Journal of Soil Science and Plant Nutrition (2022) 22:1362–1376
https://doi.org/10.1007/s42729-021-00738-z

ORIGINAL PAPER

Dynamics of Dissolved Ions in the Rhizosphere Under Flooded Conditions

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Received: 7 October 2020 / Accepted: 14 December 2021 / Published online: 4 February 2022

Abstract

Soil salinity represents one of the major threats of land degradation and desertification under arid and semi-arid environments. It has an adverse influence on soil-water-plant relationships, posing serious challenges to agricultural productivity. The main objective of this work was to monitor the effect of farmyard manure (FYM) application and irrigation with low-quality water on the dynamics of dissolved salts and yield of rice crop (*Oryza sativa L.*) under flooded conditions. Accordingly, field and column experiments were carried out with three treatments of irrigation water, namely, tap, saline-sodic, and saline, as well as three rates of FYM application (0, 12, and 24 Mg ha^{-1}). The obtained data indicated that the highest grain yields were found under the treatment with tap water followed by saline water amended with FYM at 24 Mg ha^{-1}. The loss of ions (Na^+, HCO_3^-, Cl^-, NO_3^-, SO_4^{2-}) from the soil irrigated with saline water was greater than that from irrigated with saline-sodic water. The addition of FYM led to an increase in the leaching of most ions (Na^+, HCO_3^-, and Cl^- in particular) and decreased their accumulation in soils irrigated with saline and saline-sodic waters. The regression studies revealed that FYM application may be attributed to the increase in soil resistance against secondary salinization through improving water and salt flux out of the rhizosphere. Under flooded conditions, these findings support the hypothesis that using FYM in conjunction with saline irrigation water has a beneficial effect, while saline-sodic irrigation water should be used with a calcium source.

Keywords Low-quality water · Dissolved ions · FYM · Secondary salinization · Rice yield

1 Introduction

The productivity of agricultural soils in arid and semi-arid regions is affected by salt accumulation in the rhizosphere (Cominelli et al. 2013), shortage of soil organic carbon (SOC), and low-quality of irrigation water. Salinization process has a critical effect on soil health via its ability to suppress the functionality of soil microorganisms toward improving agrophysical and biological soil properties. This is in addition to its impact on the dynamics and transformations of plant nutrients and degradation of soil pollutants (Nachshon 2018). Consequently, salinization hazard may lead to serious limitations on agricultural crop productivity and consequently food security (Vargas et al. 2018). The loss of crop yield in salt-affected soils vary from 18 to 43% (FAO 2000). This amount of loss in crop yield can threaten the food security and increase the potential of hazards induced by climate change and land degradation. Recently, secondary salinization has stand up as a tremendous threat for sustaining soils irrigated with low-quality water in arid and semi-arid regions (FAO 2000; Vargas et al. 2018). Furthermore, the extensive reuse of these waste waters is considered as one of the main reasons for the secondary soil salinization. This is in addition to the long-term risk on groundwaters, soils, and crops (Hussain et al. 2019). Despite these agro-environmental problems, there is an urgent need to reuse low-quality water resources in irrigation due to the lack of freshwater supplies in these susceptible regions (Joseph et al. 2010).

In this regard, there are several interactions among soil, water, and solutes controlling plant growth and its productivity. Accordingly, understanding the agro-eco-hydrological processes is important for establishing a solid basis for agricultural management (Chen et al. 2019). Controlling salt and water regions of irrigated soils would be easier if the rate of loss of different solutes carried in water moving out of the soil could be determined (Cominelli et al. 2013). In

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addition, studying the dynamic of salts helps in reclaiming the salts-affected soils, forming accurate nutrient budgets and increase understanding of the nutrient cycling. Thus, identifying the concentration and amount of mineral fertilizers below the root zone is important to minimize the fertilizer additions taking into consideration the nutrients losses (Campbell 1994).

Different approaches have been suggested to solve these issues, such as benefit by the flooded conditions associated with rice crop cultivation, which considered an effective low-cost amelioration approach (Luo and Sun 2004; Zhao et al. 2012). These flooded conditions provided a mechanism involving prevention of adsorption or displacement of the salinity-forming cations (primarily Na^+) on the soil exchange complex surface. This mechanism prevents soil salinity and directly changed the land use and management towards reducing the soil salinization risks, especially when utilizing untreated poor-quality irrigation waters while maintaining the rapid movement of water and solutes through the soil profile (Vargas et al. 2018). Furthermore, carbon input from external sources (such as FYM) facilitates the formation of stable soil aggregates which in turn improves soil physical environment such as higher porosity, lower bulk density, higher infiltration, and lower penetration resistance (Oldfield et al. 2018) and, therefore, increased water and salt movement through the soil profile.

The research aimed to monitor the effect of organic matter application on dissolved salts dynamic, soil leachability, and rice yield under irrigation with low-quality waters, with a benefit of irrigation water composition. Results of this work can help develop appropriate recommendations for reusing poor-quality irrigation waters in Egypt's flooded irrigated farming systems.

Table 1 Initial physico-chemical properties of the studied soil

Soil attribute	Unit	Value
pH†	-	8.54 ± 0.40
Electrical conductivity (EC)††	dS m^{-1}	2.64 ± 0.11
Organic matter (OM)	%	0.79 ± 0.06
Calcium carbonate ($CaCO_3$)	%	1.28 ± 0.14
Hydraulic conductivity (K_S)	m day^{-1}	0.04 ± 0.01
Sand	%	11.19 ± 0.69
Silt	%	38.07 ± 1.53
Clay	%	50.74 ± 1.78
Texture class	-	Clayey
Soluble cations††		
Sodium (Na^+)	$cmol_{(p+)}$ kg^{-1}	0.79 ± 0.11
Potassium (K^+)	$cmol_{(p+)}$ kg^{-1}	0.05 ± 0.01
Calcium (Ca^{2+})	$cmol_{(p+)}$ kg^{-1}	0.52 ± 0.10
Magnesium (Mg^{2+})	$cmol_{(p+)}$ kg^{-1}	0.32 ± 0.07
Soluble anions††		
Carbonate (CO_3^{2-})	$cmol_{(p+)}$ kg^{-1}	ND
Bicarbonate (HCO_3^-)	$cmol_{(p+)}$ kg^{-1}	0.42 ± 0.09
Chloride (Cl^-)	$cmol_{(p+)}$ kg^{-1}	0.70 ± 0.13
Sulfate (SO_4^{2-})	$cmol_{(p+)}$ kg^{-1}	0.53 ± 0.11
Available nutrients		
Nitrogen (N)	mg kg^{-1}	60 ± 2.10
Phosphorus (P)	mg kg^{-1}	12 ± 0.54
Potassium (K)	mg kg^{-1}	235 ± 4.50

† Measured in soil paste, †† measured in saturation extract at 25 °C

ND means not detected (below the detection limit), mean values ± SD, $n = 3$

2 Material and Methods

2.1 Site Description

Field and column experiments were carried out to study the impact of farmyard manure application on reducing the negative effects of low-quality irrigation water on rice crop *(Oryza sativa L.)* under flooded conditions. The field experiment was done at the experimental station of the Faculty of Agriculture, Mansoura University (latitude 31° 04 N, longitude 31° 35 E, and altitude of 6.42 m above the sea level), Egypt. The initial physical and chemical analyses of the studied soil are represented in Table 1.

2.2 Analyses of FYM and Irrigation Water

The FYM used in this study was analyzed for $pH_{1:5}$, $EC_{1:5}$, OC, and total NPK and the obtained values were 7.38, 2.82, 26.5%, 1.16%, 0.78% and 0.43%, respectively. The irrigation water used in this work was collected every five days from an agricultural drainage canal at Mit Khames Village, Mansoura District. This water was kept in a polyethylene tank and preserved by toluene against microbial transformation. The average values of water chemical analyses throughout the cultivation season are represented in Table 2.

2.3 Field Experiment

The field experiment was carried out using a split-plot design with three replicates for each treatment. The main plots consisted of three water treatments: (i) control (tap water), (ii) saline-sodic, and (iii) saline water and the sub-plots made up of three FYM rates (0, 12, and 24 Mg ha^{-1}). The plot area was 10 m^2 (2.0×5.0 m). The rice seeds (variety of Sakha104) were planted by broadcasting (direct throwing) over the soil surface on May 2017, subsequently incorporated by plowing, and then the soil was irrigated until it was saturated with water. Afterwards, the soil was irrigated approximately every five days with a constant level of (5–7 cm) until the stage of yellow ripe. The depth of flooded water was tested

Table 2 Chemical analyses of different irrigation waters

Water parameter	Unit	Tap water (I_1)	Saline-sodic water (I_2)	Saline water (I_3)	Recommended maximum concentration††
pH	-	7.14 ± 0.11	9.48 ± 0.15	7.34 ± 0.17	6.5-8.4
Electrical conductivity (EC)	dS m^{-1}	0.47 ± 0.03	3.17 ± 0.09	4.61 ± 0.10	0.0-3.0
Adjusted sodium adsorption ratio (SAR_{adj})	-	1.69 ± 0.04	20.82 ± 0.21	5.77 ± 0.08	6.0-24.0
Residual sodium carbonate (RSC)	me L^{-1}	ND	2.52 ± 0.07	ND	1.25-2.50
Chloride (Cl^-)	mmol L^{-1}	2.50 ± 0.07	13.96 ± 0.27	7.31 ± 0.10	4.0-10.0
Sulfate (SO_4^{2-})	mmol L^{-1}	0.40 ± 0.02	8.49 ± 0.12	14.44 ± 0.23	0.0-20.0
Bicarbonate (HCO_3^-)	mmol L^{-1}	1.80 ± 0.05	14.4 ± 0.29	8.21 ± 0.16	1.5-9.0
Nitrate (NO_3^-)	mg L^{-1}	ND	3.47 ± 0.03	11.00 ± 0.03	0.0-30.0
Ammonium (NH_4^+)	mg L^{-1}	ND	2.91 ± 0.03	6.61 ± 0.03	0.0-5.0
Water Class†	-	Good	Severe salty and sodic	Severe salty	-

† According to Ayers and Westcot (1985), †† adapted from NAS - NAE (1972) and Pratt (1972)

ND means not detected (below the detection limit), mean values ± SD, $n = 3$, heavy metals and micronutrients were within the optimum limits

every two days by a meter stick at several points in the field to ensure the constant water depth. Both pest and weed control were carried out using the recommended methods as described by the Rice Research and Training Center (RRTC 2003). Ammonium sulfate was applied at the rate of 360 kg ha^{-1} in three doses (before cultivating, after 30 and 70 days). Calcium superphosphate was applied at the rate of 240 kg ha^{-1} in one dose before cultivation. Potassium sulfate was applied at the rate of 120 kg ha^{-1} according to RRTC (2003).

