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CHANGES IN SOME CHEMICAL PROPERTIES OF SALINE-SODIC SOILS OVER TIME AS AFFECTED BY ORGANIC RESIDUES: AN INCUBATION STUDY

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Abstract. Salinization and sodification of agricultural lands in arid and semi-arid regions of the world are two limiting factors in the crop production. This study was conducted to evaluate the effect of readily available agricultural residues on changing some chemical properties of saline-sodic soils. Wheat, potato, sunflower, and canola residues were separately added into three saline-sodic soils at a rate of 2% by weight and thoroughly mixed with soils. Control and treated soils were incubated for 168 days at a constant moisture and temperature. The pH, electrical conductivity (EC), soluble cations, available nitrate (NO_3^-) and phosphorous (P), cation exchange capacity (CEC), and exchangeable sodium percentage (ESP) were measured during the incubation. The EC increased in the response to the incorporation of plant residues, whereas the pH was reduced. The application of organic components in soils increased CEC and decreased ESP. The results showed that the maximum reduction in ESP was observed in the potato treatment because of the highest Ca^{2+} concentration. The average reduction in ESP of treated soil samples at the end of incubation followed this order: 16.1% (potato residue-treated soil) >12.7% (canola residue-treated soil) >11.1% (wheat residue-treated soil) >9.6% (sunflower residue-treated soil). The potato residue was the most effective amendment in changing the chemical properties of saline-sodic soils in comparison with other organic residues. The results indicated that the application of organic residues had a positive impact on reducing the soil sodicity and improving the soil fertility depending on their chemical composition.

Keywords: salinity, sodicity, agricultural residues, bioremediation, incubation

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INTRODUCTION

Salinity and sodicity are two of soil destructive factors (Qureshi *et al*. 2008) seriously increasing due to the improper use of soil and water resources. Formation of saline and sodic soils is affected by parent materials, climate, topography, and human activities such as inefficient management of irrigation and drainage systems (Tan and Kang 2009). Population growth and the subsequent increase in the demand for more food and fiber have led to the cultivation in saline and sodic soils. However, the excessive accumulation of salts in the rhizosphere results in decreasing available water and increasing osmotic pressure and toxicity of some elements for plants. In contrast to saline soils, sodic soils have excessive levels of sodium (Na^+) adsorbed onto cation exchange sites. Soil sodicity causes the degradation of soil structure due to the clay dispersion. A poor physical structure leads to the difficulty of soil tillage and seed germination and plant growth restriction. Therefore, the remediation of saline-sodic soils is essential prior to cultivation.

The remediation of salt-affected soils is possible through the leaching of solutes from the root zone, development of drainage systems, cultivation of plants with deep roots, and application of amending materials (Manjunatha *et al*. 2004, Qadir *et al*. 2008, Qureshi *et al*. 2008). Reclamation of sodic soils involves the replacement of the exchangeable Na^+ by calcium (Ca^{2+}). Physical and chemical techniques for remediation of saline and sodic soils are expensive and somewhat complicated (Qadir *et al*. 2015). Application of chemical amendments such as gypsum can provide soluble Ca^{2+} within the soil, however, cost-effective and environmentally-friendly ways for the reclamation of sodic soils have been investigated due to the high cost of chemical amendments and the importance of maintaining environmental health (Qadir *et al*. 2006, Li and Keren 2008). One of these methods is called "bioremediation" which may facilitate the dissolution of native $CaCO_3$ and the subsequent reclamation of sodic soils (Qadir and Oster 2002, 2004, Mishra *et al*. 2004). The efficiency of some organic components has previously been reported in the reclamation of saline-sodic soils (Wichern *et al*. 2006). The importance of soil organic matter (SOM) in maintaining physicochemical properties of soils has also been established. Organic matter improves soil structure and aggregation (Oades 1993) and increases the hydraulic conductivity (Hussain *et al*. 2001), level of soil nutrients, and cation exchange capacity (Von Lutzow *et al*. 2002, Jalali and Ranjbar 2009a). Li and Keren (2009) indicated that the application of corn stalks was effective in the reclamation of calcareous sodic soils under laboratory conditions.

Although the native $CaCO_3$ in arid and semi-arid regions is a potential source of Ca^{2+}, the low solubility of this mineral prohibits the reclamation of sodic soils. The solubility of calcite is dependent on pH, partial pressure of CO_2 (PCO_2), and hydrolysis of carbonic acid in the soil solution. In alkaline conditions, the concentration of CO_2 in the soil solution is the main factor controlling the dissolution of calcite (Plummer *et al*. 1978). In natural environments, SOM and its decomposition rate control the PCO_2 in the soil air (Li and Keren 2009). Due to the respiration of plant roots and microbial oxidation, the PCO_2 in the soil air is much higher than its pressure in the atmosphere. Higher PCO_2 in the rhizosphere and release of proton (H^+) produced by roots of some plant species increase the dissolution of calcite (Qadir *et al*. 2005) and consequently enhance the replacement of Na^+ with Ca^{2+} on exchangeable sites (Robbins 1986, Sekhon and Bajwa 1993).

Application of agricultural residues as cost effective and easily available materials reduces the cost of soil reclamation activities and adverse effects of their disposal on the environmental quality in developing countries, where many of these residues are usually burned in farms after harvesting of crops. Furthermore, application of these materials for the reclamation of calcareous sodic soils helps to prevent the use of acids or other chemicals, and hence reduces the risks of chemical amendments to the environment (Li and Keren 2009). Meanwhile, organic amendments can improve the soil fertility by releasing macro nutrients including nitrogen (N), phosphorous (P), and potassium (K). Therefore, the reclamation of saline and sodic soils through bioremediation which includes the increase of the native calcite dissolution in the root zone by exporting protons from plant roots, releasing organic acids from decomposing organic residues, increasing PCO_2, and thereby providing a sufficient level of soluble Ca^{2+} for replacing exchangeable Na^+ has strongly been recommended (Robbins 1986, Ilyas *et al*. 1997, Qadir *et al*. 2001).

