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Soil conditioners as candidates to mitigate salt/water stress effects on sorghum growth and soil properties

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Abstract

In arid and semiarid regions the use of saline water is common in agricultural irrigation, due to the scarcity of high-quality irrigation water. Thus, agriculture faces a challenge in developing strategies to grow crops under such adverse conditions in these regions. The objectives of this research are to study soil chemical properties and sorghum growth response to saline irrigation levels and application of soil conditioners. A greenhouse experiment (4x5) was carried out using a Cambisol cultivated with sorghum and irrigated with five saline water levels: 100%, 80%, 60%, 40% and 20% of soil field capacity (FC). Soils were treated with no soil conditioner (control), organic matter, elemental sulfur (S^0) + organic matter and gypsum + organic matter, applied to the soils 30 days before sorghum planting. At 60 days after plant emergence, measurements were recorded for: leaf water potential, plant dry weight, soil P availability, and soil chemical properties. Increasing saline water levels reduced exchangeable and soluble cations and saline variables. Organic matter + elemental sulfur promoted the highest levels of P in the soil and soil saturation extract. This mixture and the saline irrigation of 60% of field capacity promoted the greatest plant growth. However the organic matter + gypsum mixture promoted higher leaf water potential in relation to the other conditioners tested. The saline irrigation level equivalent to 60% of field capacity and the incorporation of organic matter + S^0 were sufficient to reduce soil salinity and sodicity, maintaining P and soluble/exchangeable cations contents to a level that best promoted sorghum growth.

Keywords: Irrigation management; plant stress; soil salinization; sustainable agriculture.

Introduction

In arid and semiarid regions, water and salt account for the major stresses faced by crops (Yahmed et al., 2016). In these regions, due to the scarcity of high-quality irrigation water, the use of saline water is common in agricultural irrigation, which has affected production and led to soil degradation over the years of cultivation (da Silva Filho et al., 2019).

The quality of irrigation water affects soil physicochemical conditions and consequently crop yield, causing loss of fertility, as plants facing salt stress suffer alterations in their physiology that adversely affect their growth (Parihar et al., 2015). Regarding the availability of phosphate in saline soils, it's reduced due to ionic strength effects, which reduce the activity of phosphate (Fageria et al., 2011). Thus, it is important to investigate possible management strategies which might decrease the detrimental effects of saline irrigation on crop yield and productivity as well as decrease or avoid soil degradation by the use of these saline waters.

As an alternative to alleviate the effects of salinity on crops, the efficiency of soil conditioners has been evaluated by several studies (Stamford et al., 2015). Gypsum has frequently been used as a sodic soil conditioner due to its low cost (Prapagar et al., 2012). In contrast, sulfur decisively contributes to the improvement of the poor physical conditions frequently found in alkaline soils (Stamford et al., 2015). The use of organic matter sources have long been known to facilitate the reclamation of saline/sodic soils (Ouni et al., 2013).

Another strategy that makes plant production possible in areas affected by salts is the use of salinity tolerant crops. In this regard, Sorghum (*Sorghum bicolor* L.) is becoming an increasingly important crop in many regions of the world (Hussein et al., 2010) and is a valuable alternative crop in agricultural systems where salinity stress is likely to occur, mainly due to its high tolerance to saline and drought conditions (Ding et al., 2018).

To evaluate the possibility of irrigating sorghum with saline water, it is necessary to investigate its performance and tolerance in the presence of low and high water content in the soil. Further, in order to seek a balance between the entry and exit of salts in the soil, it is important to evaluate the magnitude of soil salinization by the use of saline waters in sorghum cultivation. Additionally it is essential to verify the effectiveness of the use of soil conditioners in improving the chemical properties of the soil and increase the availability of nutrients, especially P, to mitigate the saline effects on the plants. In light of these considerations, the objectives of this research are to study sorghum growth response to saline irrigation level and the application of soil conditioners, as well the ways these factors interact, and to investigate the influence of saline irrigation and soil conditioners on P availability and soil chemical proprieties.