Crop irrigation was stopped at the yellow ripe stage. This is in order to make rice dry naturally until grain harvest at a moisture content of about 13%. The crop was harvested on October 2017 at 146 days, and the crop yield (straw and grain) was recorded. Representative surface soil samples at 30 cm depth were collected at different times during the growing season at the vegetative (65 days), tillering (95 days), and harvesting (146 days) stages.

2.4 Column Leaching Experiment

A column leaching experiment was carried out using the same conditions as the field experiment continued for 135 days and consists of nine treatments with six replicates. Plastic columns made up of polyvinyl chloride (PVC) were used in this experiment. These columns were 50 cm in length and 5 cm in internal diameter. The soil length in the column was 30 cm. The soil leachate (resulted from using irrigation water treatments) and the leaching solution (resulted from using tap water after low-quality water) were collected after 65, 95, and 135 days (the last irrigation of rice plant). The irrigation water level was kept constant at approximately 10 cm above the soil surface, and the leachate volume was 100 cm^3. At the end of each stage, two columns were excluded, from the experiment, after leaching with good-quality water (tap water). The effluent from each column was analyzed for EC, soluble ions, and the cumulative amount (Q_i) of ion in the leachate and leaching solution.

2.5 Analytical Methods

Collected soil samples were prepared according to (ISO 11464: 2006). Bulk density, particle size distribution, and total carbonate (expressed as $CaCO_3$%) were conducted according to Piper (1966). Hydraulic conductivity was measured using the constant head permeameter method in undisturbed soil as described by Singh (1980). Organic carbon (OC) was determined by dry combustion using the Thermo Scientific Flash 2000 elemental analyzer (ISO 10694: 1995). Organic matter (OM) was calculated by multiplying the OC in 1.724. Soil pH was measured using the pH meter (Jenway 3505 pH/mV/temperature meter), and the electrical conductivity (EC) was measured using the EC-meter (Jenco 3173) according to Jackson (1967). Water-soluble cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) and anions (CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-}) were determined according to Hesse (1971). Available soil phosphorus was determined in sodium bicarbonate extract (Olsen et al. 1954; van Schouwenburg and Walinga 1967). Available potassium was determined in ammonium acetate extract using the flame photometer (Stanford and English 1949). Available nitrogen (NH_4^+ and N-NO_3^-) was measured in KCl extract using the Kjeldahl method (Bremner and Keeney 1966).

The pH and EC of FYM were determined by AOAC (1995). Organic carbon (OC) and total nitrogen (TN) were determined by a Thermo Scientific Flash 2000 elemental analyzer (ISO 10694: 1995; ISO 13878: 1998). In addition, subsamples were digested using triple acid (HNO_3:H_2SO_4:$HClO_4$—9:2:1) extract (Hesse 1971) for the determination of total phosphorus (Hesse 1971) and total potassium (Piper 1966).

The irrigation water criteria of the three water types were estimated by USSLS (1954). Furthermore, inorganic elements were determined using an inductively coupled plasma (Thermo Scientific^{TM}iCAP^{TM} 7000 Plus Series ICP-OES) (Ammann 2007).

The soluble HCO_3^-, Cl^-, and EC of leachates and leaching solutions were estimated according to USSLS (1954), while the ions of Na^+, Ca^{2+}, Mg^{2+}, K^+, and S were measured by an inductively coupled plasma (Thermo Scientific^{TM}iCAP^{TM} 7000 Plus Series ICP-OES). The cumulative amount (Q_i, mg) of ion in the leachate relative to its amount in the leaching solution was calculated according to the following equation:

$$Q_i = \sum (C_{ij}C_{is})V_j \quad (1)$$

where C_{ij} (mg L^{-1}) and C_{is} (mg L^{-1}) are the ion concentrations in the leachate and leaching solution, respectively, at a given volume V_j as described by Jalali and Merrikhpour (2008).

The flux of solutes (J_C) was calculated using the following equation of Hillel (2004):

$$J_C = qc = -c\left[K\left(\frac{dH}{dx}\right)\right] \quad (2)$$

where $q = -K\ (dH/dx)$ is the Darcy's law, q is the volume of liquid flowing through a unit area per unit time, c is the mass of solute per unit volume of solution, and J_C is the mass of solute passing through a unit cross-sectional area of soil per unit time.

The average residence time of a solute (t_r, hours) was calculated by the following equation:

$$t_r = \frac{L}{\tilde{v}} \quad (3)$$

where L is the thickness of soil and $\tilde{v}$ is the distance of travel of a solute per unit time as given by Hillel (2004).

2.6 Quality Control and Assurance

The accuracy of OC and TN was verified by calibrating the equipment with a certified reference material (Aspartic acid, $C_4H_7NO_4$). For the accuracy verification of multi-element determination by ICP-OES, the calibration curves of standard solution (ICP multi-element standard solution IV, Merck, 1000 mg l^{-1}) were prepared and recorded ($R^2 \geq 0.99$) and average recovery was adjusted between 98.11 and 101.90%. The EC meter was internally calibrated by standard solution (HANNA, HI 7031, 1413 µS cm^{-1}) at 25 °C, and the pH meter was calibrated by two Merck standard buffer solutions at (20 °C): di-sodium hydrogen phosphate/potassium hydrogen phosphate (7) and boric acid/potassium chloride/sodium hydroxide (10), both of them traceable to SRM from NIST and PTB. The precision of the analytical methods was obtained by repeating the samples twice (repeatability test) and expressed as the standard deviation. In addition, precision specification was determined by calculating the relative standard deviation (RSD); the measurement set is considered to be precise if the RSD from the average of the set did not exceed 2%. Furthermore, all the research analyses were subjected to a laboratory control sample for validation and were checked by the quality control charts.

2.7 Statistical Analysis

The analyses of variance (ANOVA) were performed using the CoStat software package (Version 6.30, CoHort, USA, 2004) and the IBM SPSS statistics (Version 23, 2015). The Duncan test was used to compare the treatments at a 95% significance level ($p < 0.05$). Microsoft Excel was used to calculate the standard deviation values (Version 2016, Microsoft Corporation, USA).

3 Results

3.1 Field Experiment

3.1.1 Rice Yield

Data in Figure 1 show the impact of irrigation with low-quality water and application of FYM on rice yield (grain and straw). These data indicate that the control treatment (irrigation with tap water with and without FYM application) had the highest grain and straw yield. This was followed by the irrigation with saline water (I_3) amended with FYM. This reveals that the application of FYM results in an increase the productivity of rice plants irrigated with low-quality water. Moreover, the irrigation with poor-quality waters caused an increase in straw yield compared with grain yield.

3.1.2 Soil Salinity and Alkalinity

Data show the effect of irrigation with low-quality water and application of FYM on soil salinity (EC) and alkalinity (pH). Average values of electrical conductivity were used to monitor soil salinity under the field conditions because of its high correlation with the amount of soluble salts. It was noticed that the irrigation with low-quality water had a remarkable trend in increasing soil salinity (Figs. 2 and 3). The effect of water treatments on increasing soil salinity was in this order $I_3 > I_2 > I_1$. The accumulative hazard of irrigation water on soil salinity was significantly decreased ($p < 0.05$) with the application of FYM. On the other hand, the application of FYM had a moderate effect on decreasing soil pH. The pH values

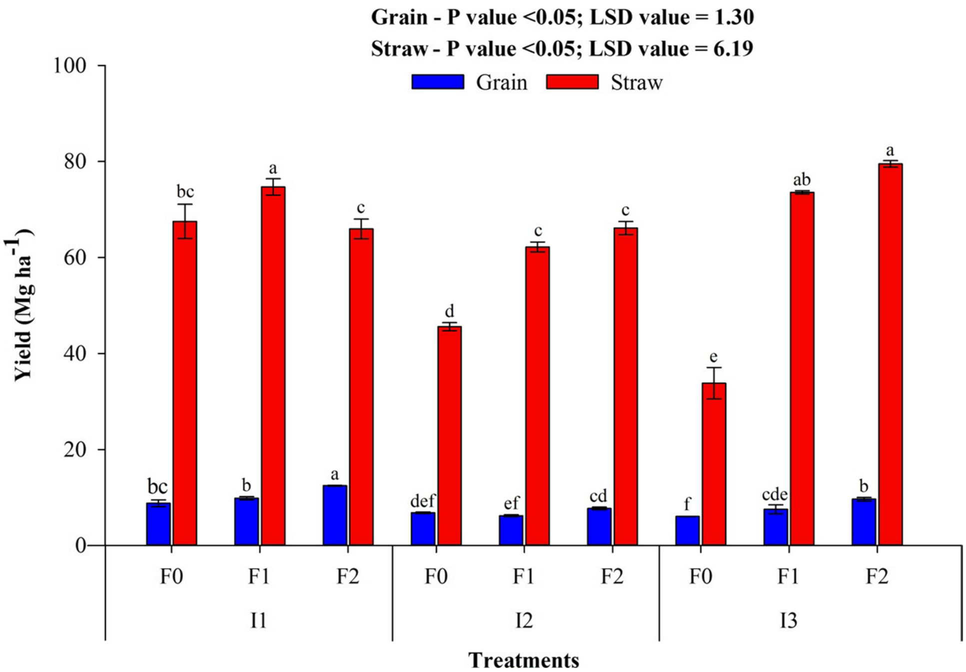

Fig. 1 Straw and grain yield of rice crop as affected by irrigating with different water qualities and FYM application. I_1 Tap water, I_2 Saline-sodic water, I_3 Saline water, F_0 Control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}. Dissimilar letters were significantly different at p <0.05 according to the Duncan test. Bars on the columns stands for ± standard deviation (SD). LSD least significant difference test