As mentioned above, salinity and sodicity affect the land productivity in semi-arid regions in which a large portion of world population lives. Therefore, it is of great importance to use environmentally-friendly and cost-effective ways to reclaim salt- and/or sodium-affected soils. Although many studies have been reported on the improvement of bio-physiochemical properties of saline-sodic soils using organic amendments, it is necessary to extend such works to more areas as their effects are highly depended on soil properties, the type of organic materials, and local climate. Some agricultural lands in Hamedan, western Iran, have lost their quality due to the salinity and sodicity problems caused by rising saline aquifers and application of low-quality irrigation waters and accumulation of salts leached from surrounding areas in lowlands with a poor drainage. So, this study was conducted to investigate the ability of organic amendments to ameliorate saline-sodic soils. Amendments were residues of four types of crops mainly cultivated in Hamedan including wheat, potato, sunflower, and canola. A number of chemical properties were measured to examine the processes that occur over time when organic materials were incorporated with saline-sodic soil samples under laboratory incubation conditions.

MATERIALS AND METHODS

Soil sampling and characterization

The composite surface (0–30 cm depth) soil samples were collected from agricultural lands of Hamedan province, western Iran, which lies between longitudes 48°20'E and 49°27'E and latitudes 34°36'N and 35°15'N. The climate is semi-arid with an annual precipitation of approximately 300 mm which occurs from October to May, with a maximum during November and February of each year (Sabziparvar 2003). Seventeen agricultural fields in Nushijan, Viyan, and Asad Abad located in Hamedan with areas ranging from 5 ha to 20 ha were sampled in a simple random pattern with a hand shovel (depth of 0–30 cm). The number of soil samples taken from each field varied from 20 to 80 depending on the area. The soil samples of each field were mixed together to obtain a composite sample per field. The samples were then transferred to the laboratory, air dried and passed through a 2-mm sieve. The particle size distribution was determined by hydrometer method (Gee and Bauder 1986). The pH and electrical conductivity (EC) were measured in both saturated paste and 1:5 soil to water extracts. The equivalent calcium carbonate (ECC) was determined by back titration (Rowell 1994) and SOM was measured by wet oxidation with potassium dichromate (Walkley and Black 1934). The exchangeable cations (K^+, Ca^{2+}, Mg^{2+}, and Na^+) were extracted with alcoholic 1.0 M NH_4Cl solution (Rowell 1994). The CEC was considered as the sum of exchangeable K^+, Ca^{2+}, Mg^{2+}, and Na^+ as they were dominant at the exchangeable sites of soils in the study area (Rowell 1994). So, the exchangeable sodium percentage (ESP) was calculated using the following equation:

$$\text{EPS (\%)} = \frac{\text{Ex Na}^+}{\text{Ex Ca}^{2+} + \text{Ex Mg}^{2+} + \text{Ex Na}^+ + \text{Ex K}^+} \times 100$$

Among seventeen composite soil samples collected, three samples with the greatest ESP values were selected for the incubation study. The properties measured for these soil samples are given in Table 1. The pH and EC values in 1:5 soil to water extracts varied from 9.8 to 10.3 and 0.9 to 2.2 dS/m, respectively. The EC values ranged from 3.9 to 9.2 dS/m in saturated paste extracts. The ECC averaged 28.0% and varied from 22.4 to 32.1%. The clay contents averaged 474 g/kg and ranged from 463 to 483 g/kg. The CEC and ESP values varied from 11.4 to 22.7 cmol_c/kg and 52.9 to 82.5%, respectively. The values of pH and EC measured in the saturated extracts and ESP indicated that the soil samples were saline-sodic. The soil samples were classified as Calcic Solonetz according to the world reference base (WRB) for soil resources 2014.

Table 1. Some physicochemical properties of soil samples

Soil no.	Place of sampling	Sand	Silt	Clay	Texture	pH	EC	CEC	ECC	ESP	OM
		g/kg	g/kg	g/kg			dS/m	$cmol_c/kg$	%	%	%
1	Nushijan	115.2	421.6	463.2	Silty clay	10.3 (9.1)*	2.2 (9.2)	19.3	32.1	82.5	0.7
2	Viyan	102.4	414.4	483.2	Silty clay	9.9 (8.6)	0.9 (4.1)	11.4	29.4	52.9	0.8
3	Asad Abad	184.4	338.0	477.6	Clay	10.2 (9.0)	1.0 (4.7)	22.7	22.4	77.1	0.7

* values given in parentheses refer to measurements in the saturated paste extract

Flame emission spectroscopy was used to measure K^+ and Na^+, while a complexometric titration procedure with EDTA was used to determine the concentration of Ca^{2+} and Mg^{2+}. Available phosphorus (P) was extracted using the Olsen extraction method (Olsen *et al.* 1954) and determined through the Murphy and Riley (1962) method. Available nitrate (NO_3^-) was extracted with 1.0 M KCl (1:5 w/v soil: solution ratio) and measured by colorimetric method (Rowell 1994).

