doi:10.14720/aas.2025.121.2.18513 Original research article / izvirni znanstveni članek

Effect of high residual sodium carbonat (RSC) water and amendments on soil properties under rice-mustard (*Brassica juncea* 'Khanpur Raya') rotation

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Received April 03, 2024, accepted April 08, 2025
Delo je prispelo 3. april 2024, sprejeto 8. april 2025

Effect of high residual sodium carbonat (RSC) water and amendments on soil properties under rice-mustard (*Brassica juncea* 'Khanpur Raya') rotation

Abstract: A trial was designed to study the deleterious effect of high RSC water on soil properties under rice-mustard crop rotation. Treatments included were; T_1: high RSC water, T_2: gypsum on the basis of RSC of water, T_3: H_2SO_4 on the basis of RSC of water, T_4: green manuring with guar, T_5: farm yard manure (FYM) at the rate of 10 t. ha^{-1}. For irrigation tube well water having (electrical conductivity (EC) 1.37 dS m^{-1}, sodium adsorption ratio (SAR) 8.40 (mmol l^{-1})$^{1/2}$ and RSC 7.85 me l^{-1}) was used. The results revealed that lowest paddy (2.22 t ha^{-1}) and grain yield (1.00 t ha^{-1}) of rice and mustard were recorded when irrigated with high RSC water. In case of soil analysis, long-term use of high RSC water induces secondary salinity by increasing pH (1.92 %), EC (5.73 %) and SAR (35.71 %) over their initial values. Harmful effects of high RSC water were thwarted by all the treatments; however, positive effects of gypsum were more visible that increased crop growth and grain yield of rice-mustard crops by promoting soil properties. Gypsum recorded the highest paddy and grain yield (3.66 t ha^{-1}, 1.70 t ha^{-1}) of rice and mustard crop and decreased soil pH_s (4.98 %), EC_e (29.93 %) and SAR (54.54 %) over their initial values.

Key words: residual sodium carbonate, rice, mustard, salinity, sodic water, gypsum, sulfuric acid, guar

Učinek velikih vsebnosti rezidualnega natrijevega karbonata (RSC) v vodi in dodatkov na lastnosti tal v kolobarju riža in gorjušice

Izvleček: Poskus je bil izveden z namenom preučiti škodljive učinke velikih vsebnosti natrijeva karbonata na lastnosti tal v kolobarju riža in gorjušice. Obravnavanja so bila; T_1: velika vsebnost RSC v vodi, T_2: dodatek sadre vodi z veliko vsebnostjo RSC, T_3: dodatek H_2SO_4 vodi z veliko vsebnostjo RSC , T_4: zeleno gnojenje z guarom, T_5: dodatek hlevskega gnoja (FYM) v odmerku 10 t ha^{-1}. Za namakanje je bila uporabljena voda iz vodnjakov naslednjih lastnosti: električna prevodnost (EC 1.37 dS m^{-1}), razmerje adsorbiranega natrija (SAR; 8.40 mmol l^{-1})$^{1/2}$ in RSC 7.85 me l^{-1}). Rezultati so pokazali, da je bil najmanjši pridelek biomase (2,22 t ha^{-1}) in zrnja (1,00 t ha^{-1}) v kolobarju riža in gorjušice pri zalivanju z RSC vodo. Analize tal so pokazale, da je dolgotrajno namakanje z RSC vodo povzročilo sekundarno salinizacijo s povečanjem pH (1,92 %), EC (5,73 %) in SAR (35,71 %) glede na začetne vrednosti. Škodljivi učinki namakanja z vodo z veliko vsebnostjo rezidualnega natrijeva karbonata so bili oblaženi z vsemi obravnavanji vendar je bil največji pozitivni učinek opažen pri dodatku sadre zaradi izboljšanja lastnosti tal, kar je povečalo rast poljščin in pridelek zrnja riža v kolobarju riža z gorjušico. Dodatek sadre je dal največji pridelek biomase in zrnja riža (3,66 t ha^{-1}, 1,70 t ha^{-1}), zmanjšal pH (4,98 %), električno prevodnost ($EC_{e;}$ 29,93 %) in SAR (54,54 %) glede na njihove izhodiščne vrednosti.