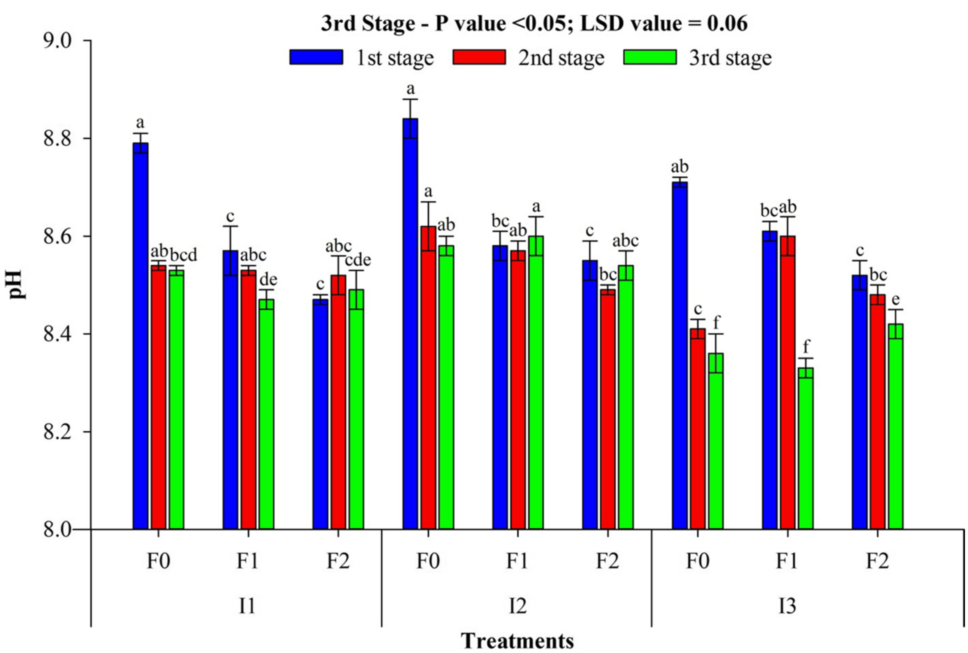

Fig. 2 Changes in soil pH values as affected by irrigating with different water qualities and FYM application. I_1 Tap water, I_2 Saline-sodic water, I_3 Saline water, F_0 Control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1} 1st stage 65 days, 2nd stage 95 days, 3rd stage 146 days. Dissimilar letters were significantly different at $p <$ 0.05 according to the Duncan test. Bars on the columns stands for ± standard deviation (SD). Interaction for 1st and 2nd stages do not differ significantly at (p < 0.05) by the least significant difference test (LSD)

of soil irrigated with I_1 and I_3 were decreased during the whole growing season. These values where first decreased with saline-sodic water treatment (I_2) at 65 and 95 days, then they were increased at the harvest stage (146 days). Regardless of the positive effect of adding FYM on soil pH, there were no significant effects at the vegetative (65 days) and the tillering (95 days) stages.

3.2 Column Experiment

3.2.1 Composition of Soil Leachate

Data in Tables 3 and 4 show the variations in concentrations of soluble ions before and after the leaching process at three periods of time (65, 95, and 135 days). These data

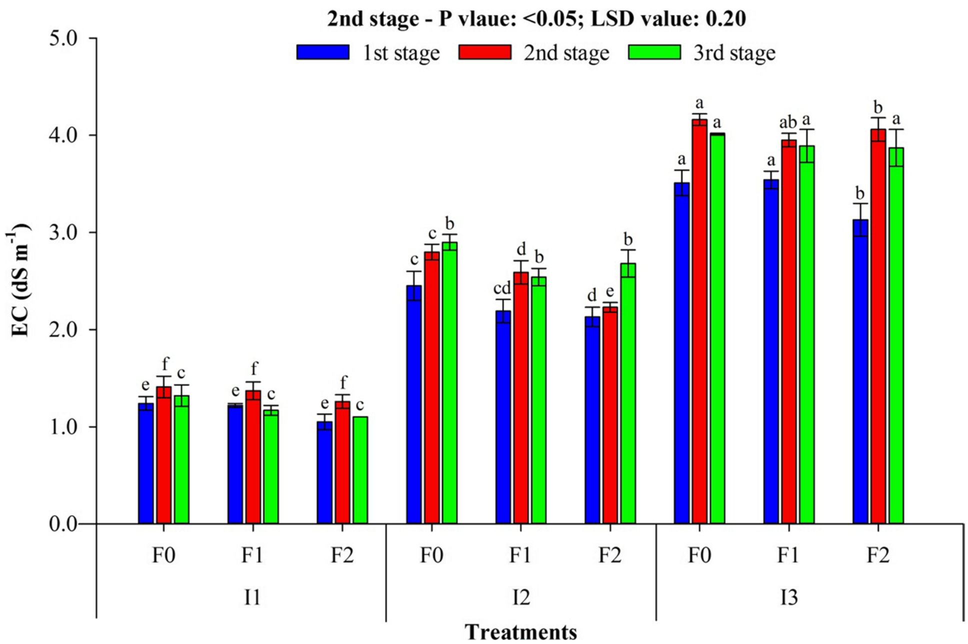

Fig. 3 Changes in soil EC values as affected by irrigating with different water qualities and FYM application. I_1 Tap water, I_2 Saline-sodic water, I_3 Saline water, F_0 Control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1} 1st stage 65 days, 2nd stage 95 days, 3rd stage 146 days. Dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test. Bars on the columns stands for ± standard deviation (SD). Interaction for 1st and 3rd stages do not differ significantly at ($p < 0.05$) by the least significant difference test (LSD)

indicated that the type of irrigation water had a significant effect on the composition of soil leachate.

The leachate salinity and its content of soluble Na^+, Cl^-, Ca^{2+}, and NO_3^- values were decreased after 65 days due to application of FYM in the soil irrigated with saline-sodic water (I_2). Moreover, the application of FYM with saline water (I_3) caused a decrease in EC, Na^+, NH_4^+, and NO_3^- when compared to the control (F_0).

After the second and third periods (95 and 135 days), the levels of most soluble ions and subsequently soil salinity were increased in soils treated with FYM and irrigated with low-quality waters when compared to the control. A negative relation was also noticed between Na^+ and Ca^{2+} concentrations in soil leachate with a progressive increase of Na^+ concentration with a noticeable decrease of Ca^{2+} ions.

In general, the leachate of soil irrigated with saline-sodic water (I_2) contained a large amount of Na^+, HCO_3^-, and Cl^-, whereas the content of Na^+, Mg^{2+}, Ca^{2+}, NH_4^+, SO_4^{2-}, and NO_3^- were prevalent in soil irrigated with saline water (I_3).

3.2.2 Composition of Leaching Solution

The leaching process with tap water (I_1) was carried out on the irrigation treatments with low-quality waters during the three studied periods. The use of FYM (in addition to the Ca^{2+} content of irrigation water) had a high leachability for most soluble ions. The leaching process caused a decrease in the salinity of leaching solution (LS) at all the studied periods and consequently decreased the soil salinity. Moreover, the application of FYM at 12 Mg ha^{-1} had attributed to increase of ion concentrations in the LS, especially soluble Na^+, Mg^{2+}, Cl^-, and SO_4^{2-} in soil irrigated with I_2. However, the concentrations of soluble K^+, Mg^{2+}, Ca^{2+}, and SO_4^{2-} were increased in soil irrigated with I_3 after 65 days when compared to the control. After 95 days, the application of FYM with saline-sodic water (I_2) decreased the leached ions of LS; in contrast, the leached ions from soil irrigated with saline water (I_3) were increased by adding FYM at 12 and 24 Mg ha^{-1} when compared to control treatment. After 135 days, I_2F_2 treatment recorded an increase in most leached ions. All the leached ions were decreased by adding FYM and irrigated with saline water (I_3) except Cl^- ions.

3.2.3 Leaching Losses of Dissolved Ions

The leaching losses of cations and anions during the studied periods were affected by the quality of irrigation water and FYM application as represented in Tables 5 and 6. The irrigation with saline-sodic water (containing higher Na^+ ions than divalent Ca^{2+} and Mg^{2+} ions with SAR_{adj} value of 20.8) had a harmful effect on increasing the cumulative amount of dissolved ions in the leachate during the studied periods, particularly without FYM application (F_0). On the other hand, the irrigation with saline water (containing relatively more Ca^{2+} ions than Na^+ ions with SAR_{adj} value of 5.8) had a moderate effect on increasing the cumulative amount of dissolved ions in the leachate.