Soil treatments and incubation

Four types of agricultural residues including straw, stubble, and not harvested parts of wheat, potato, canola, and sunflower were oven dried at 70°C, crushed, and passed through a 2 mm sieve. The characteristics of the crop residues have been described in details by Ranjbar and Jalali (2012). The organic amendments were separately added to three soil samples at a rate of 2% by weight and then thoroughly mixed. Three control soil samples (with no amendment) and twelve treated soil samples were placed in polyethylene containers in duplicate as initial samples (i.e. 30 samples) and incubated for 168 days at the field capacity moisture and room temperature (25 ± 1°C). Moist subsamples of 20 g were taken from initial samples on 1, 3, 7, 14, 21, 42, 70, 105, and 168 days of the incubation, air dried, and passed through a 2 mm sieve for chemical analyses (i.e. pH, EC, Olsen-P and available NO_3^-, and soluble cations including Ca^{2+}, Mg^{2+}, K^+, and Na^+). The exchangeable cations were only determined on days 1, 21, 42, 105, and 168 of the incubation period. The analysis of pH, EC, and soluble cations during the incubation was performed using 1:5 soil to water extracts. The initial samples were weighed at the beginning of the experiment and re-weighed periodically to check for any significant loss of moisture by considering the weight loss as a result of taking moist subsamples during the incubation. Lost moisture was compensated by adding distilled water.

Statistical analysis

The analysis of variance (ANOVA) and comparison of means were performed by repeated measures arranged in a randomized complete block design and Duncan's multiple range test ($P < 0.05$), respectively using SAS software (v. 9.1). The organic residues, soils, and time were considered as factor A (main factor), blocks, and factor B, respectively. The comparison of means was performed based on the effect of organic residues on some chemical properties measured in soil samples over time.

RESULTS AND DISCUSSION

In this section, only the trend of changes in control and treated soil samples 1 was shown in figures, however, ANOVA and comparison of means were completely given in tables.

Changes in pH and EC

Fig. 1a shows that pH values of control and treated soil samples 1 have been reduced at the end of incubation. The results of ANOVA (Table 2) indicated that the effects of organic residues, soil, time and interactions between residues and soil and between residues and time were significant on soil pH. The comparison of means (Table 3) also showed that the application of organic residues caused a decrease in pH of treated soil samples compared with control samples. In general, it can be said that the release of H^+ during the decomposition of residues has led to a reduction in soil pH. This slight reduction was similar to the results provided by Clark *et al*. (2007) who attributed the limited effect of residues on pH to the high buffer capacity of soils resulted from clay content. On the other hand, the significant change in pH due to the addition of organic residues has been reported in acid sandy soils with low buffer capacity (Tang and Yu 1999, Tang *et al*. 1999, Xu *et al*. 2006).