Ključne besede: rezidualni natrijev karbonat, riž, gorjušica, slanost, slana voda, sadra, žveplena kislina, guar

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1 INTRODUCTION

Freshwater resources has long played a critical role in production and cultivation of agricultural crops throughout history, it is primarily used as 75 % in global agriculture (Assouline et al., 2015). However, increasing population, industrial productions and agricultural expansion has led the huge difference between supply and demand of freshwater resources and most of the countries of the world are facing shortage of fresh water resources (Gilbert, 2018). In recent years, global warming, inadequate rainfall, droughts and strong wind under climate change scenario further aggravated water scarcity and poses a great challenge to food safety and human health (Kummu et al., 2010). So, to solve the problem of global water deficit, new technical measures are being developed in the utilization of non-conventional water resources (Chen et al., 2016). Underground poor-quality water has emerged as potential alternative way source of irrigation that could relive the water pressure, almost 27 countries are utilizing underground brackish water for agricultural crops (Zhu et al., 2021). Irrigated agriculture is the primary source of Pakistan's economy and groundwater is a big source primarily used to meet the > 40 % of countries irrigational requirements but unfortunately 70-75 % of underground is of poor quality (Cheema et al., 2014). Brackish water irrigation changes the soil physical, chemicals and structural properties. It has been reported that irrigating with poor quality water reduces soil permeability (Li et al., 2018), increased soil electrical conductivity (Yang et al., 2020) and interfere with nutrient uptake (Chen et al., 2018). Sodic water may degrade the soil porosity from 8.8 to 12.5 % and 7.4–13.8 %, and bulk density from 7.4–13.8 % (Öztürk et al., 2023). Poor quality water also has a direct effect on the morphophysiological of plant (Viana et al., 2021). Water with high soluble salts and Na content may create drought conditions in rhizosphere, inhibiting water uptake, limited CO_2 assimilation, stomatal closure and disrupting photosynthetic activity (Leite et al., 2017; Sá et al., 2018). Yang et al. (2020) irrigated cotton crop with saline water ($1 g·l^{-1}$, $3 g·l^{-1}$, $6 g·L^{-1}$, $9 g·l^{-1}$ and $12 g l^{-1}$). They reported that saline water causes secondary soil salinization by increasing salts in rootzone, soil pH increases but the cotton yield decreases as salt content increased in saline water. Similarly, it is reported by Wiedenfeld (2008) that water having EC (3.4 dS m^{-1}) used to irrigate the sugarcane crop results in 17 % reduction in cane and sugar yield. Arora et al. (2018) studied the results of tap water having EC (0.7 dS m^{-1}), alkli water (RSC) of 2.5 and 10 me l^{-1}) and saline water (EC 5.0 and 10 dS m^{-1}) on growth and grain yield performance of rice-wheat crops. They reported that alkali water builds up soil sodicity by increasing soil pH and exchangeable sodium percentage. While maximum grain mortality in rice-wheat crop was recorded when irrigation with saline water of EC (10 dS m^{-1}) was done.