Results

Soil chemical properties

The effect of the saline irrigation levels on the saline properties is shown in Figure 2. It was observed a reduction of soil salinity in response to increasing applied irrigation level, which can be evidenced by the reductions in EC values for all conditioners tested (Figure 2a). SAR values in response to irrigation levels showed reduced values with increasing irrigation levels (Figure 2b). On the other hand, the values of ESP and soil pH both increased with increasing irrigation levels (Figures 2c and d), presenting an inverse behavior to EC and SAR. These results indicate the difficulty in handling saline and alkaline waters, since increasing the amount of applied water reduces excesses of ions, EC and SAR, this may imply increases in ESP values, which affects soil structure, as well as in the soil pH, tending to make the soil more alkaline - which makes it difficult to manage the soil because it affects nutrient availability.

P availability and geochemistry

The increase of the saline irrigation levels promoted a reduction in the available P contents from 111.26 mg kg^{-1} - with the irrigation level equivalent to 20% of the field capacity - to 90.07 mg kg^{-1} - with the irrigation level equivalent to 100 % of the field capacity (Figure 3a). These results indicate that there was higher leaching of P due to the increase of the applied irrigation levels. On the other hand, levels of P in the soil saturation extract were not significantly influenced by the applied irrigation levels (Figure 3b).

The application of organic matter + S^0 promoted higher levels of P in the soil and soil saturation extract - 111 mg kg^{-1} and 16 mg L^{-1} respectively (Figures 4a and b). It is important to note that the absence of soil conditioners (control) promoted the lowest levels of P in the soil. However, in the saturation extract, the application of gypsum resulted in the lowest levels of soluble P (Figure 4b).

Through the analysis of the ionic speciation of P (Table 3) it was possible to observe that the main forms of P in soil solution with no soil conditioners (control) added were HPO_4^{2-} (21.13%), $H_2PO_4^-$ (25.52%) and $CaHPO_4$ (27.98%). These are also the predominant forms of P in the soil solution with only organic matter was applied as soil conditioner, with small variations in the proportions of these forms - HPO_4^{2-} (18.94%), $H_2PO_4^-$ (28.79%) and $CaHPO_4$ (26.08%). The P forms associated with Mg^{2+} ($MgHPO_4$) were also expressive and similar in these two conditions.

The application of organic matter + S^0 promoted greater formations of the $H_2PO_4^-$ (70.64%) and $CaH_2PO_4^+$ (20.22%) forms, while the addition of organic matter + gypsum promoted higher proportions of P forms bound to Ca^{2+} ($CaHPO_4$ - 42.37% and $CaH_2PO_4^+$ - 9.71%). This demonstrates the main dominant species of P utilizing the tested conditioners under irrigation with saline and alkaline water. In this way, these will be the predominate forms of P in the solution of the soil under each condition, which will directly influence the absorption of this element by the plant as well as the dynamics of this element in the soil.

Sorghum growth and water status

Leaf water potential was significantly ($P < 0.05$) affected by the irrigation, with the plants irrigated with the highest irrigation level showing higher leaf water potential than the plants under reduced irrigation levels (Figure 5a). Plant growth was also significantly affected by irrigation ($P < 0.05$). The results observed in this study indicate that the saline irrigation level equivalent to 60% of field capacity best promoted plant growth (Figure 5b), although this saline irrigation level was not the most effective at reducing soil salinity (Figure 2a).

Soil conditioners significantly influenced leaf water potential ($P < 0.05$), and among the applied soil conditioners, the organic matter + gypsum mixture promoted the highest leaf water potential of the conditioners used in the experiment (Figure 6a). In the same way, soil conditioners also significantly influenced plant growth ($P < 0.05$), however, the organic matter + S^0 mixture promoted higher plant growth, evaluated by the greater weight of dry matter (Figure 6b).

Discussion

The results obtained in this work indicated that the saline irrigation level equivalent to 60% of the field capacity was enough to remove excess salts, and it was not necessary to apply irrigation levels higher than 60% of field capacity for this purpose (Figures 2a and b). Similar results were obtained by de Andrade et al. (2018), who also verified the saline irrigation level corresponding to 60% of field capacity as ideal for reducing soil salinity and to better promote sorghum growth.