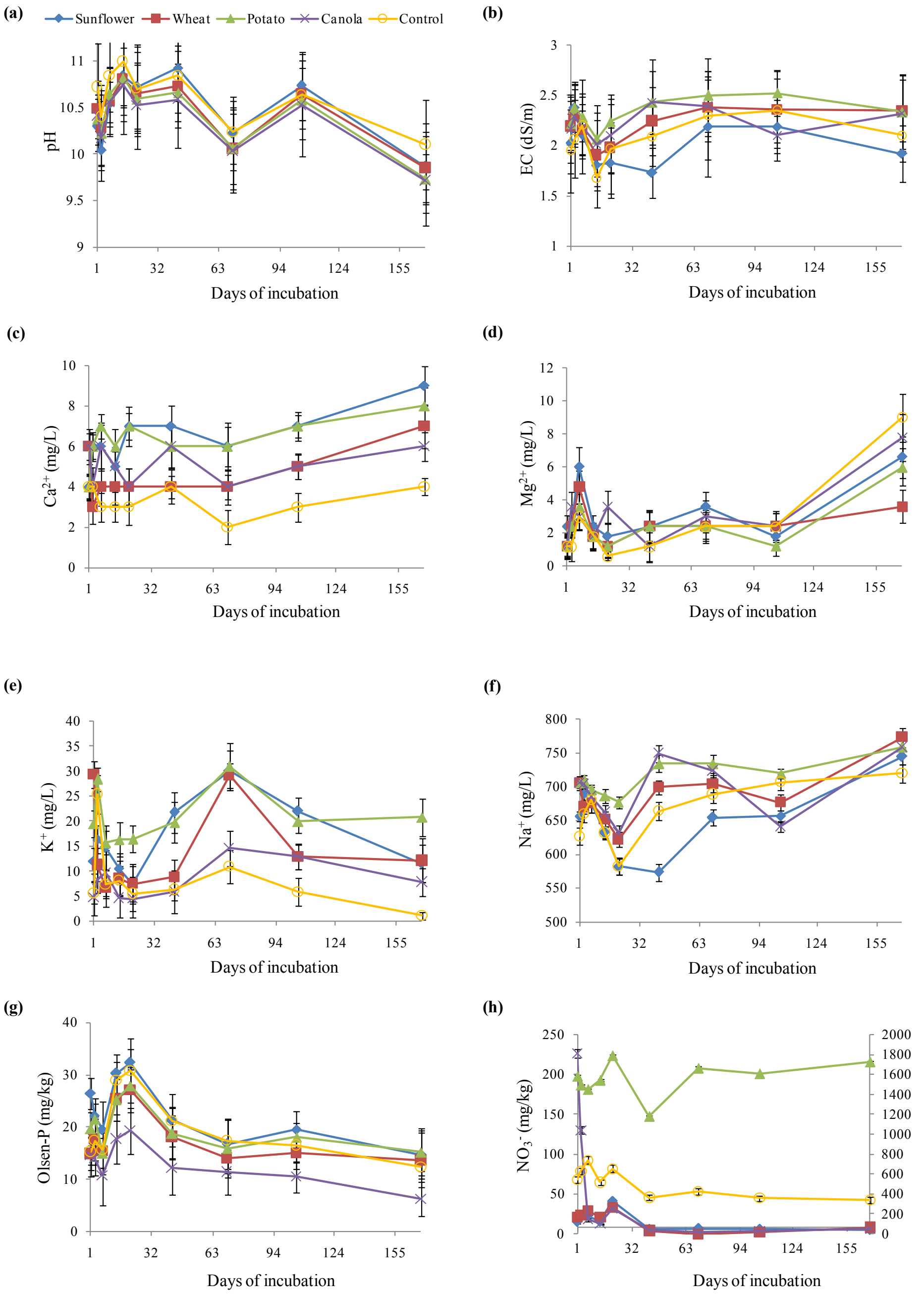

Fig. 1. Trend of changes in pH (a), EC (b), soluble Ca^{2+} (c), soluble Mg^{2+} (d), soluble K^+ (e), soluble Na^+ (f), Olsen-P (g) and available NO_3^- (h) in control and treated soil samples 1. The secondary y-axis in graph (h) is related to NO_3^- concentration in potato residue-treated sample. Vertical bars represent the standard deviation (SD)

Table 2. *F* values obtained from ANOVA for pH, EC, soluble cations, Olsen-P, and available NO_3^-

	pH	EC	Soluble cations (mg/L)				Olsen-P	Available NO_3^-
		dS/m	Ca^{2+}	Mg^{2+}	K^+	Na^+	mg/kg	mg/kg
SOV†								
Organic residues	8.5**	33.7**	1.0	1.7	3.7	12.6**	67.5**	9.3**
Soil	57.6**	1800**	15.5**	8.4*	74.4**	1468**	163.2**	0.9
Time	107.9**	8.8**	4.9**	5.3**	8.6**	10.8**	131.9**	2.4
Interaction of residues × soil	7.9**	0.9	3.3**	2.8**	1.5	2.0	1.2	68.6**
Interaction of residues × time	3.5**	0.5	1.2	0.7	0.8	0.7	1.3	0.9

† source of variations

** significant at the level of 99% ($P < 0.01$); * significant at the level of 95% ($P < 0.05$)

Table 3. Comparison of means indicating the effect of organic residues on pH, EC, soluble cations, Olsen-P, and available NO_3^- of three soils

Parameters	pH	EC	Soluble cations (mg/L)				Olsen-P	Available NO_3^-
			Ca^{2+}	Mg^{2+}	K^+	Na^+	mg/kg	mg/kg
Control	10.5 a	1.3 c	8.6 a	5.3 a	34.2 ab	435.7 c	23.8 b	113.8 b
Std Dev	±0.3	±0.6	±6.0	±3.2	±32.9	±166.0	±7.5	± 2.4
Sunflower	10.3 ab	1.4 c	8.6 a	5.1 a	45.3 a	438.2 c	26.3 a	19.6 b
Std Dev	±0.4	±0.5	±3.5	±2.8	±34.9	±160.7	±7.4	±0.7
Wheat	10.2bc	1.5 b	7.6 a	3.6 a	33.2 ab	457.8bc	22.0 c	20.1 b
Std Dev	±0.4	±0.5	±3.3	±2.4	±23.7	±169.4	±6.8	±1.3
Potato	10.1 c	1.6 a	7.5 a	3.6 a	33.9 ab	492.4 a	25.3 a	992.0 a
Std Dev	±0.5	±0.5	±2.5	±2.1	±23.5	±168.1	±7.0	±23.6
Canola	10.1 c	1.5 b	6.5 a	3.9 a	25.4 b	469.9 b	17.6 d	54.7 b
Std Dev	±0.4	±0.5	±2.2	±2.3	±21.4	±168.7	±6.0	±3.3

Note: Means followed by dissimilar letters within a column are significantly different at $P < 0.05$ according to the Duncan test.

In addition to carbonic acid, nitric acid is produced under aerobic decomposition conditions. These acids lead to a decrease in pH and the subsequent increase in the dissolution of soil native calcium carbonate. But the presence of carbonic acid plays a major role in this process (Tan 1994) and the effect of nitric acid on reducing pH is less than carbonic acid. In fact, formation of carbonic acid from CO_2 produced during the decomposition of organic residues in soils is the main component responsible for decreasing pH. However, as the population of decomposing microorganisms (heterotrophs) declines, N mineralization by chemoautotrophs increases and consequently the role of nitric acid in the dissolution of native calcite enhances (Brady 1990, Jin *et al*. 2008).

Hanay *et al*. (2004) reported that application of a compost produced from solid municipal wastes slightly increased soil pH, while Wahid *et al*. (1998) indicated that the addition of farmyard manure led to a decrease in pH. The difference between these results is probably related to the degree of compost maturity. When fresh organic materials such as raw manures are applied in soils, an increase in microbial activities and the subsequent production of organic acids results in the reduction of pH. Li and Keren (2009) also reported that the soil pH decreased after application of various amounts of corn stalks to a calcareous sodic soil and incubation for 30 and 60 days.

The reduction in pH in this study was likely due to an increase in microbial activities resulted from the production of CO_2 and formation of carbonic acid during the incubation. However, the soil pH was balanced after 3 days due to the buffer capacity of soils associated with clay content and ECC. Although it is often expected that organic components reduce the soil pH due to the release of H^+ ions through the decomposition process, they can increase soil pH for two reasons: 1) release of organic anions mineralized to CO_2 and water and the subsequent removal of protons; and/or 2) their alkaline nature (Helyar 1976). Xu *et al*. (2006) showed that the use of plant residues increased the soil pH. They suggested that the release of alkalinity during the decomposition of organic residues and the ammonification of organic nitrogen can increase soil pH, while the nitrification process leads to its reduction. Therefore, the effect of organic residues on soil pH depends on the dominance of these processes. Clark *et al*. (2007) also reported an increased soil pH by adding organic amendments under incubation conditions.

