extracted under vacuum according to the saturation paste method [19]. In the extract was measured electrical conductivity (EC 25 °C), soluble cations Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry, and Na^+ and K^+ by flame emission photometry. Soil pH was measured in water in the proportion of 1:2.5 (soil:water).

Particle size distribution was performed using the pipetting method modified by Ruiz [22]. To each 10-g sample was added 50 mL of NaOH solution (0.1 mol L^{-1}) and 150 mL of deionized water; the mixture was stirred with a glass rod and left to settle overnight. The mixtures were then dispersed by shaking at 12,000 rpm for 15 min, after which the suspension was passed through a 0.053-mm sieve to quantify the total sand, and then this total was passed through a 0.2-mm sieve to separate and quantify the fine sand and coarse sand fractions.

Silt and clay fractions were collected in a 500-mL graduated cylinder and shaken again. Immediately afterward, we collected 25 mL of the silt + clay suspension and allowed it to settle for the time calculated by Stokes' Law for the ambient temperature. Then we collected another 25 mL of the suspension from 5 cm below the surface (clay fraction). All fractions were oven-dried at 100 °C and weighed to calculate the percentages of coarse sand, fine sand, silt, and clay. Soil chemical and physical characterization are in Table 2.

Table 2. Soil chemical characteristics and particle size distribution of the soil collected at the experiment set up (0–30 cm layer).

EC [2] dS m^{-1}	pH 1:2.5	Exchange Complex [1]				CEC [3]	ESP [4]	Soil Particle Size [5]			
		Na^+	K^+	Ca^{2+}	Mg^{2+}			Coarse Sand	Fine Sand	Silt	Clay
		cmol$_c$ kg^{-1}					%	g kg^{-1}			
5.48	7.23	5.99	1.05	1.59	0.68	9.51	64	51.0	712.0	75.0	162.0

[1] USSL Staff [19]. [2] Electrical conductivity; [3] Cation exchange capacity; [4] Exchangeable sodium percentage; [5] Ruiz [22]. Clay (≤2 µm); silt (2–53 µm); fine sand (53–200 µm); coarse sand (200–2000 µm). Average values of thirty-two soil samples collected in the 0–30 cm layer.

In the experiment set up, the soil prior to treatments (0–30 cm depth) was saline-sodic, EC = 6.48 dS m^{-1} and ESP = 64% (Table 2). Despite the sandy loam texture, the exchangeable cations are maintained in the soil exchange complex in the sequence $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$. And pH is slightly alkaline.

2.7. Statistical Analysis

First, we applied the normality test to the evaluated variables, using the Kolmogorov-Smirnov test. Subsequently, an analysis of variance was performed using Fisher's F test, both with 5% significance. For significant variables, the means obtained were submitted to the Student's T test, comparing the effects of orthogonal contrasts for treatments, compared the effects at 5% probability. The Skott-Knott test was applied at 10% probability for the means of salinity and sodicity variables (pH, EC, SAR, and ESP). The results were evaluated according to the treatments applied at different sampling times.

3. Results

The growth rate of *A. nummularia* was uniform until eight months after transplantation (MAT), after this period, the increase was less pronounced until 18 MAT. Although, the growth rate of *A. indica* and *L. leucocephala* the increase was less pronounced after 12 MAT and after 10 MAT to *M. caesalpinifolia*.

The height of Atriplex, Leucaena, and Neem plants showed higher mean values observed in the individualized treatments compared to the associated treatments, possibly due to competition between species. However, Atriplex plant development was observed regardless of soil salinity in the area. In contrast, inhibition of the growth dynamic of Sabiá plants was observed both when cultivated alone and in association with Atriplex.

The *A. nummularia* and *L. leucocephala* showed no signs of stress. The adaptive responses of *M. caesalpinifolia* were more evident visually, expressed by the yellowing of leaves and early foliar senescence, resulting in a reduced number of leaves, which may be associated with the toxicity caused by saline ions. It is also possible to state that as a criterion of adaptability to stress conditions, there was a halt in the growth of *M. caesalpinifolia*, with a loss of biomass production. Signs of stress were also observed in *A. indica*, with a number and position of branches frequent in the lower parts of the plants. This is a common mechanism in stressed neem plants to reduce the effects of soil salt concentrations.

3.1. Exchangeable Cations

There was no difference for exchangeable Na^+ and K^+ in soil between applied treatments at 9 months of growth at 0–10, 10–30, and 30–60 cm layers (Figure 2). However, changes occurred in these exchangeable cations at 18 months of cultivation. In general, the cultivation of plants promoted a decrease in exchangeable Na^+ and K^+ contents in the soil.