The lowest amounts of leached ions (Na^+, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-}) were recorded in the control treatment (F_0) under different water qualities. Concentrations of these ions in leachate were increased under irrigating with saline-sodic water (I_2) in the initial stage (65 days) with FYM rate of 12 Mg ha^{-1} then with the rates of 24 Mg ha^{-1} at 95 and 135 days. However, rapid

Table 3 Soluble cations of leachate and leaching solution at 65, 95, and 135 days

Treatments		Before leaching					After leaching				
		Soluble cations (mmol L^{-1}) in soil leachate					Soluble cations (mmol L^{-1}) in leaching solution				
		K^+	Na^+	Mg^{2+}	Ca^{2+}	NH_4^+	K^+	Na^+	Mg^{2+}	Ca^{2+}	NH_4^+
65 days											
I_1	**F_0**	$0.03^d \pm 0.02$	$8.59^e \pm 0.31$	$4.20^{bc} \pm 0.57$	$3.30^c \pm 0.42$	ND	-	-	-	-	-
	F_1	$0.26^c \pm 0.05$	$10.13^{de} \pm 0.63$	$3.12^{cd} \pm 0.45$	$3.20^c \pm 0.14$	ND	-	-	-	-	-
	F_2	$0.17^c \pm 0.02$	$11.32^d \pm 0.21$	$3.40^{cd} \pm 0.42$	$3.20^c \pm 0.28$	ND	-	-	-	-	-
I_2	**F_0**	$0.41^b \pm 0.02$	$25.06^a \pm 0.09$	$0.70^e \pm 0.14$	$3.60^c \pm 0.28$	ND	$0.34^{ab} \pm 0.01$	$22.54^a \pm 0.07$	$3.40^{ab} \pm 0.04$	$1.40^d \pm 0.02$	ND
	F_1	$0.47^{ab} \pm 0.06$	$21.99^b \pm 0.57$	$1.65^{de} \pm 0.21$	$3.70^c \pm 0.14$	$0.65^d \pm 0.06$	$0.28^{ab} \pm 0.01$	$24.49^a \pm 0.23$	$3.70^a \pm 0.13$	$1.50^d \pm 0.04$	ND
	F_2	$0.43^{ab} \pm 0.08$	$20.81^b \pm 0.31$	$3.50^c \pm 0.42$	$3.30^c \pm 0.14$	$0.32^d \pm 0.11$	$0.25^b \pm 0.04$	$15.47^b \pm 0.19$	$2.60^{abc} \pm 0.14$	$2.30^b \pm 0.07$	ND
I_3	**F_0**	$0.40^b \pm 0.01$	$22.38^b \pm 0.71$	$4.60^{bc} \pm 0.07$	$5.00^b \pm 0.21$	$6.13^a \pm 0.31$	$0.26^{ab} \pm 0.02$	$18.15^b \pm 0.07$	$0.40^c \pm 0.04$	$1.60^d \pm 0.04$	ND
	F_1	$0.43^{ab} \pm 0.01$	$18.81^c \pm 0.35$	$7.20^a \pm 0.28$	$5.80^a \pm 0.08$	$1.46^c \pm 0.35$	$0.30^{ab} \pm 0.02$	$17.66^b \pm 0.05$	$3.60^a \pm 0.03$	$3.10^a \pm 0.07$	ND
	F_2	$0.53^a \pm 0.08$	$17.81^c \pm 0.42$	$5.50^{ab} \pm 0.58$	$5.50^{ab} \pm 0.32$	$3.50^b \pm 0.22$	$0.37^a \pm 0.04$	$12.79^c \pm 0.02$	$1.10^{bc} \pm 0.06$	$2.00^c \pm 0.03$	ND
LSD (p 0.05)		0.10	1.81	1.70	NS	0.80	NS	3.17	2.23	0.42	-
95 days											
I_1	**F_0**	$0.03^e \pm 0.02$	$13.49^d \pm 0.31$	$4.40^d \pm 0.28$	$4.00^{cd} \pm 0.14$	ND	-	-	-	-	-
	F_1	$0.07^e \pm 0.01$	$11.52^e \pm 0.31$	$5.15^{cd} \pm 0.57$	$3.65^{de} \pm 0.21$	$0.33^{bc} \pm 0.03$	-	-	-	-	-
	F_2	$0.26^d \pm 0.01$	$16.18^c \pm 0.45$	$5.50^{cd} \pm 0.42$	$3.50^e \pm 0.42$	ND	-	-	-	-	-
I_2	**F_0**	$0.21^d \pm 0.01$	$24.19^a \pm 0.34$	$5.70^{bc} \pm 0.14$	$1.80^f \pm 0.06$	ND	$0.24^b \pm 0.01$	$12.79^a \pm 0.07$	$1.80^e \pm 0.04$	$4.40^a \pm 0.04$	ND
	F_1	$0.32^{cd} \pm 0.04$	$22.22^b \pm 0.27$	$6.00^{bc} \pm 0.57$	$3.30^e \pm 0.14$	$0.41^{bc} \pm 0.04$	$0.07^d \pm 0.04$	$12.06^a \pm 0.17$	$2.20^e \pm 0.03$	$2.10^e \pm 0.14$	ND
	F_2	$0.89^a \pm 0.08$	$21.22^b \pm 0.48$	$6.00^{bc} \pm 0.14$	$4.40^c \pm 0.28$	$0.69^{ab} \pm 0.02$	$0.50^a \pm 0.02$	$6.45^{bc} \pm 0.12$	$2.90^d \pm 0.13$	$3.10^c \pm 0.14$	ND
I_3	**F_0**	$0.44^c \pm 0.02$	$13.27^d \pm 0.14$	$7.60^a \pm 0.28$	$7.50^a \pm 0.14$	$0.69^{ab} \pm 0.08$	$0.13^{cd} \pm 0.01$	$4.99^c \pm 0.07$	$8.20^a \pm 0.03$	$2.80^d \pm 0.05$	ND
	F_1	$0.57^b \pm 0.07$	$15.97^c \pm 0.23$	$7.90^a \pm 0.28$	$6.10^b \pm 0.14$	ND	$0.17^{bc} \pm 0.01$	$7.42^b \pm 0.19$	$6.40^b \pm 0.07$	$4.10^b \pm 0.12$	ND
	F_2	$0.40^c \pm 0.01$	$14.17^d \pm 0.11$	$6.90^{ab} \pm 0.14$	$7.30^a \pm 0.14$	$1.08^a \pm 0.18$	$0.18^{bc} \pm 0.01$	$6.45^{bc} \pm 0.07$	$5.20^c \pm 0.14$	$3.00^{cd} \pm 0.08$	ND
LSD (p 0.05)		0.13	1.45	NS	NS	0.40	0.07	1.42	0.42	0.24	-
135 days											
I_1	**F_0**	$0.14^c \pm 0.02$	$9.54^f \pm 0.35$	$2.95^{de} \pm 0.07$	$2.60^e \pm 0.28$	$0.05^b \pm 0.02$	-	-	-	-	-
	F_1	$0.12^c \pm 0.02$	$8.64^f \pm 0.34$	$1.80^e \pm 0.15$	$2.80^{de} \pm 0.28$	ND	-	-	-	-	-
	F_2	$0.21^{bc} \pm 0.08$	$13.76^e \pm 0.41$	$2.25^{de} \pm 0.25$	$2.90^{de} \pm 0.31$	ND	-	-	-	-	-
I_2	**F_0**	$0.21^{bc} \pm 0.04$	$16.20^d \pm 0.51$	$3.75^{cd} \pm 0.20$	$4.00^{cd} \pm 0.23$	$0.15^b \pm 0.01$	$0.18^b \pm 0.01$	$11.32^b \pm 0.15$	$5.50^{ab} \pm 0.12$	$1.10^b \pm 0.14$	ND
	F_1	$0.51^a \pm 0.05$	$22.78^b \pm 0.42$	$5.15^{bc} \pm 0.32$	$3.35^{cde} \pm 0.07$	ND	$0.17^b \pm 0.01$	$12.79^b \pm 0.07$	$6.40^a \pm 0.09$	$1.40^b \pm 0.07$	ND
	F_2	$0.51^a \pm 0.04$	$19.05^c \pm 0.44$	$6.85^{ab} \pm 0.43$	$4.25^c \pm 0.19$	ND	$0.47^a \pm 0.02$	$17.42^a \pm 0.13$	$3.30^{ab} \pm 0.11$	$1.40^b \pm 0.03$	ND
I_3	**F_0**	$0.49^a \pm 0.06$	$19.46^c \pm 0.37$	$6.80^{ab} \pm 0.34$	$7.50^a \pm 0.21$	$0.19^a \pm 0.02$	$0.35^{ab} \pm 0.05$	$14.49^{ab} \pm 0.06$	$4.40^{ab} \pm 0.07$	$4.40^a \pm 0.05$	ND
	F_1	$0.45^a \pm 0.01$	$22.78^b \pm 0.40$	$6.70^{ab} \pm 0.14$	$5.90^b \pm 0.35$	$0.27^a \pm 0.01$	$0.32^{ab} \pm 0.04$	$14.01^b \pm 0.13$	$1.50^b \pm 0.07$	$5.30^a \pm 0.11$	ND
	F_2	$0.38^{ab} \pm 0.09$	$25.62^a \pm 0.22$	$8.20^a \pm 0.28$	$5.50^b \pm 0.14$	ND	$0.30^{ab} \pm 0.04$	$14.01^b \pm 0.11$	$2.40^{ab} \pm 0.13$	$4.00^a \pm 0.12$	ND
LSD (p 0.05)		0.18	1.40	NS	NS	NS	0.17	3.08	NS	NS	-