The changes in EC of control and treated soil samples 1 during the incubation are demonstrated in Fig. 1b. The pattern of EC variations was contrary to the trend of changes in pH. The application of organic residues caused an increase in EC of treated soils. The EC variations were mainly affected by the type of residues. A slight increase in soil EC at the end of incubation compared to the initial values (first day of incubation) varied from 0.07 to 0.3 dS/m. A comparison between Figs. 1a and 1b indicates that the decreased pH corresponds with the increased EC at each point of measurement. As mentioned above, the decrease in pH is related to the formation of carbonic acid caused by the raised PCO_2 and production of organic acids from organic residues being decomposed, whereas the increase in EC followed by the addition of organic compounds is mainly due to the production of organic acids (Wong *et al*. 2009), the release of cations and anions during the decomposition process, and an increase in the dissolution of carbonate minerals caused by the increment of PCO_2 (Li and Keren 2009).

The results of ANOVA (Table 2) indicated that the effect of organic residues, soil, and time was significant on EC, while the interactions between residues and soil and between residues and time were not. The statistical comparison of means also showed that the application of organic residues significantly increased soil EC (Table 3). The increment of EC in soils treated with potato residue was higher than that in other treatments due to the presence of higher concentration of soluble cations and anions in this type of amendment. Ranjbar and Jalali (2011) indicated that the incorporation of potato residue in a non-saline-sodic soil for a one-month incubation period had the highest influence on increasing the soil EC in comparison with other organic treatments. Li and Keren (2009) reported that the soil EC increased after the application of corn stalks and incubation for 30 and 60 days. They related this increase to the enhancement of $CaCO_3$ dissolution induced by the elevated PCO_2 resulted from the decomposition of corn stalks.

Changes in soluble cations

Fig. 1c indicates that the concentration of soluble Ca^{2+} in control and treated soil samples 1 has remained nearly constant till day 105 and then increased. The results of ANOVA and comparison of means (Tables 2 and 3) indicated that organic residues had no significant effect on the soluble Ca^{2+} concentration when compared to the control soils. The trend of variations in the soluble Mg^{2+} in control and treated soil samples 1 during the incubation has been illustrated in Fig. 1d. The soluble Mg^{2+} concentration increased at the end of incubation in all control soil samples and ranged from 6.0 to 7.8 mg/L while, it decreased in treatments. Like the soluble Ca^{2+}, application of organic residues had no significant effect on the soluble Mg^{2+} concentration (Tables 2 and 3). This can be associated with more replacement of soluble divalent cations (i.e. Ca^{2+} and Mg^{2+}) with exchangeable Na^+ in organic residue-treated soil samples compared to the controls. The changes in soluble K^+ in soil samples 1 over time has been demonstrated in Fig. 1e. The results of ANOVA and comparison of means (Tables 2 and 3) showed that the addition of residues did not significantly influence the increase of the concentration of soluble K^+ in treated soil samples when compared to the controls. Fig. 1f illustrates the variations in soluble Na^+ in control and treated soil samples 1 during the incubation. The increase in soluble Na^+ concentration during the incubation was mainly related to the substitution of exchangeable Na^+ with other soluble cations and release of soluble Na^+ as a result of decomposition of organic residues. The results of statistical analysis (Tables 2 and 3) showed that the concentration of soluble Na^+ increased in potato and canola treatments in contrast with control soils. The increase in the Na/Ca ratio in the solution phase of treated soils indicated that Na^+ desorbed from exchangeable sites.

The differences in the concentration of cations released in soil samples treated with organic residues during the incubation were directly related to the chemical composition of organic residues. Ranjbar and Jalali (2012) reported that total concentration of Ca^{2+}, Mg^{2+}, K^+, and Na^+ was higher in potato residue compared to the other amendments. Furthermore, the increased concentrations of soluble cations likely resulted from the dissolution of minerals caused by the elevated PCO_2 or formation of organic acids.

Changes in Olsen-P and available NO_3^-

The results indicated that at the end of incubation, the level of Olsen-P decreased from 15.3 to 12.4 mg/kg in control, 14.6 to 6.3 mg/kg in canola residue-, 19.7 to 15.3 mg/kg in potato residue-, 14.9 to 13.7 mg/kg in wheat residue-, and 26.4 to 14.8 mg/kg in sunflower residue-treated soil sample 1 (Fig. 1g). The reduction in the concentration of Olsen-P during the incubation can be attributed to its retention or precipitation by calcium carbonate (Lindsay and Moreno 1960).

According to the average of all soil samples, the Olsen-P in controls (23.8 mg/kg) increased by 10.6% and 6.2% in sunflower residue- (26.3 mg/kg) and potato residue-treated soils (25.3 mg/kg), respectively, whereas it decreased by 7.6% and 25.9% in wheat residue- (22.0 mg/kg) and canola residue-treated ones (17.6 mg/kg), correspondingly (Table 3). This can be attributed to higher concentration of P and lower level of C/P ratio in sunflower and potato residues compared to canola and wheat residues (Jalali and Ranjbar 2009b). The C/P ratio of bacteria ranges from 200 to 300, therefore, if C/P of organic component is less than 200, mineralization can occur, whereas if this ratio is more than 300, the inorganic P can be immobilized by microorganisms (Havlin *et al.* 1999). So, the application of wheat and canola residues with C/P > 300 led to a reduction in the concentration of Olsen-P. Jalali and Ranjbar (2009b) reported that the release of inorganic P had a significant positive correlation with total P concentration in organic residues and a negative correlation with C/P ratio. It has been shown that an increased microbial activity due to the application of biofertilizers for remediation of salt-affected soils facilitates the transformation of unavailable organically bound P into available forms (Seenivasan *et al.* 2015, Nisha *et al.* 2018).