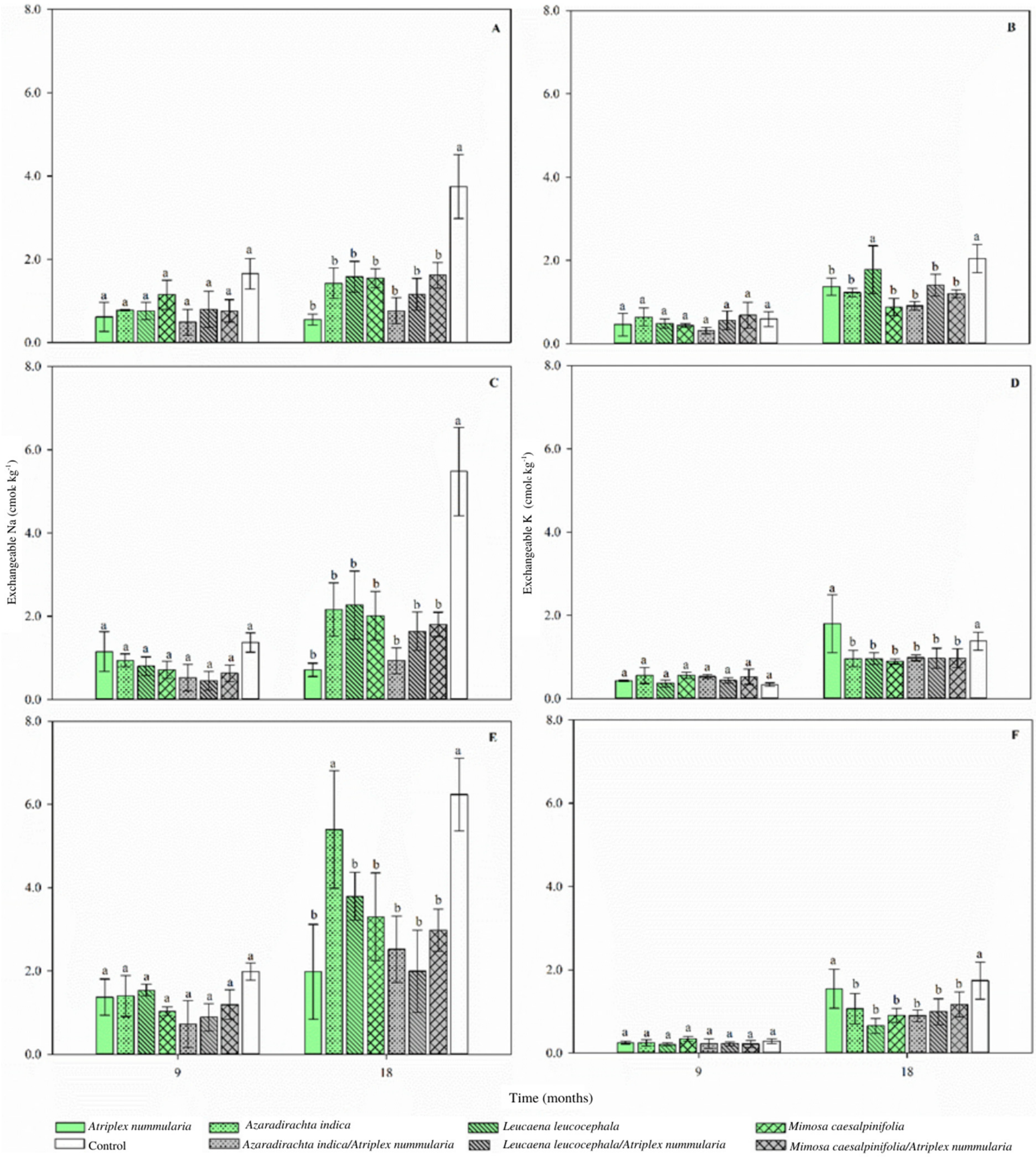

Figure 2. Exchangeable Na^+ [(**A**) 0–10 cm; (**C**) 10–30 cm; (**E**) 30–60 cm] and K^+ [(**B**) 0–10 cm; (**D**) 10–30 cm; (**F**) 30–60 cm] at 9 and 18 months as result of the applied treatments (Averages of four replications). Averages followed by the same letter have no difference in the same layer and time of sampling by the Skott-Knott test ($p \leq 0.05$).

These Na^+ values influenced the results of contrasts at 9 months, a significant difference was observed between the groups for the variables of sodicity (SAR and ESP), were significant for SAR at 0–10 cm and 10–30 cm layers; and for ESP at 0–10 cm and 30–60 cm layers. At the same sampling time, the contrasts (All treatments × control), (Associations × control), and (Isolated cultures × associations) were significant for pH at 30–60 cm layer; and the contrast (No leguminous × leguminous) at 10–30 cm layer. For EC, only contrasts (Isolated cultures × control) and (Leguminous × control) were significant at the 30–60 cm layer.

The effect of growing plants on mean values of SAR and ESP was verified, ESP was decreased and the soil did not remain as sodic at 9 months in the evaluated layers, except for *A. indica* treatment in the first layer and control treatment at 0–10 cm and 30–60 cm layers (Table 3). Initial changes in SAR and ESP were observed under growing plants in some soil layers.

Table 3. Orthogonal contrasts of chemical attributes pH (potential of hydrogen), EC (electrical conductivity), SAR (sodium adsorption ratio), and ESP (exchangeable sodium percentage) in the soil at 0–10, 10–30, and 30–60 cm depth as a function of applied treatments at 9 months.

Contrast	pH			EC			SAR			ESP		
	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm
All treatments × control	0.253	0.695	2.169 *	−2.003	−1.242	−2.075	−0.095	−0.950	−0.439	−1.139	−1.261	−1.219
Isolated cultures × control	−0.247	0.582	1.414	−1.860	−1.239	−2.198 *	−0.146	−0.789	−0.393	−0.840	−0.814	−0.873
Associations × control	0.867	0.751	2.860 **	−1.926	−1.084	−1.644	−0.018	−1.034	−0.441	−1.377	−1.674	−1.506
Leguminous × control	−0.710	−0.531	1.463	−1.631	−1.534	−2.286 *	−0.084	−0.908	0.168	−0.888	−1.239	−0.905
No leguminous × control	0.258	1.593	1.119	−1.765	−0.728	−1.728	−0.183	−0.532	−0.886	−0.646	−0.248	−0.688
Isolated cultures × associations	−1.672	−0.284	−2.254 *	0.189	−0.174	−0.732	−0.187	0.408	0.092	0.852	1.338	1.000
No leguminous × leguminous	1.185	2.601 *	−0.422	−0.165	0.986	0.684	−0.121	0.460	−1.291	0.296	1.214	0.266
Atriplex × all treatments	−0.463	0.602	−0.683	−0.044	−0.628	−0.768	−1.389	−0.774	−1.044	−0.378	1.740	1.000

* Significant at 0.05 probability; ** Significant at 0.01 probability.

At 18 months of cultivation, exchangeable Na^+ and K^+ contents of the soil increased in relation to those recorded at 9 months (Figure 2), although the Na^+ values remained below those found in the initial characterization of the soil (Table 2).