I_1 tap water, I_2 saline-sodic water, I_3 saline water, F_0 control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}, *ND* means not detected (below the detection limit), mean values followed by dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test, mean ± SD, $n = 2$, *LSD* least significant difference test, *NS* non-significant

Table 4 Soluble anions of leachate and leaching solution at 65, 95, and 135 days

Treatments		Before leaching					After leaching				
		EC dS m^{-1}	Soluble anions (mmol L^{-1}) in soil leachate				EC dS m^{-1}	Soluble anions (mmol L^{-1}) in leaching solution			
			HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-		HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-
65 days											
I_1	F_0	$1.92^{d} \pm 0.02$	$6.10^{d} \pm 0.14$	$5.10^{g} \pm 0.14$	$8.25^{d} \pm 0.21$	ND	-	-	-	-	-
	F_1	$1.95^{d} \pm 0.03$	$7.25^{c} \pm 0.35$	$6.40^{f} \pm 0.14$	$6.05^{f} \pm 0.21$	ND	-	-	-	-	-
	F_2	$2.04^{d} \pm 0.01$	$7.30^{c} \pm 0.14$	$5.50^{fg} \pm 0.13$	$7.10^{e} \pm 0.14$	$0.45^{e} \pm 0.06$	-	-	-	-	-
I_2	F_0	$3.32^{c} \pm 0.05$	$5.35^{d} \pm 0.07$	$19.10^{a} \pm 0.15$	$6.50^{ef} \pm 0.42$	$2.20^{d} \pm 0.06$	$2.85^{a} \pm 0.14$	$12.80^{a} \pm 0.14$	$9.40^{b} \pm 0.04$	$6.30^{ab} \pm 0.07$	ND
	F_1	$3.22^{c} \pm 0.06$	$8.20^{b} \pm 0.44$	$16.80^{b} \pm 0.43$	$6.65^{ef} \pm 0.35$	$0.50^{e} \pm 0.14$	$2.99^{a} \pm 0.13$	$10.70^{bc} \pm 0.18$	$12.30^{a} \pm 0.17$	$6.89^{a} \pm 0.13$	ND
	F_2	$3.17^{c} \pm 0.15$	$9.30^{a} \pm 0.21$	$14.30^{c} \pm 0.42$	$8.30^{d} \pm 0.42$	ND	$2.16^{b} \pm 0.17$	$10.10^{c} \pm 0.14$	$5.80^{c} \pm 0.16$	$5.72^{ab} \pm 0.16$	ND
I_3	F_0	$4.35^{a} \pm 0.03$	$3.30^{e} \pm 0.14$	$11.60^{d} \pm 0.28$	$10.60^{c} \pm 0.11$	$18.00^{a} \pm 0.42$	$2.00^{b} \pm 0.07$	$11.20^{b} \pm 0.02$	$5.60^{c} \pm 0.07$	$3.16^{c} \pm 0.04$	ND
	F_1	$3.95^{b} \pm 0.04$	$3.80^{e} \pm 0.13$	$10.20^{e} \pm 0.16$	$14.00^{a} \pm 0.23$	$11.50^{b} \pm 0.20$	$2.23^{b} \pm 0.04$	$10.80^{bc} \pm 0.05$	$4.30^{d} \pm 0.07$	$7.16^{a} \pm 0.08$	ND
	F_2	$3.83^{b} \pm 0.08$	$3.80^{e} \pm 0.28$	$12.50^{d} \pm 0.21$	$13.00^{b} \pm 0.43$	$9.04^{c} \pm 0.30$	$1.61^{c} \pm 0.11$	$8.20^{d} \pm 0.10$	$3.80^{d} \pm 0.06$	$4.05^{bc} \pm 0.07$	ND
LSD (p 0.05)		0.20	0.79	1.10	0.86	0.81	NS	1.00	1.25	2.24	-
95 days											
I_1	F_0	$2.17^{f} \pm 0.05$	$8.40^{c} \pm 0.21$	$4.10^{e} \pm 0.14$	$9.40^{ef} \pm 0.28$	ND	-	-	-	-	-
	F_1	$2.07^{f} \pm 0.04$	$5.90^{de} \pm 0.15$	$4.70^{de} \pm 0.14$	$9.80^{de} \pm 0.28$	$0.32^{e} \pm 0.01$	-	-	-	-	-
	F_2	$2.53^{e} \pm 0.07$	$9.25^{b} \pm 0.07$	$5.25^{d} \pm 0.21$	$10.70^{cd} \pm 0.42$	$0.05^{f} \pm 0.04$	-	-	-	-	-
I_2	F_0	$3.15^{abc} \pm 0.09$	$10.35^{a} \pm 0.21$	$11.15^{b} \pm 0.50$	$8.50^{f} \pm 0.14$	$1.47^{d} \pm 0.21$	$1.98^{a} \pm 0.01$	$5.80^{a} \pm 0.07$	$6.60^{a} \pm 0.04$	$7.37^{b} \pm 0.02$	ND
	F_1	$3.23^{ab} \pm 0.08$	$5.00^{f} \pm 0.28$	$16.65^{a} \pm 0.21$	$10.80^{cd} \pm 0.27$	ND	$1.66^{c} \pm 0.05$	$5.40^{b} \pm 0.05$	$6.50^{a} \pm 0.06$	$4.73^{c} \pm 0.08$	ND
	F_2	$3.32^{a} \pm 0.06$	$6.20^{d} \pm 0.28$	$15.70^{a} \pm 0.37$	$11.40^{c} \pm 0.26$	ND	$1.31^{e} \pm 0.08$	$5.80^{a} \pm 0.02$	$4.00^{b} \pm 0.10$	$3.35^{c} \pm 0.09$	ND
I_3	F_0	$2.95^{d} \pm 0.08$	$5.00^{f} \pm 0.14$	$5.05^{de} \pm 0.37$	$16.10^{a} \pm 0.42$	$3.35^{a} \pm 0.07$	$1.58^{cd} \pm 0.04$	$2.40^{e} \pm 0.01$	$2.20^{e} \pm 0.06$	$11.16^{a} \pm 0.07$	ND
	F_1	$3.05^{bcd} \pm 0.11$	$5.20^{ef} \pm 0.28$	$7.70^{c} \pm 0.14$	$15.00^{b} \pm 0.45$	$2.55^{b} \pm 0.07$	$1.82^{b} \pm 0.04$	$4.30^{c} \pm 0.07$	$2.50^{d} \pm 0.14$	$11.35^{a} \pm 0.07$	ND
	F_2	$2.99^{cd} \pm 0.06$	$5.70^{def} \pm 0.14$	$7.25^{c} \pm 0.21$	$15.20^{ab} \pm 0.27$	$1.70^{c} \pm 0.04$	$1.48^{d} \pm 0.02$	$3.60^{d} \pm 0.04$	$3.40^{c} \pm 0.03$	$7.80^{b} \pm 0.04$	ND
LSD (p 0.05)		0.17	0.68	1.07	0.99	0.21	0.15	0.14	0.20	1.55	-
135 days											
I_1	F_0	$1.53^{g} \pm 0.03$	$3.65^{e} \pm 0.21$	$5.30^{de} \pm 0.14$	$6.55^{e} \pm 0.35$	ND	-	-	-	-	-
	F_1	$1.32^{h} \pm 0.06$	$4.10^{de} \pm 0.13$	$3.45^{e} \pm 0.07$	$5.60^{e} \pm 0.28$	$0.09^{d} \pm 0.08$	-	-	-	-	-
	F_2	$1.84^{f} \pm 0.01$	$6.40^{a} \pm 0.26$	$5.75^{de} \pm 0.07$	$6.15^{e} \pm 0.35$	$0.09^{d} \pm 0.08$	-	-	-	-	-
I_2	F_0	$2.43^{e} \pm 0.07$	$4.70^{cd} \pm 0.13$	$11.20^{c} \pm 0.25$	$9.00^{d} \pm 0.40$	ND	$1.86^{c} \pm 0.08$	$7.50^{a} \pm 0.14$	$6.70^{b} \pm 0.13$	$4.36^{c} \pm 0.15$	ND
	F_1	$3.16^{d} \pm 0.01$	$5.80^{ab} \pm 0.27$	$16.50^{ab} \pm 0.19$	$9.50^{d} \pm 0.42$	ND	$1.59^{d} \pm 0.02$	$4.70^{b} \pm 0.15$	$7.00^{b} \pm 0.12$	$4.24^{c} \pm 0.09$	ND
	F_2	$3.07^{d} \pm 0.01$	$6.50^{a} \pm 0.12$	$19.20^{a} \pm 0.14$	$12.10^{c} \pm 0.43$	ND	$2.30^{a} \pm 0.01$	$8.50^{a} \pm 0.14$	$9.70^{a} \pm 0.18$	$4.75^{c} \pm 0.05$	ND
I_3	F_0	$3.45^{c} \pm 0.05$	$4.80^{cd} \pm 0.29$	$9.00^{cd} \pm 0.29$	$15.30^{a} \pm 0.19$	$5.35^{a} \pm 0.07$	$2.37^{a} \pm 0.11$	$7.10^{a} \pm 0.18$	$3.30^{c} \pm 0.08$	$13.30^{a} \pm 0.16$	ND
	F_1	$3.61^{b} \pm 0.03$	$5.40^{bc} \pm 0.28$	$12.50^{bc} \pm 0.42$	$13.60^{b} \pm 0.08$	$4.60^{b} \pm 0.14$	$2.26^{ab} \pm 0.03$	$6.90^{a} \pm 0.11$	$3.60^{c} \pm 0.11$	$12.07^{ab} \pm 0.09$	ND
	F_2	$3.93^{a} \pm 0.07$	$6.30^{a} \pm 0.15$	$16.70^{ab} \pm 0.32$	$14.70^{a} \pm 0.13$	$1.60^{c} \pm 0.18$	$2.09^{b} \pm 0.05$	$7.30^{a} \pm 0.14$	$3.40^{c} \pm 0.06$	$10.15^{b} \pm 0.12$	ND
LSD (p 0.05)		0.14	NS	NS	1.03	0.37	0.17	1.53	1.69	NS	-