Fig. 1h demonstrates that the application of organic residues with the exception of potato residue has led to a decrease in NO_3^- concentration in treated soil samples 1 in contrast with the control. Higher NO_3^- concentration in potato residue-treated soil samples may be due to higher NO_3^- concentration in the structural composition of this amendment. The results of ANOVA (Table 2) indicated that only the effects of organic residues and their interaction with soil were significant on NO_3^- variations. The comparison of means (Table 3) showed that just application of potato residue had a significant effect on increasing the concentration of NO_3^- in treated soils relative to the controls, whereas the incorporation of other residues into soils caused a decrease in NO_3^- concentration. Table 3 indicated that the level of available NO_3^- in soils treated with potato residue was 878.2 mg/kg more than control soils on average, while the incorporation of sunflower, wheat, and canola residues decreased the available NO_3^- content by 94.2, 93.7, and 59.1 mg/kg, respectively. The organic components with high C/N ratio (i.e. >30) cause to immobilize the inorganic N, while those with low C/N ratio (i.e. < 20) result in the net N mineralization (Mitchell *et al*. 2000, Seenivasan *et al*. 2015). The C/N ratio was near to 20 in potato residue, while it was more than 30 in other organic residues (Jalali and Ranjbar 2009b).

Changes in the exchange complex

The trend of variations in the exchangeable Ca^{2+} in control and treated soil samples 1 during the incubation has been shown in Fig. 2a. The exchangeable Ca^{2+} remained unchanged in control soil sample 1, while it varied from 2.4 to 4.4 $cmol_c$/kg in canola residue-, 1.9 to 4.3 $cmol_c$/kg in potato residue-, 4.9 to 5.8 $cmol_c$/kg in wheat residue-, and 5.9 to 6.8 $cmol_c$/kg in sunflower residue-treated soil samples 1. On average, the application of crop residues led to an increase in the exchangeable Ca^{2+} from 2.9 $cmol_c$/kg in controls to 3.8 $cmol_c$/kg in canola residue-, 4.0 $cmol_c$/kg in potato and wheat residue-, and 4.8 $cmol_c$/kg in sunflower residue-treated soils. However, results of the statistical analysis (Tables 4 and 5) showed that there was no significant difference between the levels of exchangeable Ca^{2+} in treatments and control soils. The increment of exchangeable Ca^{2+} as a result of using amendments over time ranged from 0.9 $cmol_c$/kg in sunflower residue-treated soil sample 1 to 3.1 $cmol_c$/kg in potato residue-treated soil samples 2.

Table 4. *F* values obtained from ANOVA for CEC, exchangeable cations, and ESP

	CEC	Exchangeable cations ($cmol_c$/kg)				ESP
	$cmol_c$/kg	Ca^{2+}	Mg^{2+}	K^+	Na^+	%
SOV†						
Organic residues	23.8**	1.5ns	10.1**	4.2*	0.6ns	4.1*
Soil	185.5**	0.2ns	9.4**	13.5**	254.6**	70.9**
Time	28.4**	15.2**	37.7**	1.7ns	12.2**	13.8**
Interaction of residues × soil	5.4**	19.0**	50.3**	2.8*	9.2**	22.6**
Interaction of residues × time	2.4*	1.5ns	3.1**	0.4ns	0.9ns	1.0ns

† source of variations

**significant at the level of 99% ($P < 0.01$); *significant at the level of 95% ($p < 0.05$); ns not significant

Table 5. Comparison of means indicating the effect of organic residues on CEC, exchangeable cations, and ESP of three soils

Parameters	CEC	Exchangeable cations ($cmol_c$/kg)				ESP
	$cmol_c$/kg	Ca^{2+}	Mg^{2+}	K^+	Na^+	%
Control	16.8 b	2.9 a	2.3 b	0.3 b	11.4 a	61.0 a
Std Dev	±5.7	±0.7	±0.8	±0.2	±6.4	±23.5
Sunflower	22.6 a	4.8 a	5.3 a	0.8 ab	11.8 a	49.9 b
Std Dev	±4.9	±1.5	±2.1	±0.6	±4.8	±13.0
Wheat	22.2 a	4.0 a	5.5 a	0.9 a	11.9 a	51.4 ab
Std Dev	±4.9	±0.7	±2.2	±0.7	±5.0	±15.1
Potato	23.2 a	4.0 a	7.1 a	1.2 a	10.9 a	44.9 b
Std Dev	±4.9	±1.1	±1.1	±0.9	±4.8	±14.6
Canola	22.4 a	3.8 a	6.4 a	0.7 ab	11.6 a	48.3 b
Std Dev	±5.0	±0.7	±0.8	±0.3	±5.6	±17.2

Note: Means followed by dissimilar letters within a column are significantly different at $p < 0.05$ according to Duncan test.