The increase of the irrigation levels raised the ESP values of the soils (Figure 2c), except for the treatments where the gypsum + organic matter were applied, due to the high calcium contents added by this salt (Stamford et al., 2015). Soils in which organic matter + S^0 were applied were the least efficient in reducing ESP and EC with increasing irrigation levels. Soil pH values showed an inverse relation to EC, increasing with rising saline irrigation levels (Figure 2d). A rise in soil pH levels was observed relating to saline irrigation levels, which occurred

Table 1. Physical and chemical properties of the Cambisol used in the experiment.

Exchangeable complex		Soluble complex	
pH	6.60	pH	7.38
Ca^{2+} (cmol$_c$ dm^{-3})	4.41	EC (dS m^{-1})	0.47
Mg^{2+} (cmol$_c$ dm^{-3})	0.88	Ca^{2+} (mmol$_c$ L^{-1})	9.73
Na^{+} (cmol$_c$ dm^{-3})	0.39	Mg^{2+} (mmol$_c$ L^{-1})	3.72
K^{+} (cmol$_c$ dm^{-3})	0.54	Na^{+} (mmol$_c$ L^{-1})	4.53
CEC (cmol$_c$ dm^{-3})	6.22	K^{+} (mmol$_c$ L^{-1})	5.02
ESP (%)	6.27	Cl^{-} (mmol$_c$ L^{-1})	15.0
P (mg kg^{-1})	62.04	SO$_4^{2-}$ (mmol$_c$ L^{-1})	1.56
OC (dag kg^{-1})	0.75	CO$_3^{2-}$ (mmol$_c$ L^{-1})	0.0
Sand (%)	70.49	HCO$_3^{-}$ (mmol$_c$ L^{-1})	21.43
Silt (%)	18.12	SAR (mmol$_c$ L^{-1})$^{0.5}$	1.75
Clay (%)	11.39		

CEC: Cation Exchange Capacity; ESP: Exchange Sodium Percentage; OC: Organic Carbon; EC: Electrical Conductivity; SAR: Sodium Adsorptium Ratio.

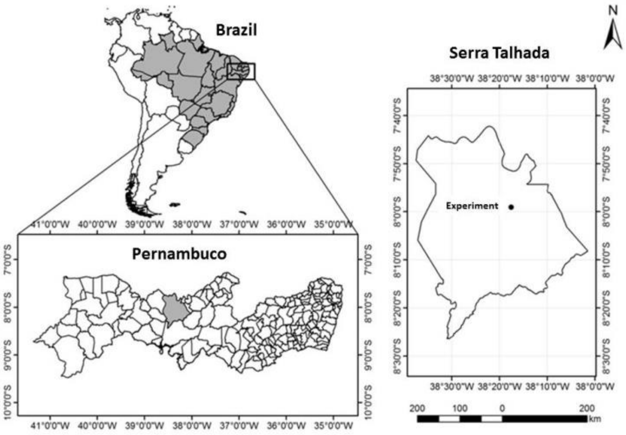

Fig 1. Location map for the experimental site.

Table 2. Chemical composition of saline water used for forage sorghum irrigation.

pH	EC^1 (dS m^{-1})	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Cl^{-}	SO$_4^{2-}$	CO$_3^{2-}$	HCO$_3^{-}$	SAR^2 (mmol$_c$ L^{-1})^{0,5}
		mmol$_c$ L^{-1}								
8.59	2.70	0.68	0.83	1.87	25.89	20.50	1.88	2.80	20.40	29.80

^{1}Electrical Conductivity; ^{2}Sodium Adsorptium Ratio

Table 3. Speciation of P in saturation extract for each conditioner applied in saline soil.

P species (%)	Control	OM	OM + S^0	OM + G
NaH$_2$PO$_4$	1.52	1.73	4.76	1.20
HPO$_4^{-2}$	21.13	18.94	0.84	15.44
H$_2$PO$_4^{-}$	25.52	28.79	70.64	23.57
MgHPO$_4$	13.67	13.90	0.84	3.77
CaHPO$_4$	27.98	26.08	1.61	42.37
CaPO$_4^{-}$	0.63	0.46	-	0.70
CaH$_2$PO$_4^{+}$	4.18	5.07	20.22	9.71
NaHPO$_4^{-}$	4.77	4.26	0.20	2.78
KHPO$_4^{-}$	0.32	0.42	0.02	0.24
KH$_2$PO$_4$	0.16	0.26	0.79	0.16
Na$_2$HPO$_4$	0.11	0.10	-	0.05
H$_3$PO$_4$	-	-	0.09	-

*Control = without soil conditioner; OM = organic matter; OM + S^0 = organic matter + elemental sulfur; OM + G – organic matter + gypsum.