These Na^+ values changes influenced the results of variables of sodicity SAR and ESP at 18 months, a significant difference was observed at any of the layers evaluated (Table 4).

Table 4. Chemical attributes pH (hydrogen potential), EC (electrical conductivity), SAR (sodium adsorption ratio), and ESP (exchangeable sodium percentage) in the soil at 0–10, 10–30, and 30–60 cm depth as a function of treatments at 9 and 18 months (mean of four replicates).

Treatment	pH 1:2.5			EC [1] dS m^{-1}			SAR [2] $(mmol_c\ L^{-1})^{0.5}$			ESP [3] %		
	9 Months											
	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm
Atriplex nummularia	7.15 a	7.31 a	7.30 a	1.23 a	1.32 a	3.23 a	5.72 b	6.52 b	6.22 a	9.33 b	12.61 a	14.41 a
Azaridachta indica	7.28 a	7.48 a	7.21 a	1.24 a	2.94 a	4.50 a	13.38 a	12.59 a	7.37 a	17.73 a	9.54 a	11.38 a
Leucaena leucocephala	7.00 a	7.10 a	7.34 a	0.82 a	1.30 a	2.54 a	10.37 a	7.53 b	8.87 a	8.43 b	7.81 a	13.57 a
Mimosa caesalpinifolia	7.09 a	7.10 a	7.23 a	1.88 a	1.39 a	4.16 a	9.53 a	9.03 b	8.99 a	12.00 b	7.42 a	10.54 a
A. indica/A. nummularia	7.32 a	7.16 a	7.48 a	1.19 a	2.07 a	5.26 a	13.34 a	6.43 b	8.59 a	8.19 b	6.59 a	7.43 b
L. leucocephala/ A. nummularia	7.22 a	7.34 a	7.37 a	2.11 a	2.01 a	1.85 a	4.16 b	5.20 b	4.48 a	9.78 b	5.27 a	9.72 a
M. caesalpinifolia/ A. nummularia	7.46 a	7.29 a	7.58 a	1.32 a	1.35 a	4.19 a	13.15 a	12.43 a	10.16 a	9.44 b	6.73 a	11.75 a
Control	7.15 a	7.18 a	7.10 a	2.54 a	2.85 a	5.51 a	10.30 a	11.39 a	8.58 a	17.80 a	13.01 a	17.83 a
CV (%)	5.41%	11.43%	11.83%	28.01%	32.81%	34.94%	35.28%	36.47%	55.74%	34.60%	66.08%	38.25%
	18 Months											
	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm
Atriplex nummularia	6.77 a	6.59 a	6.57 a	0.97 b	1.08 a	1.34 b	8.55 b	9.36 b	15.84 a	8.09 c	10.39 c	10.59 c
Azaridachta indica	6.36 a	6.64 a	6.41 a	2.76 a	3.06 a	3.23 a	18.92 a	13.08 b	18.24 a	15.52 b	22.82 b	44.81 a
Leucaena leucocephala	6.10 a	6.20 a	6.46 a	2.56 a	2.97 a	2.67 a	10.02 b	7.87 b	6.95 c	17.65 b	19.41 b	32.75 a
Mimosa caesalpinifolia	6.23 a	6.21 a	6.36 a	3.78 a	4.92 a	4.75 a	9.77 b	7.78 b	11.11 b	20.35 b	26.69 b	28.26 b
A. indica/A. nummularia	6.06 a	6.10 a	6.43 a	1.96 a	1.91 a	2.12 a	9.96 b	12.73 b	13.57 b	10.92 c	19.43 b	28.55 b
L. leucocephala/ A. nummularia	6.30 a	6.37 a	6.73 a	1.71 a	1.49 a	1.71 b	13.02 b	12.31 b	17.02 a	14.13 b	18.52 b	19.52 b
M. caesalpinifolia/ A. nummularia	6.35 a	6.49 a	6.53 a	2.23 a	1.94 a	2.58 a	9.14 b	6.87 b	9.39 b	19.78 b	20.12 b	27.90 b
Control	6.52 a	6.64 a	6.64 a	4.54 a	3.85 a	5.51 a	23.28 a	29.58 a	21.29 a	41.03 a	48.07 a	48.53 a
CV (%)	8.61%	8.32%	8.57%	22.19%	39.25%	27.14%	27.16%	29.82%	26.28%	35.60%	32.22%	35.12%

[1] Electrical conductivity; [2] Sodium adsorption ratio; [3] Exchangeable sodium percentage. (Averages of four replications). Averages followed by the same letter have no difference in the same layer and time of sampling by the Skott-Knott test ($p \leq 0.10$).

At 18 months, an effect of treatments with the use of the studied species was observed on EC compared to the control treatment. The influence on salinity reduction (EC values) by the Atriplex treatment in isolated culture was significantly observed ($p \leq 0.10$) at the 0–10 cm and 30–60 cm layers (Table 4).

In the 0–10 and 10–30 cm layers, the exchangeable Na^+ of the soil in all treatments had a difference in relation to the control, showing the efficiency of plant cultivation in not allowing the increase in Na^+ contents in the exchange complex of soil (Figure 2). However, in the last evaluated layer (30–60 cm), isolated *A. indica* cultivation was not able to reduce the content of this element in relation to the soil without plants. The other tested treatments, with the use of isolated or associated intercropped plants, promoted a decrease in exchangeable Na^+ contents of the soil.

There was an increase in the levels of exchangeable Ca^{2+} in the soil at 9 months (Figure 3) in relation to the initial values (Table 2); the contents were higher than 2 $cmol_c$ kg^{-1} in the soil of all treatments in the three layers. Nevertheless, the soil exchangeable Ca^{2+} contents were reduced at 18 months of cultivation, with no difference between treatments.