I_1 tap water, I_2 saline-sodic water, I_3 saline water, F_0 control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}, *ND* means not detected (below the detection limit), mean values followed by dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test, mean ± SD, $n = 2$, *LSD* least significant difference test, *NS* non-significant

Table 5 Amounts of ions leached from different treatments as affected by irrigating with saline-sodic water (I_2) and FYM application at different periods

Soluble Ions	Input (mg column^{-1})	Output (mg column^{-1})			Difference (mg column^{-1})		
		I_2			I_2		
		F_0	F_1	F_2	F_0	F_1	F_2
65 days							
Na^+	1752	− 91^d ± 13	1193^a ± 35	629^b ± 21	+1843^a ± 13	+559^c ± 47	+1123^b ± 21
K^+	52	17^c ± 1	122^a ± 5	65^b ± 9	+34^a ± 1	− 70^c ± 20	− 14^c ± 5
Ca^{2+}	668	458^b ± 11	817^a ± 14	98^c ± 17	+209^c ± 35	− 149^c ± 12	+570^b ± 11
Mg^{2+}	242	− 369^e ± 11	− 65^c ± 5	− 149^d ± 17	+610^a ± 53	+307^c ± 5	+391^b ± 24
HCO_3^-	1492	− 4172^c ± 66	− 803^a ± 77	− 1190^a ± 68	+5664^b ± 207	+2296de ± 218	+2683^d ± 68
Cl^-	757	3060^b ± 73	4337^a ± 89	3093^b ± 65	− 2304^b ± 214	− 3580^a ± 212	− 2336^b ± 136
SO_4^{2-}	672	− 245^d ± 7	1424^c ± 22	1594^c ± 26	+917^d ± 78	-752^c ± 37	− 922^c ± 72
95 days							
Na^+	2336	250^d ± 14	3474^b ± 42	4285^a ± 34	+2087^c ± 63	− 1138^b ± 19	− 1949^a ± 37
K^+	69	− 62^c ± 3	127^b ± 8	273^a ± 6	+131^c ± 3	− 58^b ± 8	− 204^a ± 6
Ca^{2+}	890	− 338^c ± 28	1082^{ab} ± 46	1006a^b ± 48	+1228^{ab} ± 28	− 192^c ± 34	− 115^c± 15
Mg^{2+}	323	− 127^d ± 5	212^b ± 12	353^a ± 10	+450^d ± 5	+111^e ± 9	− 31^e ± 10
HCO_3^-	1990	− 150^c ± 17	145^c ± 21	928^b ± 38	+2140^a ± 138	+1845^a ± 92	+1062^b ± 79
Cl^-	1009	− 263^d ± 29	2576^b ± 20	3928^a ± 42	+1271^c ± 111	− 1567^b ± 6	− 2920^a ± 251
SO_4^{2-}	896	− 1300^e ± 41	2827^b ± 38	4373^a ± 39	+2196^a ± 178	− 1932^c ± 150	− 3477^c ± 169
135 days							
Na^+	3115	2514^a ± 22	227^{bc} ± 31	1987^{ab}±12	+2901^a ± 247	+2888^b ± 218	+1128^{ab} ± 187
K^+	92	41^b ± 7	50^b ± 9	104^a ± 7	+51^b ± 11	+42^{bc} ± 7	− 12^d ±1
Ca^{2+}	1187	811^{bc}±24	545^d ± 22	878^b ± 21	+376^e ± 24	+642^d ± 26	+310^e ± 49
Mg^{2+}	430	18^c ± 4	− 631^d ± 16	285^{abc} ± 21	+1412^a ± 56	+1061^{ab} ± 45	+145^c ± 21
HCO_3^-	2653	− 481^b ± 34	− 439^b ± 40	577^{ab} ± 29	+3134^{ab} ± 231	+3092^{ab} ± 195	+2077^b ± 50
Cl^-	1345	− 462^c ± 24	− 407^c ± 32	2318^b ± 21	+1807^a ± 88	+1752^a ± 46	− 972^c ± 29
SO_4^{2-}	1194	2315^{bc} ± 26	1554^c ± 29	5063^a ± 27	− 1121^a ± 26	− 360^c ± 17	− 3869^a ± 123

I_2 saline-sodic water, F_0 control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}, input refers to the amount of salt entering to the column, output refers to the amount of salts outputting from the column, difference refers to the difference between input and output, mean values followed by dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test, mean ± SD, $n = 2$

The negative sign (−) indicates leached from soil, while the positive sign (+) indicates added to soil

leaching of ions was observed under irrigation with saline water when soil was treated with 24 Mg FYM ha^{-1} at all the studied periods. The accumulation of Ca^{2+} was obviously higher in soil irrigated with saline water (I_3) than that in the soil irrigated with saline-sodic water (I_2) particularly with 24 Mg FYM ha^{-1}. Adding FYM to soil irrigated with saline-sodic water (I_2) resulted in leaching of Ca^{2+} ions despite their accumulation in the control treatment.

3.2.4 The Flux of Soil Solutes

It is well known that if the water flow in the soil is hindered, the salt flow will also decrease to the minimum. The data verified the variation in the salt distribution according to the change in water flow. The movement of solutes was affected by the rate of water flow and the composition of irrigation water. This movement was increased when using saline water (with high EC and low SAR_{adj}) more than other irrigation waters. The solutes flux was also increased at all treatments when a 24 Mg ha^{-1} of FYM was applied. The excess solutes (leached salts) were leached out of the rhizosphere (30 cm) due to their high flow, particularly when using tap and saline waters. The relation between salt flux and ions of leachate was also illustrated in Fig. 4.

The average residence time (t_r) of solutes through 30 cm of soil depth under the flooded conditions was affected by the high movement of Ca^{2+} ions more than Na^+ in irrigation water and by FYM application. Accordingly, the solutes took a short time to move out of the studied layer as shown in Fig. 5. This rapid movement stimulated the growth of rice plant regardless the quality of irrigation water.

Table 6 Amounts of ions leached from different treatments as affected by irrigating with saline water (I_3) and FYM application at different periods

Soluble Ions	Input (mg column^{-1})	Output (mg column^{-1})			Difference (mg column^{-1})			LSD (p 0.05) Σ output for I_2 and I_3
		I_3			I_3			
		F_0	F_1	F_2	F_0	F_1	F_2	
65 days								
Na^+	771	$315^{c} \pm 34$	$340^{c} \pm 22$	$452^{bc} \pm 20$	$+456^{c} \pm 34$	$+431^{c} \pm 22$	$+319^{c} \pm 42$	255.20
K^+	93	$61^{b} \pm 10$	$72^{b} \pm 5$	$60^{b} \pm 5$	$+32^{ab} \pm 10$	$+21^{b} \pm 5$	$+34^{a} \pm 5$	24.43
Ca^{2+}	1649	$838^{a} \pm 65$	$721^{a} \pm 64$	$827^{a} \pm 66$	$+811^{a} \pm 65$	$+928^{a} \pm 45$	$+822^{a} \pm 87$	169.17
Mg^{2+}	741	$657^{a} \pm 31$	$576^{b} \pm 28$	$675^{a} \pm 13$	$+84^{e} \pm 3$	$+165^{d} \pm 42$	$+66^{e} \pm 12$	72.83
HCO_3^-	850	$-6520^{d} \pm 63$	$-3212^{b} \pm 50$	$-1191^{a} \pm 44$	$+7370^{a} \pm 255$	$+4062^{c} \pm 162$	$+2041^{e} \pm 56$	501.64
Cl^-	1445	$2661^{b} \pm 70$	$2769^{b} \pm 67$	$2443^{b} \pm 75$	$-1216^{c} \pm 20$	$-1324^{c} \pm 109$	$-999^{c} \pm 28$	NS
SO_4^{2-}	1598	$3521^{b} \pm 13$	$4028^{b} \pm 23$	$5348^{a} \pm 21$	$-1923^{b} \pm 55$	$-2430^{b} \pm 320$	$-3749^{a} \pm 233$	539.85
95 days								
Na^+	1028	$2166^{c} \pm 15$	$2276^{c} \pm 46$	$2567^{c} \pm 50$	$-1138^{b} \pm 14.98$	$-1248^{b} \pm 80$	$-1539^{ab} \pm 102$	453.21
K^+	124	$158^{b} \pm 4$	$169^{b} \pm 12$	$135^{b} \pm 8$	$-34^{b} \pm 4.01$	$-45^{b} \pm 9$	$-11^{b} \pm 2$	88.38
Ca^{2+}	2198	$1252^{a} \pm 22$	$783^{b} \pm 26$	$757^{b} \pm 15$	$+946^{b} \pm 22.17$	$+1415^{a} \pm 71$	$+1441^{a} \pm 15$	424.89
Mg^{2+}	988	$-139^{d} \pm 14$	$54^{c} \pm 2$	$358^{a} \pm 22$	$+1127^{a} \pm 13.88$	$+934^{b} \pm 2$	$+630^{c} \pm 40$	81.38
HCO_3^-	1133	$859^{b} \pm 40$	$1159^{b} \pm 13$	$1769^{a} \pm 43$	$+274^{c} \pm 17.20$	$-26^{d} \pm 13$	$-636^{d} \pm 26$	NS
Cl^-	1926	$1312^{c} \pm 28$	$3093^{ab} \pm 44$	$3134^{ab} \pm 55$	$+614^{d} \pm 69.25$	$-1166^{b} \pm 67$	$-1207^{b} \pm 61$	1044.57
SO_4^{2-}	2131	$545^{d} \pm 33$	$631^{d} \pm 15$	$1696^{c} \pm 24$	$+1586^{a} \pm 68.43$	$+1500^{a} \pm 8$	$+435^{b} \pm 20$	751.68
135 days								
Na^+	1371	$-279^{c} \pm 23$	$1513^{abc} \pm 25$	$3591^{a} \pm 18$	$+1649^{ab} \pm 104$	$-142^{c} \pm 16$	$-2221^{c} \pm 122$	1998.74
K^+	166	$42^{b} \pm 6$	$41^{b} \pm 4$	$34^{b} \pm 6$	$+123^{a} \pm 9$	$+124^{a} \pm 16$	$+132^{a} \pm 21$	NS
Ca^{2+}	2931	$1352^{a} \pm 30$	$894^{b} \pm 27$	$718^{c} \pm 31$	$+1580^{c} \pm 65$	$+2037^{b} \pm 27$	$+2213^{a} \pm 45$	145.39
Mg^{2+}	1317	$102^{bc} \pm 17$	$437^{ab} \pm 16$	$462^{a} \pm 23$	$+1215^{a} \pm 98$	$+880^{ab} \pm 44$	$+855^{b} \pm 25$	325.75
HCO_3^-	1511	$-2664^{c} \pm 29$	$-784^{b} \pm 25$	$1217^{a} \pm 15$	$+4174^{a} \pm 205$	$+2295^{b} \pm 131$	$+294^{c} \pm 29$	1308.61
Cl^-	2569	$1839^{b} \pm 25$	$2432^{b} \pm 24$	$4199^{a} \pm 19$	$+729^{b} \pm 53$	$+137^{b} \pm 24$	$-1631^{c} \pm 19$	NS
SO_4^{2-}	2841	$-1516^{d} \pm 17$	$290^{cd} \pm 24$	$3795^{ab} \pm 21$	$+4357^{d} \pm 182$	$+2551^{d} \pm 144$	$-954^{a} \pm 42$	NS