Table 4. Relationship between dry matter and the evaluated soil properties.

	Soil soluble complex						
	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	P	SAR
DM	0.36^{ns}	-0.01^{ns}	0.40^{*}	0.18^{ns}	0.10^{ns}	0.72^{*}	0.03^{ns}
	Soil exchangeable complex						
	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	P	ESP
DM	-0.82^{**}	-0.44^{**}	-0.14^{ns}	-0.27^{*}	0.17^{ns}	0.81^{*}	-0.67^{**}

*EC = Electrical Conductivity; SAR = Sodium Adsorption Ratio; ESP = Exchangeable Sodium Percentage.

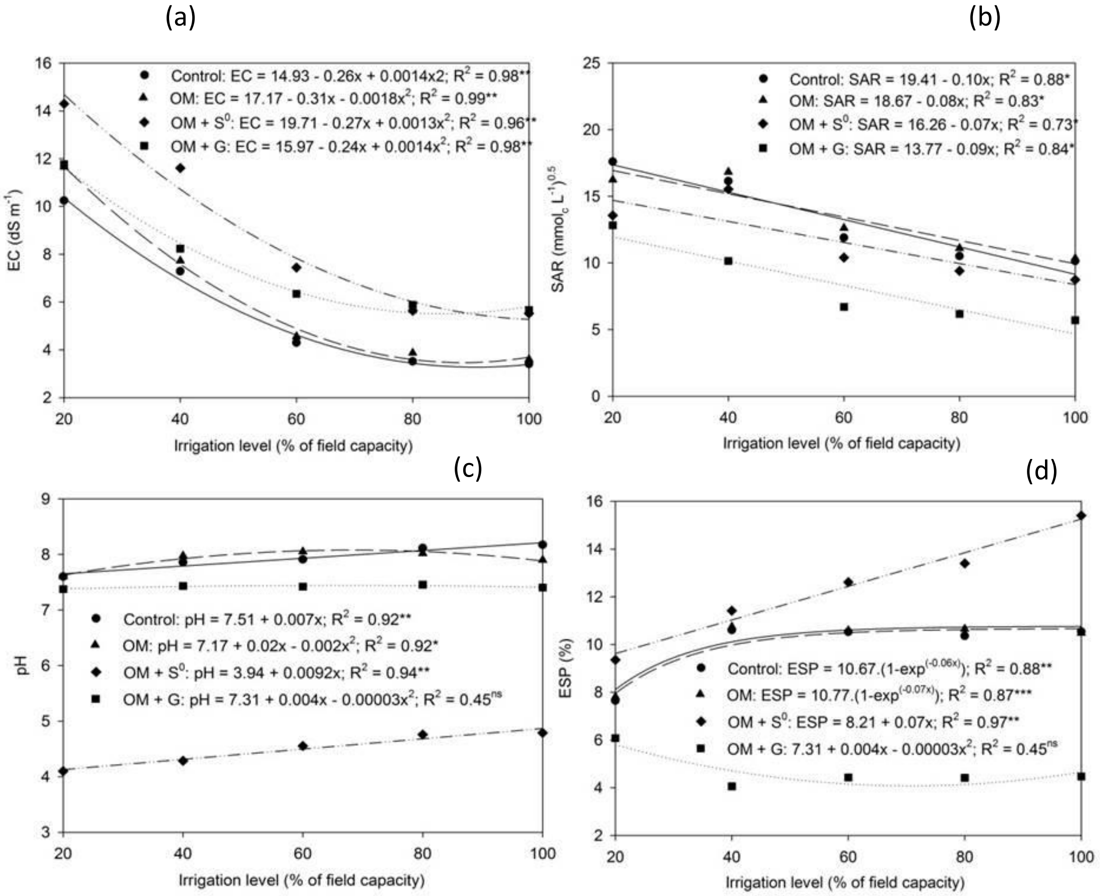

Fig 2. Salinity variables as function of saline irrigation level and applied soil conditioners: electrical conductivity - EC (a), sodium adsorption ratio - SAR (b), exchangeable sodium percentage – ESP (c) and soil pH (d).