Exchangeable Mg^{2+} contents remained stable, not differing between the treatments, neither in relation to the control for any of the layers evaluated at 9 or 18 months of plant growth (Figure 3).

3.2. Soluble Cations

No difference among treatments was recorded for concentrations of soluble cations Na^+ and K^+ at 9 months at either depth (Figure 4). The same was observed for Na^+ soluble at 18 months in the superficial layer (0–10 cm). However, differences between treatments were recorded for soluble Na^+ in the subsurface (Figure 4). Plant cultivation reduced soluble Na^+ contents to almost half of that registered in the control treatment in the soil at 10–30 cm. In the 30–60 cm layer, only the isolated cultures and association *M. caesalpiniifolia/A. nummularia* were efficient in reducing the soluble Na^+ contents in soil.

For soluble K^+, a significant difference was observed among the treatments only on the surface for an isolated culture of the *M. caesalpiniifolia* and association *A. indica/A. nummularia* and *M. caesalpiniifolia/A. nummularia*. At layers of 10–30 and 30–60 cm, no differences were found among treatments (Figure 4).

At 9 months of growing plants, there was no difference between treatments for soluble Ca^{2+} contents at 0–10 and 10–30 cm layers. Only at the layer of 30–60 cm, the isolated cultivation treatments of *A. indica*, *L. leucocephala*, and *M. caesalpiniifolia*, and the association *A. indica/A. nummularia* and *M. caesalpiniifolia/A. nummularia* differed from the control (Figure 5).

For soluble Mg^{2+}, differences to control were observed for the isolated cultivation of *L. leucocephala*, *M. caesalpiniifolia*, and for association *A. indica/A. nummularia* and *M. caesalpiniifolia/A. nummularia* at 0–10 cm layer at 9 months (Figure 5). In subsurface (10–30 cm), the increase of Mg^{2+} was observed for association treatment *A. indica/A. nummularia* with respect to the control and other plant treatments. While in the 30–60 cm layer only isolated cultures of *L. leucocephala* and *M. caesalpiniifolia* and associated *L. leucocephala/A. nummularia* and *M. caesalpiniifolia/A. nummularia* differed in relation to the control (Figure 5). The soluble Ca^{2+} and Mg^{2+} values at 18 months after plant cultivation showed no significant difference in any of the layers evaluated (Figure 5).

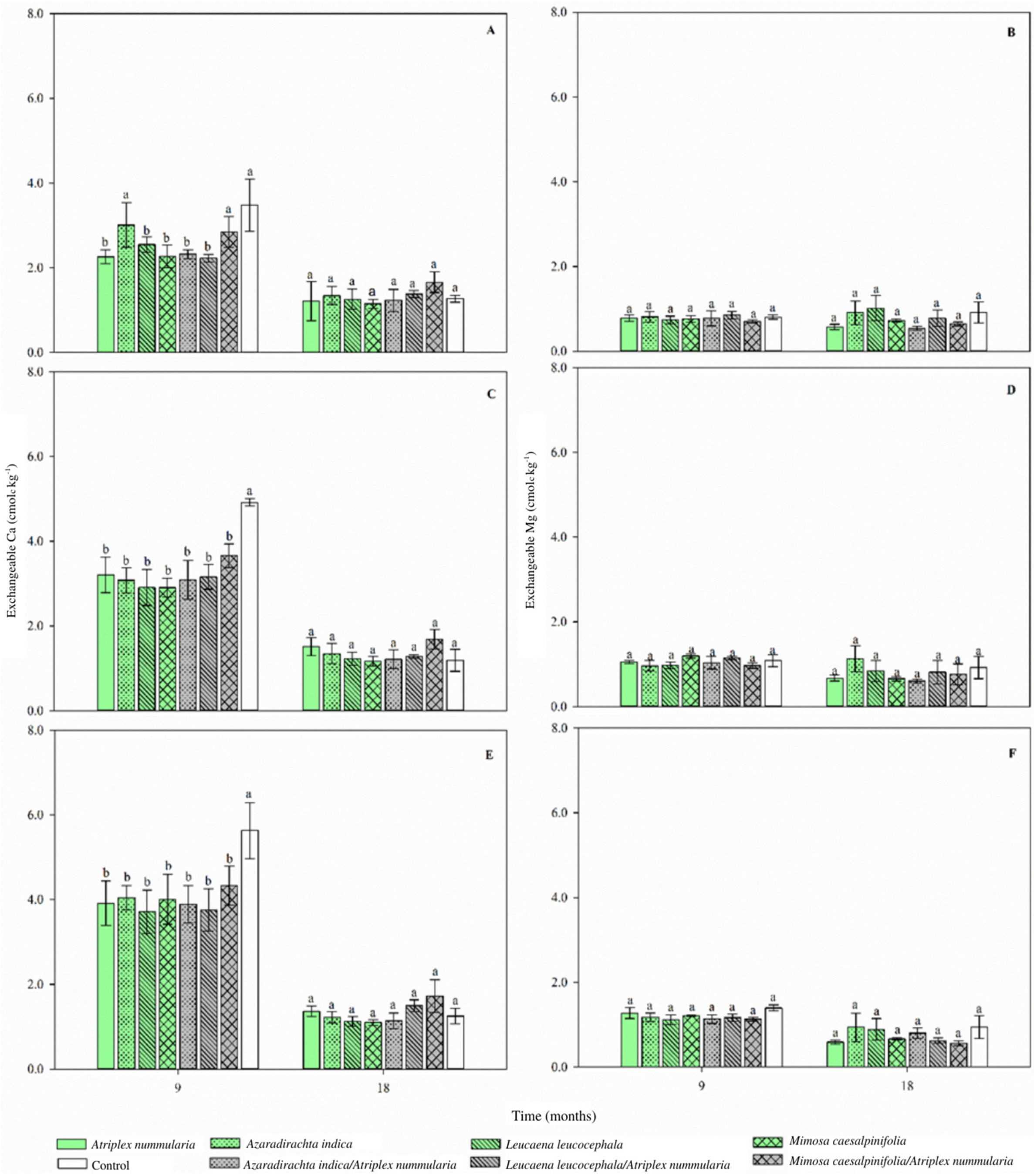

Figure 3. Exchangeable Ca^{2+} [(**A**) 0–10 cm; (**C**) 10–30 cm; (**E**) 30–60 cm] and Mg^{2+} [(**B**) 0–10 cm; (**D**) 10–30 cm; (**F**) 30–60 cm] at 9 and 18 months as result of the applied treatments. (Averages of four replications). Averages followed by the same letter have no difference in the same layer and time of sampling by the Skott-Knott test ($p \leq 0.05$).