Brackish water is rich source of beneficial micronutrients and short-term irrigation did not obviously deteriorate the soil health and can improve the quality and yield of crops (Jin et al., 2016). However, long-term brackish water irrigation may cause non-salinized soil to transform into salinized soil due to accumulation of certain toxic ions in root zone that lead to serious crop yield reduction and huge changes in the physico-chemical properties of the soil (Lee et al., 2016; Cao et al., 2016; Tahtouh et al., 2019). Therefore, secondary soil salinization is mainly determined by amount and kind of dissolved salt content of poor-quality water and utilization of brackish water has become a new problem to solve. Therefore, long run utilization of low-quality water needs to be investigated and appropriate protective measures need to framed that inhibit soil salt accumulation in soil. The damaging effect of brackish water on soil and crops can be alleviated by suitable agronomic practices, exogenous hormone regulation, proper nutrient management and application of inorganic and organic amendments that accelerate leaching of toxic salts from root zone. Gypsum application is an inexpensive, easy to handle and effective strategy that alleviate salt stress on crops by adequately leaching toxic ion from rootzone brought by brackish water into the soil (Wang and Yang, 2017). Gypsum releases sufficient amount of soluble Ca^{2+} to replace Na^{+} from exchange site (Wang et al., 2017; Koralegedaraa et al., 2019). Five-year application of gypsum improves forage yield of corn, alfalfa and emergence ratios of mignonettes (Wang et al., 2017). Qadir et al. (2019) evaluated the effect of gypsum (100 % on the basis of RSC of water), H_2SO_4 (50 % on the basis of RSC of water) poultry manure (10 t ha^{-1}) and press mud (10 t ha^{-1}) to counteract the detrimental effect of brackish water {EC = 1.17 dS m^{-1}, SAR = 6.75 and RSC = 5.30 me l^{-1}} on growth and yield of cotton and wheat crops. They reported that gypsum was most effective amendments to prevent secondary salinization by improving EC_e, pH_s and SAR and create favorable soil condition for wheat and cotton crops. Rashmi et al. (2024) reported that gypsum application at the rate of 2.5 t ha^{-1} + FYM at rate of10 t ha^{-1} resulted a reduction of 45–48 % in exchangeable sodium percentage and 3–6 % in bulk density of sodic soil leading to higher crop yield in soybean (1.21 Mg ha^{-1}) and mustard (1.39 Mg ha^{-1}).

Green manuring with leguminous crops is very careful and effective sustainable means to prevent soil salinization. Short-lived plants with low C:N ratio decomposed easily and demonstrate positive impacts on soil health by enhancing soil fertility status, improve water holding capacity, aeration and inhibit soil salt accumulation (Shah et al., 2011). Incorporation of sesbania in salt affected soils during rice-wheat crop rotation improved soil salinity and sodicity indices and grain yield of both crops (Rizwan et al., 2018). Green manuring with guar and sesbania had positive effect on soil health by up-lifting nitrogen, phosphorus and organic carbon contents, improved water holding capacity, aeration, porosity, and microbial activities (Ibrahim et al., 2000; Shindo and Nishio, 2005).

Reduction in fresh water resources of country force farming community to explore poor-quality underground water, therefore in our study we used high RSC water to explore its effect on physicochemical properties of the soil and to develop a feasible preventive measure to control secondary salinization and ensure crop growth.

2 MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The present study was conducted for four years (2016-20), following rice-mustard crop rotation, at SSRI, Pindi Bhattian, Punjab, Pakistan located at latitude 31.8950° N and longitude 73.2706° E). A field (Table 1) {($pH_{s\,=}$ 8.82, EC_e = 4.71 dS m^{-1}, sodium adsorption ratio = 26.82 (mmol $l^{-1})^{1/2}$, hydraulic conductivity = 0.67 cm hr^{-1} and bulk density = 1.37 Mg m^{-3}} was selected and prepared. An experiment was laid out in RCBD arrangement with four replications using plot size 6 x 4 m^2. During the period of (2016-20), the mean weather conditions were: sunshine hours ranging from 14h and 8 min to 7 h and 36 min, relative humidity ranges from 36.2 ± 2.8 % to 73.2 ± 4.8 % and temperature 14.5 ± 2.5 °C minimum temperature and 42.6 ± 3.5 °C maximum temperature.