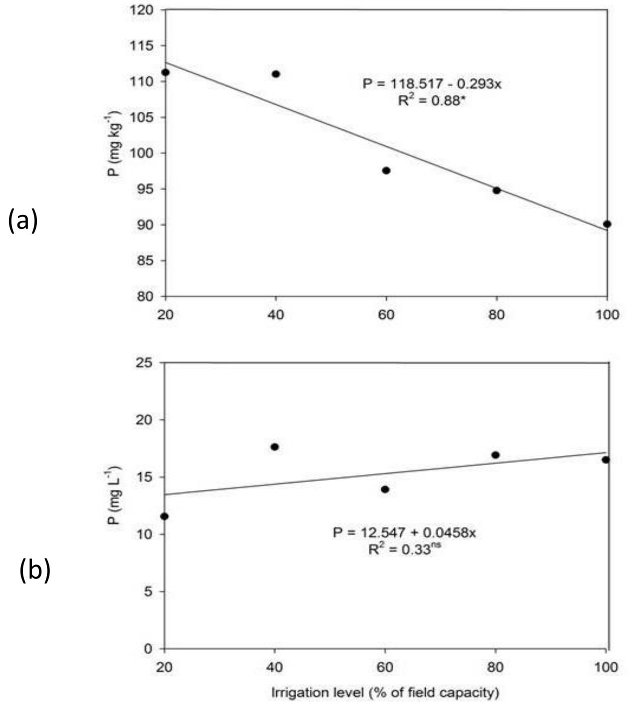

Fig 3. Levels of P in soil (a) and in the saturation extract (b), in response to saline irrigation levels.

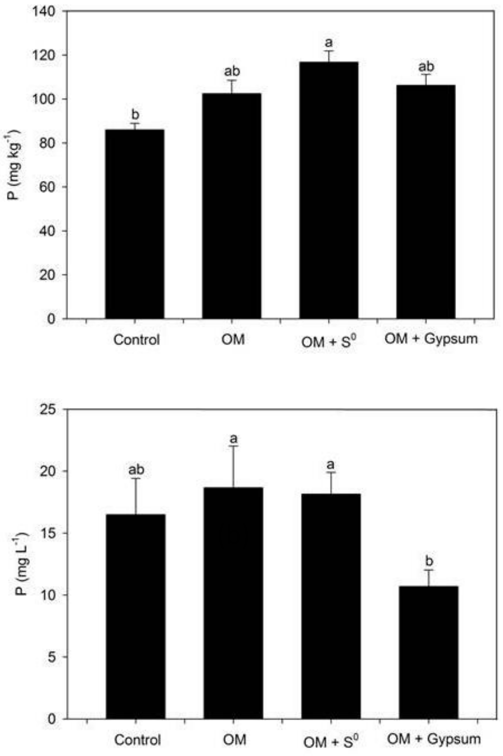

Fig 4. Levels of P in soil (a) and in the saturation extract (b), in response to the applied soil conditioners. Means with different letters are significantly different at P < 0.05.

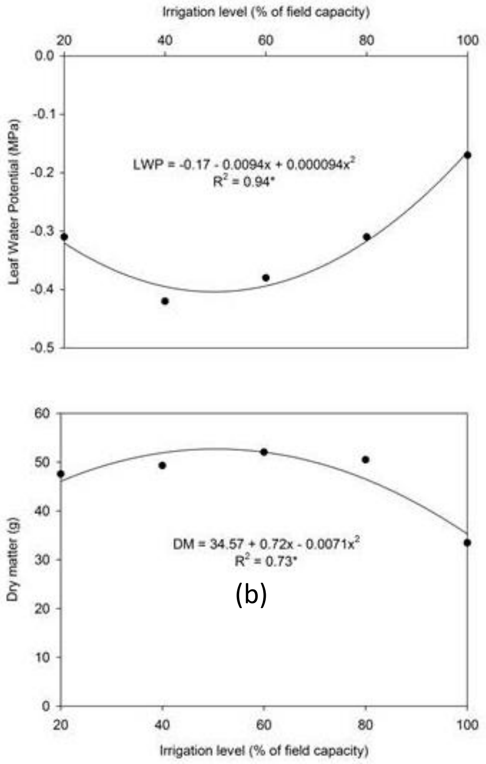

Fig 5. Leaf water potential (a) and dry matter (b) in response to saline irrigation levels.