Fig. 2b indicates that the level of exchangeable Mg^{2+} in all treated soil samples 1 has increased over time from 1.5 to 1.6 $cmol_c$/kg in control, 5.0 to 6.2 $cmol_c$/kg in canola residue-, 5.5 to 7.8 $cmol_c$/kg in potato residue-, 2.0 to 3.4 $cmol_c$/kg in wheat residue-, and 1.9 to 3.7 $cmol_c$/kg in sunflower residue-treated soils. The results of the statistical comparison of means (Table 5) showed that the exchangeable Mg^{2+} in controls (2.3 $cmol_c$/kg) significantly increased after the application of crop residues and the highest level was observed in potato residue-treated soils (7.1 $cmol_c$/kg). The increase in exchangeable Mg^{2+} from 1.0 to 2.4 units ($cmol_c$/kg) has been reported after application of organic amendments in a non saline-sodic soil (Jalali and Ranjbar 2009a, Ranjbar and Jalali 2011).

Fig. 2c indicates the trend of variations in the exchangeable K^+ from 0.3 to 0.4$cmol_c$/kg in control, 0.6 to 0.5 $cmol_c$/kg in canola residue-, 0.7 to 0.6 $cmol_c$/kg in potato residue-, 0.4 to 0.6 $cmol_c$/kg in wheat residue-, and 0.7 to 0.6 $cmol_c$/kg in sunflower residue-treated soil samples 1. On average, organic residues led to an increase in the level of exchangeable K^+ and the highest level of increment was observed in the potato treatment (Table 5). However, results of the statistical comparison of means indicated that there was no significant difference among various treatments (Table 5). The increase of exchangeable K^+ in soils from 0.04 to 0.38 unit ($cmol_c$/kg) has been reported in previous studies as a result of applying organic components (Clark *et al*. 2007, Jalali and Ranjbar 2009a, Ranjbar and Jalali 2011).

The trend of changes in the exchangeable Na^+ in control and treated soil samples 1 has been shown in Fig. 2d. At the end of incubation, a decrease in the exchangeable Na^+ was observed in control from 14.9 to 14.5 $cmol_c$/kg and potato residue-treated soil sample 1 from 13.0 to 12.3 $cmol_c/kg$. The results of the statistical analysis given in Tables 4 and 5 showed that the effect of application of organic residues on changing the exchangeable Na^+ was not significant relative to the control soils.

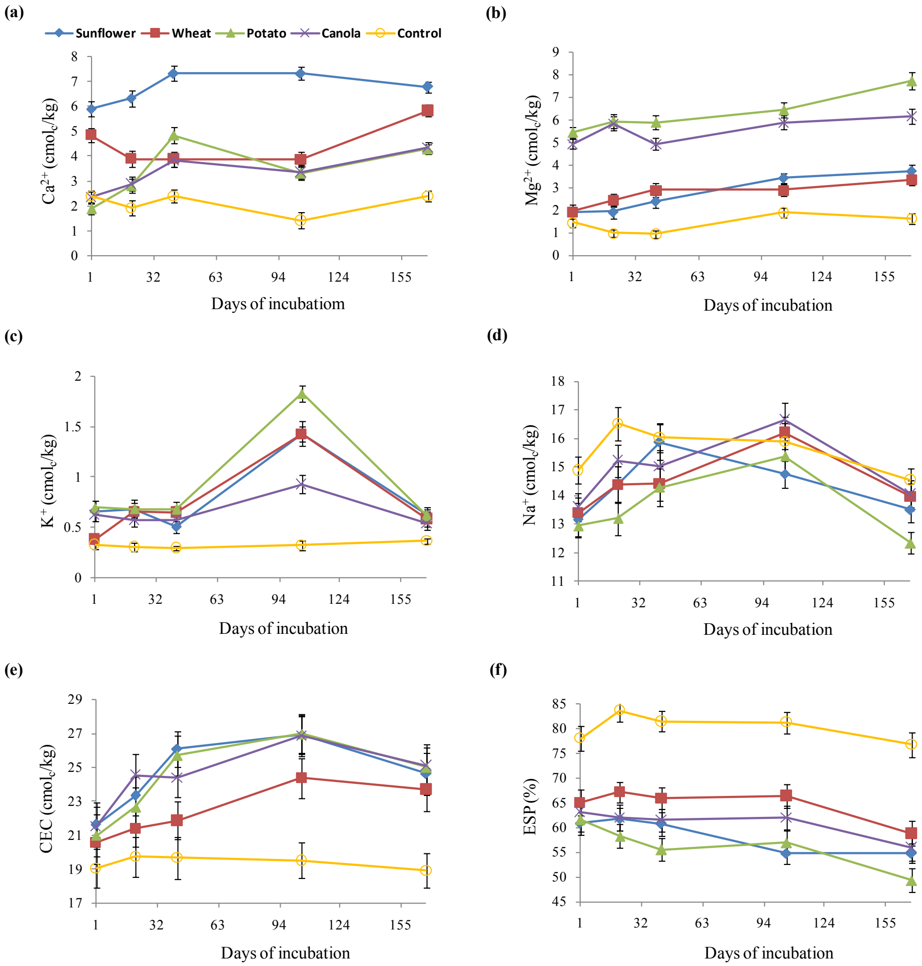

Fig. 2. Trend of changes in exchangeable Ca^{2+} (a), exchangeable Mg^{2+} (b), exchangeable K^+ (c), exchangeable Na^+ (d), CEC (e) and ESP (f) in control and treated soil samples 1. Vertical bars represent the standard deviation (SD)