I_2 saline-sodic water, I_3 saline water, F_0 control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}, input refers to the amount of salt entering to the column, output refers to the amount of salts outputting from the column, difference refers to the difference between input and output, mean values followed by dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test, mean ± SD, $n = 2$, *LSD* least significant difference test, *NS* non-significant

The negative sign (-) indicates leached from soil, while the positive sign (+) indicates added to soil

4 Discussion

4.1 Field Experiment

The negative effects of irrigation water on rice yield might be attributed to these two factors. The first factor is its direct effect on plant (Zeng and Shannon 2000) since the EC levels of water above 3.0 dS m^{-1} are considered harmful to rice production (Ayers and Westcot 1985) through increasing the osmotic pressure on cells and decreasing water availability (Mitran et al. 2017). The second factor is the increase of soil ESP and pH due to the high content of Na^+ ions in sodic or saline-sodic waters (Choudhary et al. 2004; Sharma and Minhas 2004). Other researchers reported that an increase in salinity of irrigation water above 1.9 dS m^{-1} could decrease the rice grain yield (Grattan et al. 2002).

The application of organic materials (e.g., FYM) can resist soil degradation caused by irrigation with saline and saline-sodic waters through restoring the physical quality of degraded soil and reducing soil alkalinity (Enas 2018). Also, FYM has greater sorption of Mg^{2+}, Ca^{2+}, and K^+ than Na^+ resulting in lowering soil ESP (Jalali and Ranjbar 2009) and, consequently, increasing nutrient availability and plant growth (Choudhary et al. 2011; Enas and Mansour 2019). Organic matter also increases soil permeability and water flow through the root zone, promoting ions leaching and ions uptake by rice plants (Malik et al. 1992; McNeal et al. 1966). Moreover, the rice roots have high biological activity in increases CO_2 concentration in the rhizosphere. This together with the dissolution of soil carbonates could moves part of the sodium present at the root exchange sites and promotes its leaching from the soil layer with the water flow

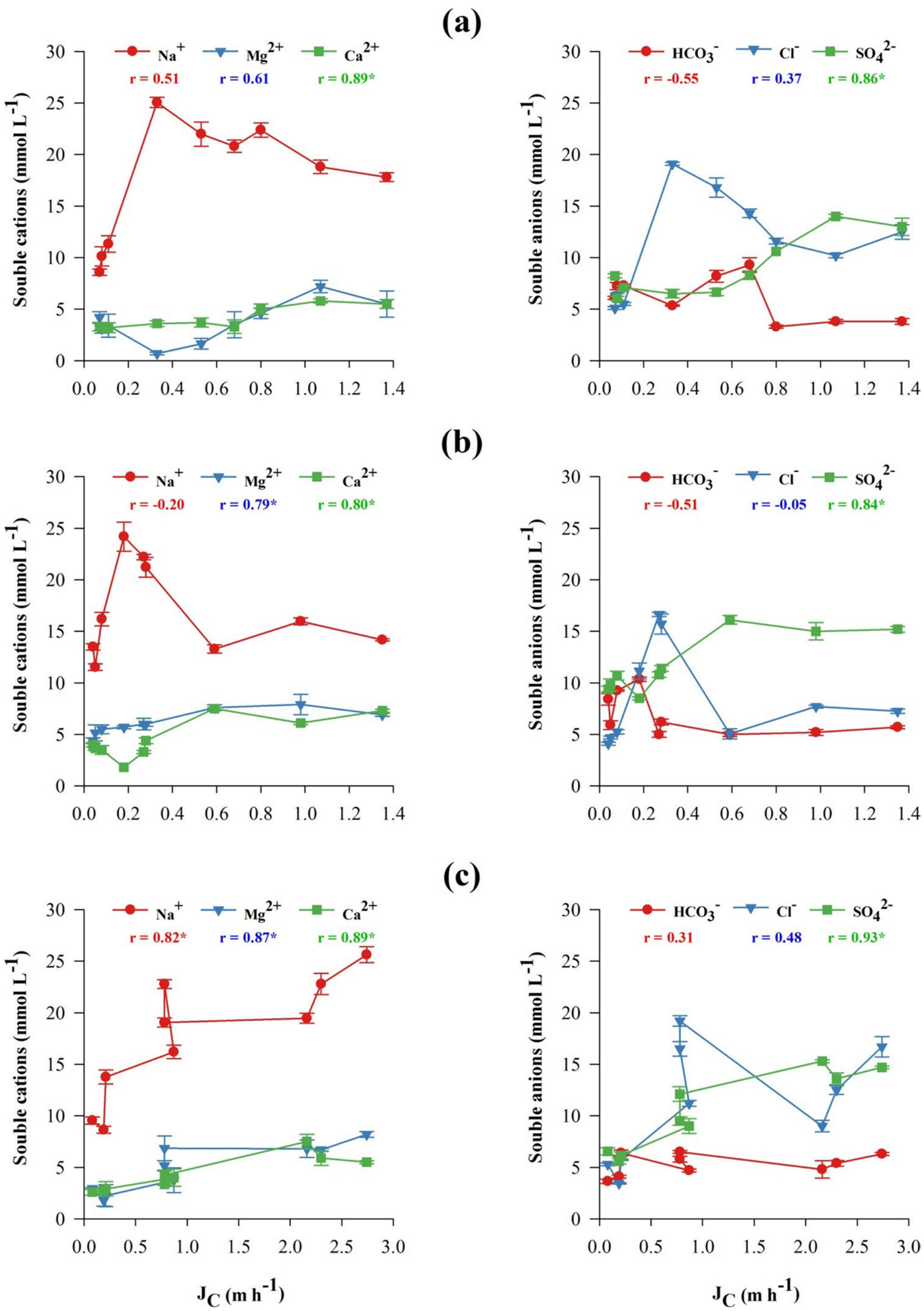

Fig. 4 The relation between ions and their flux (J_C) as affected by irrigating with different water qualities and FYM application (**a**) at 65 days, (**b**) at 95 days, (**c**) at 135 days. J_C The flux of solutes, Bars on the curves stand for ± standard deviation (SD), *r* Correlation coefficient

(Chhabra and Abrol 1977). Furthermore, the flooding system of rice field and water saturation might result in a dilution of accumulated salts.

4.2 Column Experiment

The composition of leachate is influenced by the irrigation water's composition, the period that water remained in the soil and the movement rate of water and solutes. Due to their positive effects on soil physical, chemical, and biological properties, FYM increased leaching of most salts and decreased negative salinity effects during the experiment period (Chahal et al. 2017; Iqbal et al. 2016; Leogrande and Vitti 2019; Luedeling et al. 2005; Wichern et al. 2006).