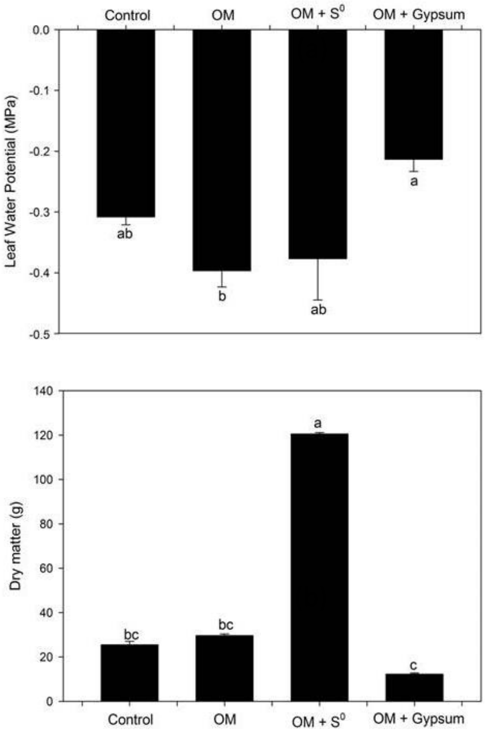

Fig 6. Leaf water potential (a) and dry matter (b) in response to applied soil conditioners. Means with different letters are significantly different at $P < 0.05$.

due to the elevated carbonate and bicarbonate content in the irrigation water (Table 2).

In general, it was observed that the organic matter + S^0 conditioner mixture applied to the soil promoted greater element solubility. This was mainly due to a higher pH reduction resulting from the addition of this mixture (Figure 2d), which also contributed to higher EC values in the soils to which this mixture was applied (Figure 2c). de Andrade et al. (2018) note that the increase in EC in saline soils as a response to elemental sulfur application occurs due to the transformation of elemental S into various sulfates and dissolution of various carbonates.

In this study it was verified that increased irrigation levels enhanced the downward movement of P, which could be observed in the reductions of soil P contents as a response to increasing applied irrigation levels (Figure 3a). Boitt et al. (2018) evaluated the effect of 62 years of different irrigation regimes on the amounts, forms and distribution of P in the soil profile to 100 cm under a grazed pasture in New Zealand, and their results clearly demonstrated that quantities of P present in the soil profile, after 62 years of identical P fertilizer inputs, were reduced depending on the irrigation inputs, where flood irrigation of grazed pasture had resulted in lower levels of P as compared to non-irrigated control treatments. Thus, our results indicate that while increasing saline irrigation level reduces soil EC (Figure 3a) it also implies losses of P.

Our results showed that the application of S^0 combined with organic matter promoted higher levels of P in both the soil and soil solution (Figures 4a and b). This occurred due to the oxidation of S into H_2SO_4 (Stamford et al., 2015), which is beneficial for alkaline soils as it increases nutrient availability by reducing pH. With the application of saline water used in this experiment it was possible evaluate that soil pH had significantly increased as compared to its initial condition (Figure 3d). Additionally, the gypsum application contributed to increased exchangeable and soluble Ca levels. Under these soil conditions, P in a solution quickly forms water-insoluble precipitates in soil with high pH and high Ca concentrations (Santos et al., 2016). These P-Ca precipitates did not form in soils with lower pH (acid) (Ch'ng et al., 2014). This explains the lower P levels in the soil solutions in response to gypsum application.