Fig. 2e indicates that organic amendments have led to an increase in CEC in treated soil samples 1 and the highest level has been obtained in the potato residue treatment. Furthermore, the comparison of the means (Table 5) indicated that the effect of residues on increasing CEC in treated soils was significant compared to the control samples, but there was no remarkable difference among treatments. The increase in CEC in all treatments of three soil samples at the end of incubation ranged from 2.6 to 5.6 $cmol_c/kg$. Although changes in exchangeable cations (except for Mg^{2+}) were not significant in organic treatments relative to the controls, the sum of them led to a significant increase in CEC. Quedraogo *et al*. (2001) observed that the application of compost in agricultural fields at the level of 10 t/ha increased the soil CEC varying from 4to 6 $cmol_c/kg$. The increase in CEC after the application of biological amendments has also been reported in previous researches (Lax 1991, Bernal *et al*. 1992, Lax *et al*. 1994, Aggelides and Londra 2000, Walker and Bernal 2004, Seenivasan *et al*. 2015, Nisha *et al*. 2018). Havlin *et al*. (1999) indicated that the addition of different types of compost into the soil increased CEC varying from 20% to 70% of initial values. They attributed the range of increase in CEC to pH values of applied composts. Walker and Bernal (2008) found that the application of poultry manure at rates of 20 and 30 g kg^{-1} increased the soil CEC ranging from 3 to 5 units ($cmol_c/kg$) after 84 days. They also reported that the increment of CEC resulted in more occupation of exchangeable sites by Ca^{2+}, Mg^{2+}, and K^+ relative to Na^+. Laird *et al*. (2010) observed CEC increases ranging from 4% to 30% when hardwood biochar was incorporated at different rates after 500 days of incubation. The SOM contributes about 20–70% to the CEC of many soils (Stevenson 1994) which plays an important role in the soil fertility and plant nutrition.

Changes in ESP

The trend of ESP variations in control and treated soil samples 1 during the incubation has been shown in Fig. 2f. ESP decreased during the incubation in control and treated soil samples 1, but the extent of reduction in treatments was more than in the control. Furthermore, the highest reduction in ESP was observed in the potato residue treatment.

The statistical comparison of means (Table 5) showed that the reduction in ESP in treated soils with the exception of wheat residue treatment was significant relative to all control soil samples. The highest percentage of decrease in ESP relative to the control was found in potato treatment (16.1%) followed by canola (12.7%), sunflower (11.1%), and wheat (9.6%) treatments. So, all of organic residues were effective in mobilizing Ca^{2+} from inherent and precipitated $CaCO_3$ resulting in the decreased pH and ESP. According to the characteristics of organic residues reported by Ranjbar and Jalali (2012), this study confirms the ability of organic amendments in reducing soil sodicity, depending on the concentrations of cations such as Ca^{2+}, Mg^{2+}, and K^+ in the structural composition of these materials.

The use of organic residues reduces the sodicity of soil samples through the supply of Ca^{2+}, Mg^{2+}, and K^+. Li and Keren (2009) indicated that ESP of soil decreased after the application of corn stalks. Hanay *et al.* (2004) reported that after three months, ESP of a saline-sodic soil decreased from 44.75% to 6.78%, 7.06%, and 7.2% as a result of the application of compost at rates of 50, 100, and 150 g/kg, respectively. Clark *et al.* (2007) indicated that the reduction in ESP of a sodic clay soil was around 10% after application of wheat, canola, and chickpea residues and chicken manure at a rate of 1% by weight and a 174-day incubation period. They attributed the reduction in ESP to an increase in the exchangeable Ca^{2+}. Akhtar *et al.* (2015) found that an increased occupation of exchangeable sites with Ca^{2+} and Mg^{2+} decreased the exchangeable Na^{+} after application of biochar to salt affected soils. Ranjbar and Jalali (2015) reported that the ESP of a saline-sodic soil decreased by 2.8% and 4.9% after a 40-day incubation period and incorporation of potato residue at the rates of 2% and 4%, respectively.

The biochemical reactions in the soil system after the application of organic residues are dynamic processes that may be influenced by incubation period. The long-term incubation results in reducing the PCO_2 due to the decreased microbial activities. From this viewpoint, this kind of incubation does not significantly affect the dissolution of native calcite. On the other hand, the long-term incubation is suitable for the replacement of Na^{+} with Ca^{2+} on exchangeable sites. Furthermore, the degree of soil sodicity influences the decomposition of organic components and dissolution of native calcite. All of these factors determine the effect of incubation period on the reclamation efficiency of calcareous sodic soils.

This study demonstrated that the application of organic amendments into saline-sodic soils could improve the soil fertility. However, some caution needs to be taken in generalizing the results of this incubation study to the field. The factors such as fluctuation in soil moisture and aeration and degree of mixing of organic amendments with soil can influence the rate of decomposition and subsequent release of nutrient in field conditions (Clark *et al.* 2007).

CONCLUSIONS

The results showed that the use of cheap and readily available amendments such as crop residues is a cost-effective and environmentally-friendly way for reclamation of saline-sodic soils. The values of pH, EC, CEC, and ESP of saline-sodic soil samples were significantly affected by application of organic amendments under controlled laboratory conditions. The incorporation of organic residues in saline-sodic soil samples after 168 days of incubation led to a reduction in pH and ESP and an increment in EC and CEC. The mechanisms responsible for the reclamation process involved the enhanced PCO_2 as a result of the decomposition of organic residues in soils and the subsequent increase in the dissolution of calcium carbonate and supply of Ca^{2+} for replacement of exchangeable Na^{+} on one side, and the increase in CEC of soils treated with organic residues and the preference for adsorption of divalent cations such as Ca^{2+} and Mg^{+} relative to monovalent ones like Na^{+}, on the other side. The efficiency of reclamation was influenced by the type of organic amendments due to having different characteristics. Potato residue was the most effective amendment in changing the chemical properties of saline-sodic soils in comparison with other organic residues. Therefore, the results suggested that the application of organic residues depending on their chemical composition had a positive impact on reducing the soil sodicity and improving the soil fertility.

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