2.2 TREATMENTS AND CROP ROTATION

The treatments applied were: T_1 = high RSC tube well water (No amendement), T_2 = gypsum application on the basis of RSC of tube well water, T_3 = H_2SO_4 application on the basis of RSC of tube well water, T_4 = green manuring with guar, T_5 = FYM @ 10 t ha^{-1}. Cluster bean or locally known as guar (*Cyamopsis tetragonoloba* (L.) Taub.) seed @ 50 kg ha^{-1} was sown in 2nd week of May and incorporated after 45 days of sowing in respective treatment plots. Gypsum (30 mesh size, 80 % pure, 1 kg/plot/ year) and FYM (Total N (%) 0.96, Total P_2O_5 (%) 0.27, Total K (%) 0.75 and pH 7.88, 24 Kg/plot/ year) were applied one-month prior rice transplanting followed by irrigation and H_2SO_4 (96 % pure, 0.3 l/plot) was applied with every irrigation. Amendments were applied once in a year before transplanting of rice. Poor-quality ground water with high residual sodium carbonate pumped from tub well located at study site was used for all treatments (Table 2). On average 16 irrigations for rice and 4 irrigations for mustard crop at the rate of 7.5 cm were applied in each season.

During Kharif season, rice ('Shaheen Basmati') nursery at the age of 30 days was shifted in the field during second week of July and during Rabi season, mustard crop (*Brassica Juncea* ?Khanpur Raya') was sown during November. Fertilizers @150-85-60 and 70-70-60 NPK (kg ha^{-1}) was broadcasted to rice and mustard crops. Phosphatic and potassium fertilizers were applied as basal dose and nitrogen was broadcasted in three installments. Other cultural and plant protection measures were taken equally when required. Data regarding crop growth and yield was recorded and crops harvested at maturity.

2.3 SOIL AND WATER ANALYSIS

Composite soil samples were collected. Samples were air dried, ground, sieved and stored in bottles after the harvest of every crop and analyzed for pH, EC_e, SAR, hydraulic conductivity and bulk density using U.S. Salinity Laboratory Staff (1954). Soil pH of saturated paste was measured through pH meter (Microcomputer pH-vision cole parmer model 05669-20). Conductivity meter (WTW conduktometer LF 191) was used to measure the EC of water and soil extract. Na^+ contents were measured using flame photometer (digiflame code DV 710) and Ca^{2+}, Mg^{2+} were measured through titration. Sodium adsorption ratio (SAR) was calculated as follows where ionic concentration of the saturation extracts is given in mmole l^{-1}. SAR = $Na^+ / [(Ca^{2+} + Mg^{2+})/2]^{1/2}$. Hydrometer method (Bedaiwy, 2012) was used for textural class determination. CO_3^{2-} and HCO_3^- were determined via titration with standard H_2SO_4. Residual sodium carbonate (RSC) was calculated by (Eaton, 1950) as follows:

$$RSC = (CO_3^{2-} \text{ and } HCO_3^-) - (Ca^{2+} + Mg^{2+}).$$

2.4 STATISTICAL ANALYSES

Recorded crop data was subjected to analysis of variance. Treatment means comparison was calculated by LSD Test at 5 % probability level (Steel et al., 1997) using STATISTIX 8.1 package software.

Table 1: Initial soil analysis

Parameter	Value	Units
Electrical conductivity of soil extract (EC_e)	4.71	(dS m^{-1})
pH of soil saturated paste (pH_s)	8.82	-
Sodium absorption ratio (SAR)	26.82	(mmol $l^{-1})^{1/2}$
Hydraulic conductivity (HC)	0.67	(cm hr^{-1})
Bulk density (BD)	1.37	(Mg m^{-3})
Available phosphorus	8.50	mg kg^{-1}
Organic matter	0.62	%
Available potassium	105	mg kg^{-1}
Textural class	sandy loam	-

Table 2: Water Analysis

Parameters	Value	Units
Electrical conductivity of irrigation water (EC_{iw})	1.37	(dS m^{-1})
Sodium adsorption ratio (SAR)	8.4	($mmol_e$ $l^{-1})^{1/2}$
Residual sodium carbonate (RSC)	7.85	(me l^{-1})
Total dissolved solids (TDS)	877	(mg l^{-1})
CO_3^{2-}	Nill	(me l^{-1})
HCO^{3-}	11.25	(me l^{-1})
Ca^{2+} + Mg^{2+}	3.40	(me l^{-1})
Na^+	10.93	(me l^{-1})
Cl^-	4.0	(me l^{-1})