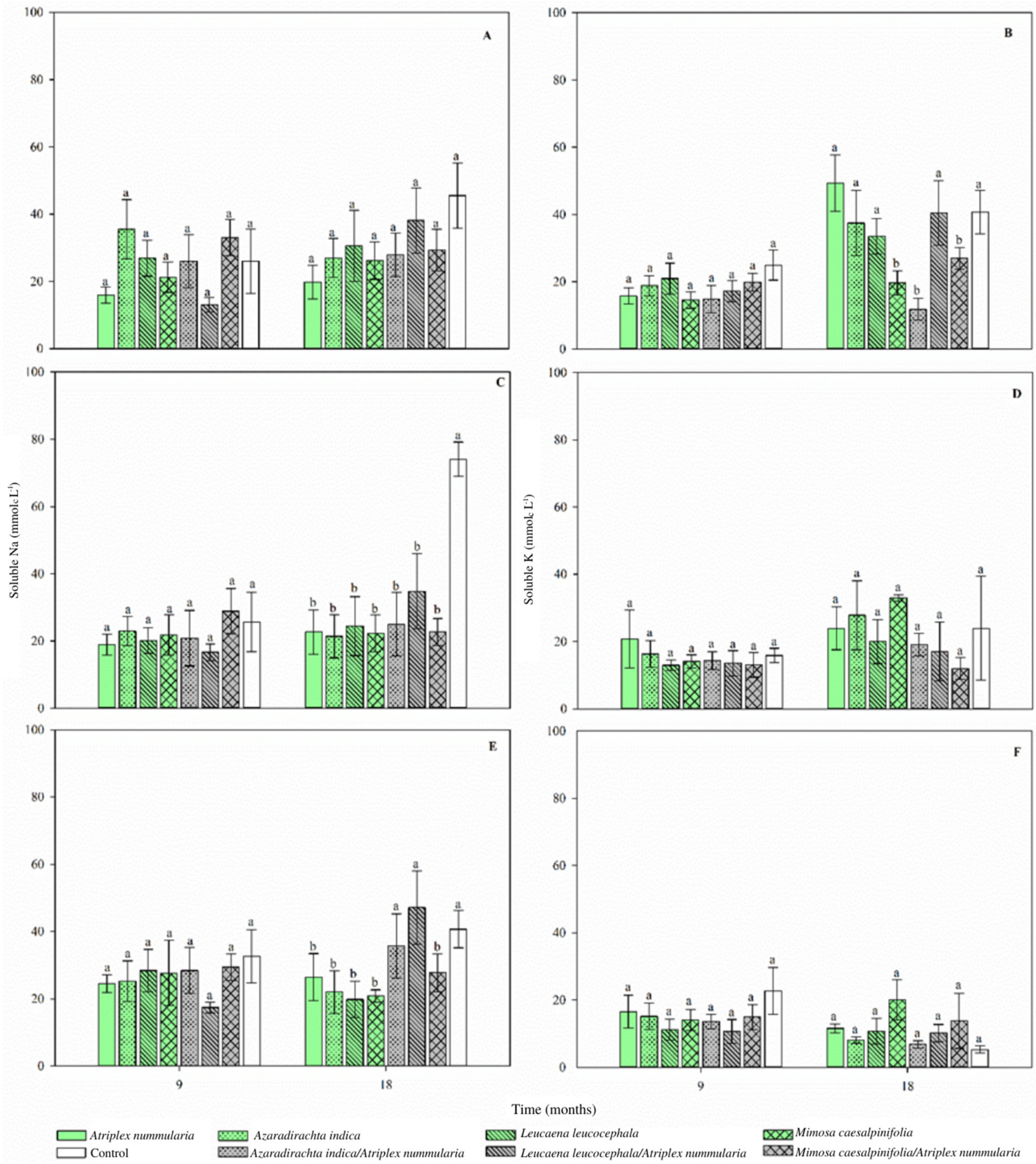

Figure 4. Soluble Na^+ [(**A**) 0–10 cm; (**C**) 10–30 cm; (**E**) 30–60 cm] and soluble K^+ [(**B**) 0–10 cm; (**D**) 10–30 cm; (**F**) 30–60 cm] at 9 and 18 months as result of the applied treatments. (Averages of four replications). Averages followed by the same letter have no difference in the same layer and time of sampling by the Skott-Knott test ($p \leq 0.05$).