Irrigation with saline-sodic water (I_2) with the application of FYM had a negative effect on soluble K^+ kept in soil during the studied periods. In contrast, the amount of soluble K^+ was increased in soil irrigated with saline water (I_3) and treated with 24 Mg ha^{-1} of FYM. The different

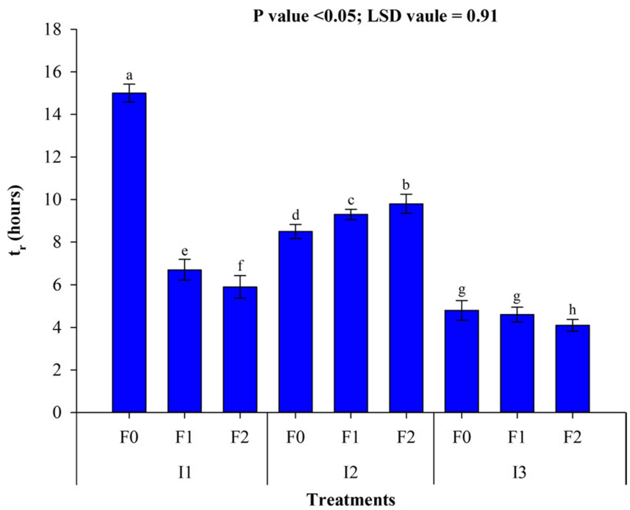

Fig. 5 The average residence time (t_r) of solutes as affected by irrigating with different water qualities and FYM application. I_1 Tap water, I_2 Saline-sodic water, I_3 Saline water, F_0 Control, F_1 FYM at 12 Mg ha^{-1}, F_2 FYM at 24 Mg ha^{-1}. t_r The average residence time of a solute. Dissimilar letters were significantly different at $p < 0.05$ according to the Duncan test, Bars on the columns stand for ± standard deviation (SD), LSD least significant difference

concentrations of soluble K^+ in soil leachate were attributed to the SAR_{adj} value of irrigation water. These values were greater in the leachate from the higher SAR_{adj} solution (30) than from the lower SAR_{adj} solution (5) (Jalali and Merrikhpour 2008). Likewise, K^+ is useful for maintaining the turgor pressure of plant under salinity stress (Wang et al. 2014).

The decrease in the concentrations of soluble Na^+, Mg^{2+}, HCO_3^-, Cl^-, and SO_4^{2-} in soil leachates without FYM application indicates that most ions were adsorbed at the soil colloidal phase preventing their movement out of the rhizosphere. Accumulation of Na^+ ions on the exchangeable sites led to swelling and dispersion of clays as well as collapse of soil aggregates. These aggregates are responsible for good soil structure needed for facilitating air and water flow through soil (Ayers and Westcot 1985).

The concentration of Na^+, Cl^-, HCO_3^-, and SO_4^{2-} ions was high at the three studied periods of time. A part of Na^+ ions was replaced with exchangeable cations, viz., Ca^{2+} and Mg^{2+} resulting in its displacement into solution, another part of Na^+ was adsorbed by exchangeable sites. On the other hand, Cl^-, HCO_3^-, and SO_4^{2-} ions had a high mobility because of their negative charge (Jalali and Merrikhpour 2008). The lower concentrations of these ions in leaching solution compared to the leachate confirm this hypothesis. Accordingly, the unsuitable chemical composition of irrigation water has a high content of Na^+ and K^+salts exceeding the contents of salts of Ca^{2+}, Mg^{2+}, and other bi- and trivalent cations (Vargas et al. 2018).

It was found that the application of FYM can improve the soil infiltration rate by about 89% and decrease soil sodicity by about 41.3%. Decreasing soil bulk density also resulted in improving soil porosity and aeration and consequently leaching of saline water from the root zone (Cha-um and Kirdmanee 2011; Hussain et al. 2001; Kahlown and Azam 2003). Accordingly, FYM application may provide a safeguard effect of plant roots against salt damages and grow more smoothly (Clark et al. 2007). A negative correlation (r = – 0.98**, – 0.87**, and – 0.81**) was observed between Na^+ in soil leachate (mmol L^{-1}) and salt flux (m h^{-1}) in soil irrigated with (I_2) at 65, 95, and 135 days, respectively. However, a positive correlation (r = 0.94**, 84**, and 0.94**) was found in soil irrigated with (I_3) at 65, 95, and 135 days, respectively. The leachate content of HCO_3^- had a similar trend with Na^+ which recorded the significant correlation (r = – 0.92**, – 0.96**, and – 0.93**) with (I_2), whereas these correlation values with I_3 were (r = 0.85**, 0.97**, and 0.98**) at 65, 95, and 135 days, respectively.

The Ca^{2+} concentration in soil leachate was increased with increasing solutes flux due to the high concentration of Na^+ in saline-sodic water (I_2). Thus, there was a positive correlation (r = 0.68*, 0.94**, and 0.82**) between Ca^{2+} and solutes flux (J_C) at 65, 95, and 135 days, respectively. However, the use of saline water (I_3) with high Ca^{2+} content maintained part of Ca^{2+} in the soil, forming a negative correlation (r = – 0.59*, – 0.65*, and – 0.81**) between Ca^{2+} and J_C at 65, 95, and 135 days, respectively. This might be attributed to the sorption of Ca^{2+} ions onto active soil colloids due to the variation of hydration shell thickness between ions, which increases the attraction between soil colloids and Ca^{2+} ions compared to Na^+ ions (Brady and Weil 2008). The current study concludes the conjunctive uses of FYM with Ca^{2+} source (from irrigation water) can significantly improve soil physico-chemical properties of salt-affected soils as compared to their sole application under paddy soil (Shaaban et al. 2013; Ullah and Bhatti 2007).

Through connecting the results of the field and lab experiments, the shortage of rice yield was mainly caused by the cumulative impact of salinity and or alkalinity stresses produced by using low-quality irrigation water during the stages of crop growth. Salts in irrigation water could accumulate in the soil, decreasing water availability to the crop and speeding up the appearance of a water deficit regardless the presence of water in the soil. Also, salts inhibit the uptake of mineral nutrients, cause premature senescence, and reduce the photosynthetic activity to a level that cannot sustain crop growth and yields (Romero-Aranda et al. 2001). These results have been confirmed by many researchers, i.e., Grattan et al. (2002) and Munns and Tester (2008). They reported that reductions in plant growth from high salinity were the consequences of both osmotic stress inducing an available water shortage and the effects of excess Na^+ and Cl^- ions on critical biochemical processes. Furthermore, Dang et al. (2008) reported that the Cl^- content in soil was more effective than Na^+ in reducing growth and yield. On the other hand, application of FYM and use of saline water (high Ca^{2+} content) may reduce bulk density while increasing porosity, void ratio, water permeability, and hydraulic conductivity (Hussain et al. 2001). As for sodicity, sodic soil might be deficient in Ca^{2+} and other nutrients. Also, the associated high HCO_3^- and pH conditions suppress the solubility of several soil nutrients and consequently limit the nutrient's availability for the plant. Tolerance of the exchangeable sodium percentage (ESP) to paddy rice may reach 20–40% describing rice as a moderate sensitive plant against sodicity (James et al. 1982). The regression studies indicated that FYM application could increase soil resistance towards using the poor-quality irrigation waters through the improving salt flux movement out of the rhizosphere. The multiple linear equations could predict the amount of salts passing through a unit area of soil per unit time for each period by monitored the electrical conductivity (EC) of soil, leachate, and leaching solution at different periods concurrently with rice growth as the following:

$$J_{C(65days)} = 3.113 - (1.325 * EC_L) - (0.570 * EC_{Le}) + (0.362 * EC_S), R^2 = 0.86 \quad (4)$$

$$J_{C(95days)} = -13.553 - (5.585 * EC_L) - (0.266 * EC_{Le}) + (0.522 * EC_S), R^2 = 0.76 \quad (5)$$

$$J_{C(135days)} = -3.108 - (0.907 * EC_L) - (0.373 * EC_{Le}) + (0.534 * EC_S), R^2 = 0.98 \quad (6)$$

where EC_L is the electrical conductivity of leachate (dS m^{-1}), EC_{Le} electrical conductivity of leaching solution (dS m^{-1}), and EC_s electrical conductivity of saturation extract (dS m^{-1}).

The previous results indicated that the application of FYM to soil irrigated with saline water could have a higher effect on sustaining soil resistance against potential degradation more than saline-sodic water (Cha-um and Kirdmanee 2011). Consequently, the application of FYM to soils irrigated with low water quality could support the growth and production of rice crop. The following equation was developed for the prediction of rice grain yield (GY) based on the values of soil EC (EC_s) and leachate (EC_L) and its movement (J_C) as:

$$GY = 6220 + (1590 \times J_C) + (334 \times EC_L) - (958 \times EC_S) \quad (7)$$

5 Conclusion

It can be concluded that the irrigation with saline-sodic water [containing more Na^+ ions than divalent Ca^{2+} and Mg^{2+} ions (SAR_{adj} = 20.82)] may result in increasing exchangeable sodium at the expense of exchangeable Ca^{2+} and Mg^{2+}. This in turn may damage soil structure and water flow and decrease the rice grain yield. On the other hand, irrigation with saline water [containing more Ca^{2+} and Mg^{2+} ions than Na^+ ions (SAR_{adj} = 5.77)] may be safe and a win-win strategy for rice production under flooded conditions. The leachability of Na^+, HCO_3^- and Cl^- in soil irrigated with saline water was more effective than that in soil irrigated with saline-sodic water. Furthermore, it maintains Ca^{2+} against loss with drainage water and improves soil physico-chemical characteristics. The presence of Ca^{2+} source along with organic amendments could represent a strong and helpful strategy for overcoming land degradation resulting from irrigation with poor-quality waters and increasing crop yield. The application of FYM is not recommended with irrigation by sodic or saline-sodic water without adding a Ca^{2+} source.

Acknowledgments The authors are grateful to the Experimentation Research Station as well as the Laboratory of Soil Fertility Testing and Fertilizers Quality Control (accredited according to ISO 17025/2017) at the Faculty of Agriculture, Mansoura University, Egypt, for supplying the materials required to carry out the experiments and sample analyses. Furthermore, we also want to express our gratitude to anonymous reviewers for their revision, comments, and suggestions, which helped improve the manuscript.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Conflict of Interest The authors declare no competing interests.

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