By the distribution of the P chemical species in the soil solution for each applied soil conditioner, as calculated by the Visual Minteq software - shown in Table 3, it is possible to observe that in soils where only organic matter was applied, the dissolved P predominantly formed complexes with Ca^{2+}, Mg^{2+} and Na^{+}, which was similar to the soil without the application of conditioner (control). In the soils where the organic matter + gypsum conditioners were applied, it was observed that the greater proportion of P formed complexes with Ca^{2+} (more than 50% - Table 3).

It was observed that the application of the organic matter + S^0 conditioners reduced the formation of P-Ca^{2+} complexes and increased the forms of P dissolved in the soil solution - especially the $H_2PO_4^-$ form (Table 3). This predominance in the soil solution as a response to the application of organic matter + S^0 can be attributed to reduced soil pH due the application of these soil conditioners (Figure 2d), which likely contributed to the reduction of the pH of the soil solution.

Consistent with previous literature (e.g. Santos et al., 2014), leaf water potential of sorghum plants grown under reduced irrigation was significantly lower (i.e. more negative) than that found for plants irrigated with higher water content (Figure 5a), indicating that these plants suffered water stress. As the increased saline irrigation levels promoted greater leaching of salts, which can be verified by the reduction of soil EC (Figure 2a), this contributed to the increase of leaf water potential in sorghum plants.

The data for leaf water potential obtained in this study indicates that the application of the gypsum + organic matter mixture resulted in higher values of leaf water potential, although no significant differences were observed as compared to organic matter + S^0 (Figure 6a).

We observed that the saline irrigation level corresponding to 60% of field capacity promoted the best plant growth (Figure 5b). This occurred because sorghum is a C4 plant which is highly efficient in its water usage (Ajeigbe et al., 2018), making it highly resistant to both drought and salt (Almodares et al., 2011). Thus, these data indicate that high levels of irrigation may damage the growth of sorghum.

Among the tested soil conditioners, it is possible to clearly observe that the organic matter + S^0 mixture promoted a higher sorghum growth, which could be verified by the greater accumulation of dry matter (Figure 6b). As can be seen in Table 4, sorghum dry matter was significantly correlated (positive correlation) with P in both the soil and soil solution. According to the data observed in Figures 4a and b, the organic matter + S^0 mixture promoted the highest levels of P in the soil and soil solution, which contributed to greater sorghum growth. Furthermore, these findings are important in that the plants preferentially absorb the P species in the solution in the form of orthophosphate (H_3PO_4, $H_2PO_4^-$ and HPO_4^{2-}) (De Conti et al., 2015), and the organic matter + S^0 mixture contributed to the formation of more than 70% of $H_2PO_4^-$ (Table 3), which explains the dry matter results found in this study.

Materials and methods

Experimental site and soil characteristics

The present study was carried out in a greenhouse at the experimental station of the Rural Federal University of Pernambuco - UFRPE (7º 59' S; 38º 17' O), located near the city of Serra Talhada, within the semiarid region in the state of Pernambuco, in Northeastern Brazil.

The experiment was established in a Cambisol, collected (0 – 20 cm layer) from the UFRPE experimental station. The soil was air dried, sieved (5 mm sieve), mixed and analyzed according to Richards (1954) and Embrapa (1997) methodologies, and kept in pots. The chemical analyses of the soil exchange complex and saturation extract, as well the soil physical analyses are found in table 1. The saline water used in the experiment was collected from the Saco reservoir.

Treatments and experimental design

Soils placed in the pots (7 kg of soil per pot) were treated with the soil conditioners: no soil conditioner - control, organic matter as cattle manure (OM), elemental sulfur (S^0) and gypsum as $CaSO_4.2H_2O$. Soil conditioner levels were calculated according to Miranda et al. (2011), and were found to be 40 kg ha^{-1} for organic matter, 7 t ha^{-1} for elemental sulfur and 30 t ha^{-1} for gypsum ($CaSO_4.2H_2O$), and were applied to the soils 30 days before sorghum planting.