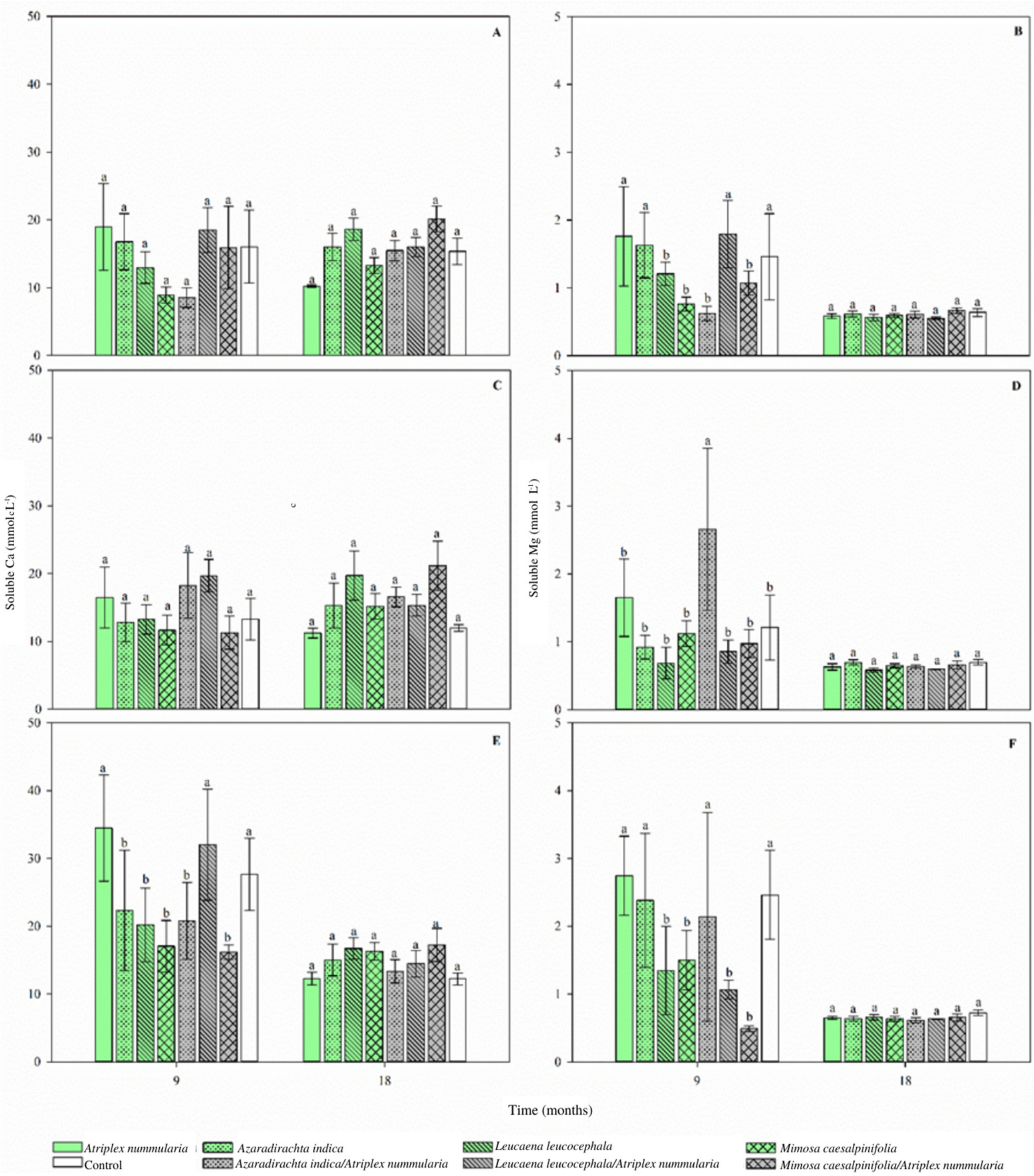

Figure 5. Soluble Ca^{2+} [(**A**) 0–10 cm; (**C**) 10–30 cm; (**E**) 30–60 cm] and soluble Mg^{2+} [(**B**) 0–10 cm; (**D**) 10–30 cm; (**F**) 30–60 cm] at 9 and 18 months as result of the applied treatments. treatments (Averages of four replications). Averages followed by the same letter have no difference in the same layer and time of sampling by the Skott-Knott test ($p \leq 0.05$).

3.3. Soil Salinity and Sodicity Variables

The orthogonal contrasts performed for pH, EC, SAR, and ESP results at 9 months after plant cultivation did not present a significant difference for any of the sodicity variables (SAR and ESP) at the layers evaluated (Table 3).

Changes were observed in EC at 9 months in the layer of 30–60 cm between the group of isolated cultivation plants and the control treatment, and the group of legumes in comparison to the control. At the same depth, pH recorded differed between the group of all plant treatments and the control, the association between plant treatments in relation to the control, and isolated cultures in relation to plant associations (Table 3).

At 18 months, the orthogonal contrasts were significant for all the arrangements confronting plants and control (all treatments × control, isolated cultures × control, plants associations × control, leguminous × control, and non-legume × control) in all evaluated layers (Table 5). In addition, there was a difference between isolated *A. nummularia* in relation to all treatments for the 30–60 cm layer.

Table 5. Orthogonal contrasts of the chemical attributes pH (hydrogen potential), EC (electrical conductivity), SAR (sodium adsorption ratio), and ESP (exchangeable sodium percentage) in the soil at 0–10, 10–30, and 30–60 cm depth as a function of treatments at 18 months.

Contrast	pH			EC			SAR			ESP		
	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm	0–10 cm	10–30 cm	30–60 cm
All treatments × control	−1.020	−1.319	−1.031	−2.382 *	−1.493	−6.059 **	−2.359 *	−5.306 **	−1.404	−3.635 **	−3.635 **	−2.838 *
Isolated cultures × control	−0.694	−1.072	−1.258	−2.600 *	−1.272	−6.010 **	−2.165 *	−5.201 **	−1.361	−3.451 **	−3.451 **	−2.504 *
Associations × control	−1.307	−1.466	−0.603	−1.790	−1.584	−5.330 **	−2.300 *	−4.748 **	−1.275	−3.397 **	−3.397 **	−2.898 **
Leguminous × control	−1.479	−1.900	−1.378	−2.096 *	−0.570	−5.868 **	−2.306 *	−5.152 **	−1.845	−2.791 *	−2.791 *	−2.120 *
No leguminous × control	0.211	−0.058	−0.919	−2.650 *	−1.751	−5.104 **	−1.647	−4.344 **	−0.639	−3.510 **	−3.510 **	−2.450 *
Isolated cultures × consortium	0.960	0.646	−0.929	−1.099	0.533	−0.739	0.308	−0.434	−0.064	0.083	0.083	0.716
No leguminous × leguminous	2.070	2.257 *	0.563	−0.678	−1.447	0.935	0.807	0.990	1.477	−0.881	−0.881	−0.404
Atriplex × all treatments	2.715 *	1.371	0.496	−1.854	−2.694 *	−1.965	−0.637	−0.203	0.536	−1.365	−1.365	−2.630 *

* Significant at 0.05 probability; ** Significant at 0.01 probability.