Plants were subjected to five saline water levels: 100%, 80%, 60%, 40 and 20% of soil field capacity (FC) – the amount of water remaining in the soil after excess water has drained away and the rate of downward movement has decreased. Saline water levels of 80 and 60% were considered to be mild and saline water levels of 40 and 20% were considered to be a severe water deficit. Thus, a greenhouse experiment, set up in a factorial 4 × 5, was conducted in a completely randomized design with three replicates for the following treatments: (1) control + 20% FC, (2) control + 40% FC, (3) control + 60% FC, (4) control + 80% FC, (5) control + 100% FC, (6) addition of OM + 20% FC, (7) addition of OM + 40% FC, (8) addition of OM + 60% FC, (9) addition of OM + 80% FC, (10) addition of OM + 100% FC, (11) addition of OM and elemental S + 20% FC, (12) addition of OM and elemental S + 40% FC, (13) addition of OM and elemental S + 60% FC, (14) addition of OM and elemental S + 80% FC, (15) addition of OM and elemental S + 100% FC, (16) addition of OM and gypsum + 20% FC, (17) addition of OM and gypsum + 40% FC, (18) addition of OM and gypsum + 60% FC, (19) addition of OM and gypsum + 80% FC, (20) addition of OM and gypsum + 100% FC.

The soil was mixed in the pots with their respective soil conditioners followed by sorghum seeds – Sudan 4202 (4 per pot) which were sown at a depth of 5 mm, and when emergence occurred, the seedlings were thinned to one per pot. Five days after emergence, P fertilizer was applied at the 20 kg ha^{-1} rate recommended for sorghum (IPA, 2008). During the experimental period, plants were irrigated every other day, with highly saline and alkaline water, for which chemical analysis is shown in Table 2.

Sorghum growth and water status

60 days after plant emergence, measurements for leaf water potential (*Ψw*) were taken immediately after plant sampling utilizing the pressure chamber method (Schölander et al., 1965). The leaf lamina was enclosed within the chamber and subjected to increasing pressure from a compressed nitrogen cylinder until free sap was visible at the petiole outside the chamber. Sorghum plants were then harvested, and the Dry Weight (DW) was obtained after oven drying at 60 °C until reaching a constant weight.

Soil measurements and P availability

After harvesting the sorghum, the soil contained in each pot was collected and was air-dried and then passed through a 2-mm sieve. The following analyses were performed on soils (sieved in a 2 mm mesh): pH; exchangeable Na^+ and cation exchangeable capacity (CEC) by ammonium acetate extraction (Richards, 1954); P by Olsen extractant (Olsen et al., 1954). ESP was calculated according to Richards (1954) – Eq 1:

Eq 1. $$ESP = \frac{Na}{CEC} x100 \qquad (1).$$

Part of the soil (sieved in a 2 mm mesh) was separated to obtain the saturated soil-paste extract in which the following analyses were carried out: pH; EC; soluble cations Ca^{2+}, Mg^{2+}

and Na^+ (Richards, 1954); P by Olsen method (Olsen et al., 1954). The sodium adsorption ratio (SAR) was calculated according to Richards (1954) – Eq 2:

Eq 2. $$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad (2).$$

The geochemical equilibrium model Visual MINTEQ version 3.0 (Gustafsson, 2010) was used to model the speciation of P in the soil solution. This model calculates the chemical compositions of various inorganic ions in aqueous systems at a single point (in our case, the saturated soil-paste extract) under the assumption of chemical equilibrium.

Statistical analysis

The results were statistically analyzed using ANOVA and simple linear regression. The differences between means were analyzed with a Tukey's test at P = 0.05. The statistical significance of correlations between data sets was calculated using Pearson's r values.

Conclusions

The present study analyzed the effect of saline irrigation levels and soil conditioner applications on sorghum growth, P availability and soil chemical properties. Our results indicate that the saline irrigation level equivalent to 60% of the field capacity was sufficient to reduce soil salinity and sodicity while maintaining P and soluble/exchangeable cations contents as well to a level that best promoted sorghum growth.

From the results of our study, it was clear that incorporation of organic matter + S^0 in soil enhanced P availability in the soil sorption complex, and although no differences were observed as compared to the soluble P content, this mixture contributes to the formation of a higher percentage of dissolved forms of P ($H_2PO_4^-$) in the soil solution, among all tested conditioners. As soil P and P of the soil solution strongly influenced sorghum growth, this mixture of soil conditioners was found to be the most effective in attenuating the effect of saline irrigation on P availability, and consequently on sorghum growth.

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