The same was observed on SAR data in relation to the same groups, differing only in the layers. Differences were significant at 0–10 and 10–30 cm layers, except for the non-legume group in relation to the control, which did not show differences at the 0–10 cm layer (Table 5).

Similarly, differences were recorded on the EC for the contrasts between the same groups, except for the depth of 10–30 cm, and for the contrast between plants associations × control group at 0–10 cm layer, which did not present a significant difference (Table 5).

4. Discussion

The present study provides new insights into reclaim of saline soils strategies. In brief, this study first reported the phytoremediation potential of the association between Atriplex plants with *M. caesalpiniifolia*, *L. leucocephala,* and *A. indica,* and under isolated cultivation of them in salt-affected soil.

Most of the evaluated variables were not modified after only 9 months of cultivation, however, the effect of the plants was more consistent at 18 months. This indicates that saline soil reclamation studies in the field should be conducted for a longer period of time. In field conditions, even the plants acting in the extraction of salts continue to be supplied to the soil.

The dynamics of groundwater in semi-arid environments have a direct influence on soil salinization in the edaphoclimatic conditions of these regions [23]. Although not measured, this fact may have influenced the increase in exchangeable levels of Na^+ and K^+ at 18 months, as a result of the probable exposure of the area to fluctuations in the water table depth and consequent entry of salts in conditions of insufficient drainage [24]. On the other hand, the reduction in exchangeable Na^+ and K^+ in the soil of the cultivated areas in relation to the control demonstrates the influence of the root system of these species on the drainage of the area [15,25].

In addition to the tolerance required to withstand the environmental conditions of salinity and sodicity [15], the extraction of salts from the environment is an essential characteristic for reclamation and contributes to the reduction of the levels of these ions in the soil [14]. It would be necessary to cut the plants to quantify the biomass production and its composition, and to estimate the extraction of salts. However, as our proposal is the improvement of the soil by revegetation, we chose the permanence of the plants in the area.

The balance between bivalent and monovalent cations in the soil exchange complex directly interferes with the proportions of these in the soluble form and in their absorption by plants. Under semiarid conditions, the constant evaporation of the water stored in the soil increases the concentration of the ions in solution with subsequent precipitation of the less soluble ions. Ions such as Ca^{2+} and Mg^{2+} precipitate first while Na^{+} remains in solution, leading to its passage to the exchangeable phase. This would explain the increase in exchangeable Na^{+} (Figure 2) and the reduction of exchangeable Ca^{2+} (Figure 3) at 18 months of plant growth.

The importance of plant utilization in the reclamation of salt-affected areas has been highlighted [26]. Although the total reclaim of the evaluated chemical attributes was not recorded, treatments with both isolated and associated plants, except for *A. indica*, were efficient in keeping Na^{+} contents low in the exchange complex at all depths even with the reduction of exchangeable Ca^{2+}.

The differences found between the cultivation of the evaluated plants and the association of these with the *A. nummularia* are important for the soils degraded by salts reclamation. It has increased the need to use species adapted to the climatic conditions of the arid and semiarid regions, where the processes of salinization and sodification of soils occur [27], mainly in the context of the reclaim of salt-affected areas and the control of the degradation process. Therefore, the use of halophyte plants that remove salt from the vicinity of roots of crop plants has more potential for alleviating saline soil conditions in the future [28].

When looking at the salt resistance of *A. nummularia*, we have to consider that its phytoextraction potential is associated with the fact that it stores significant amounts of salts in its tissues [17], due to the existence of the major mechanisms, the secretion of ions by salt glands and exclusion of accumulated toxic ions via bladder hairs that is a common strategy in *Atriplex* [29].

Another metabolic response to hyperosmotic salinity is the physiological mechanism because we maintain high photosynthetic rates with a low stomatal aperture and low transpiration simultaneously, and higher water use efficiency [30]. Finally, the biochemical mechanisms, as a consequence of synthesis and high cellular accumulation of organic and inorganic solutes adjust osmotically [31].

Even with the satisfactory establishment of the species, the reductions in soluble ion contents are not necessarily due to the accumulation of these in the plant tissue. In a reclamation study conducted in a semi-arid region of Tunisia, the reductions observed by the authors in the salinity and sodicity variables were attributed not only to the accumulation of salts in the aerial part of the species [*Tecticornia indica* (Willd.) Subsp. *Indica* and *Suaeda fruticosa* Forssk.], but also to the leaching due to physical-water improvements of the soil after the establishment of the plants.

Similar behavior in relation to Na^{+} and K^{+} was explained by Mahmoodabadi et al. [31], which demonstrated the lower mobility of bivalent cations. A factor that may have restricted the performance of the species implanted in the area over the soluble Ca^{2+} and Mg^{2+} contents along the profile. However, the permanence of these bivalent cations in solution compared to the significant reductions found for Na^{+} and K^{+} is an important factor in the ion balance of this soil. Cations adsorbed to a charged colloid surface (interface) can be replaced, by mass action, by other cations with greater activity in the soil solution [32].

Thus, soluble Ca^{2+} and Mg^{2+} can displace the exchangeable Na^{+}, reducing the sodicity characteristics of this soil [31].

Changes in EC are mainly due to the removal of soluble salts by leaching and accumulation in plant tissues, without being sufficient to cause greater changes in the proportions of basic cations in the soil exchange complex [23,33].

In addition, with respect to salt removal through plant species as a contributing factor in controlling soil salinity in saline soil, the process involves different mechanisms, such as: (1) the increase in the partial pressure of carbon dioxide (PCO_2) in the root zone, (2) release of protons in the rhizosphere of legumes, such as *L. leucocephala* and *M. caesalpinifolia* (3) can promote soil aggregation (4) root effect: the physical action of plant roots improves the soil structure and provides channels for infiltrating water, with the leaching of salts out of the root zone and (5) absorption of salts and removal of salts by aerial plant parts [34,35].

An additional consideration is that the aerial plant part also contributes toward a decrease in soil salinity, by providing shade to the soil. Furthermore, lowers soil temperature and decreases evaporation from the soil surface compared to a non-cropped surface [35].

Thus, plants that thrive under saline conditions became an option for the remediation of salt-affected soils. Especially, the halophytes, such as *A. nummularia*, that keep toxic ions in their vacuoles, accumulate compatible solutes in their cytoplasm and activate genes for salt tolerance that confer salt resistance [36].

In summary, our results suggested that reclamation was not evident at 9 months after planting, and significant results to decrease of soil salinity (EC) were verified at 18 months. Soil reclamation studies in the field should be longer so that the results be really of environmental importance. Both the effects of salt extraction from the soil are greater and the increase in salt leaching in rain events due to the action of the plant root system.

The isolated cultivation of saltbush provided environmentally better conditions for other plants, promoting coverage and protection of the soil, maintaining its humidity, and reducing its temperature. Thus, the implantation of salt-tolerant cultures, such as *A. nummularia*, offers a more sustainable system.

These results also reflect the *A. nummularia* potential to occupy areas degraded by salts where other plants would not have growing conditions and can be considered an economically viable alternative to claim the productive capacity in semiarid soils degraded by salinity.

Therefore, in soils with sodicity problems, the practice of reclamation with these species need to be managed over a period of more than nine months for significant changes in soil solution (SAR) and the percentage of sodium on the soil exchange complex (ESP). From 18 months of treatment, in similar environments to the study, a significant alteration in ESP can be observed when cultivated with *A. nummularia*, *A. indica*, *L. leucocephala*, and *M. caesalpinifolia*, in consortium or isolated culture. These changes were observed involving depths of 60 cm in relation to the surface, but these plant roots can go beyond, along with associated microorganisms. These changes can only be achieved when the modifications in the concentrations of the soluble cations are enough to cause displacement of the Na^+ ions in the exchange complex [32,37].

Although with less expressive results, the intercropping management can be indicated for reclaim of saline soil and, in parallel, it offers an alternative source of biomass production, as well as increasing the diversity of plant species in the environment, with environmental significance. It is even possible that other species associations may promote greater increases in the effects of crops on improving the properties of soils degraded by salinity.

Results entre o beginning and end of the experiment indicated that salinity and sodicity variables levels were increased in the control treatment. These fluctuations levels are associated with problems in the physical properties of the soil, causing restrictions to water and air movement in the soil profile.

An additional consideration for this behavior deals with the fact that the dynamics of rainfall and the ground-water level. In the period between November 2013 and May 2015. In 2013, 5.0 mm of rainfall was recorded until November (first soil sampling—0 times); In 2014, 740.0 mm was registered between the first and second samplings (0 and 9 months) and 253.50 mm occurred between the second and third samplings (9 to 18 months).

It was not possible to infer a significant decrease in soil ($p \leq 0.10$) salt levels (EC) during the experimental period of 9 months as a result of plant cultivation due to high rainfall events, low evapotranspiration rates, and periodic changes in groundwater level.

In addition, due to rainfall events, high evapotranspiration rates, and periodic changes in groundwater levels, it’s possible to infer a significative decrease ($p \leq 0.10$) in salinity and sodicity variables levels (EC, SAR, and ESP) during the experimental period 18 months as a result of plants cultivation, especially to *A. nummularia* individualized treatment. These plant species contribute to the improvement of soil structure by the formation of biopores, that work as alternative routes and increase the movement of water in the soil and, consequently, increase the leaching of saline ions.

Moreover, as crops include species that respond differently to salinity soil, comparative studies concerning the salt stress effects on the reclamation ability of these plants should be conducted in order to assess their potential as crops in the predicted world of climate change.

When reclamation is used, these changes in the concentrations may take longer than the conventional recovery techniques, because they depend on the ion extraction rate of the culture used and the improvements in the physical-water properties caused by the presence of the roots [15]. In this work, we demonstrated that reclamation is an alternative technique, and it could be successfully used for the removal of salts from the soil. Such a scenario would fit poorly drained soils with sodium accumulation, indicating their potential for future revegetation projects of salt-affected soils with environmental benefits.

Additionally, one of the ecological benefits of newly theses created plant cultures is the fact that they seem to be particularly suited for long-term CO_2 sequestration which counteracts the greenhouse effect.

5. Conclusions

The *Atriplex nummularia* individualized cultivation can be effective in reducing the sodicity and salinity of saline-sodic soil. However, when assessing the efficiency for the reclamation of salt-affected soils with the cultivation of *Azadirachta indica*, *Leucaena leucocephala* and *Mimosa caesalpiniifolia* individualized or even associated with *A. nummularia* contribute to improvement in the soil chemical quality due to root effect, promoting leaching of salts.

At 9 months, we were unable to detect a reduction in the electrical conductivity of the saturation extract in the soil as a result of plant species cultivation due to the variation in rainfall in the study area. However, at 18 months after planting, the results of this study showed decreases in the electrical conductivity, sodium adsorption ratio, and exchangeable sodium percentage due to cultivation.

As an important consideration is highlighted: that the degraded soil reclamation with species adapted to the semiarid would be suitable agronomic practices as well as to improve soil quality and sustainability, contributing to increased water uptake by infiltration and carbon sequestration in soils with no vegetation cover.

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