3 RESULTS

3.1 EFFECTS OF HIGH RSC WATER AND AMENDMENTS ON SOIL PROPERTIES

Soil analysis data revealed that long term use of high RSC water negatively affected the soil properties while all the remedial strategies used considerably improved the soil physico-chemical properties. Irrigation with high RSC water resulted a gradual increase in soil pH_s value at the end of every season and after four years of experimentation an increase of 1.92 % over initial soil pH_s value was observed with continuous use of high RSC water (Table 3). Meanwhile, all the remedial strategies thwarted the negative impact of high RSC water and significantly influenced soil pH_s. From the treatments maximum reduction of 5.44 % in pH_s was recorded with H_2SO_4 followed by gypsum (4.98 %), whereas, FYM and green manuring reduces the pH_s value by 3.17 % and 3.06 % respectively at the end of experiment. Effect of high RSC water and amendments on soil electric conductivity EC_e is shown in (Table 4). Data indicated that soluble salts are brought into soil with continuous irrigation with high RSC water and salt accumulated in the upper soil surface, therefore an increase of 5.73 % in EC_e with respect to initial value was recorded in control treatments at the end of study. However, at the same time amendments application can prevent the salt accumulation in top soil by accelerating the salt leaching process. Maximum improvement in soil salinity status was observed with gypsum application as a reduction of 54.54 % in EC_e was noted in this treatment. While H_2SO_4, guar and FYM showed a reduction of 49.40 %, 41.05 %, 46.71 % respectively in EC_e over initial value at the end of experiment. Similar trend was recorded in the case of soil SAR, irrigation with high RSC water (7.85 me l^{-1}) without any amendment elevated soil SAR by 35.71 % at the end of experimentation as compared to initial value (Table 5). Whereas, SAR was under safe range ($\leq$ 15) in all other treatments receiving amendments. It was observed that maximum reduction in soil SAR (54.54 %) was for gypsum followed by H_2SO_4 (49.40 %), while Guar and FYM recorded a reduction

Table 3: Effect of high RSC water and amendments on soil pHs

Treatments	1st year	2nd year	3rd year	4th year	+ % increase or -%decrease over initial value
High RSC water	8.84	8.90	8.96	8.99	(+1.92)
Gypsum @ RSC of water	8.58	8.46	8.41	8.38	(-4.98)
H2SO4 @ RSC of water	8.57	8.46	8.39	8.34	(-5.44)
Green manuring with guar	8.72	8.68	8.66	8.55	(-3.06)
FYM @ 10 t ha^{-1}	8.70	8.65	8.61	8.54	(-3.17)

Table 4: Effect of high RSC water and amendments on soil ECe

Treatments	1st year	2nd year	3rd year	4th year	+% increase or -% decrease over initial value
High RSC water	4.75	4.81	4.85	4.98	(+5.73)
Gypsum @ RSC of water	3.48	3.37	3.32	3.30	(-29.93)
H2SO4 @ RSC of water	3.87	3.84	3.79	3.70	(-21.44)
Green manuring with guar	3.91	3.87	3.85	3.80	(-19.32)
FYM @ 10 t ha^{-1}	3.92	3.86	3.81	3.76	(-20.16)

Table 5: Effect of high RSC water and amendments on soil SAR

Treatments	1st year	2nd year	3rd year	4th year	+% increase or -% decrease over initial value
High RSC water	30.70	32.20	33.50	36.40	(+35.71)
Gypsum @ RSC of water	16.80	15.30	14.40	12.19	(-54.54)
H2SO4 @ RSC of water	17.65	16.40	15.30	13.57	(-49.40)
Green manuring with guar	19.40	17.80	17.50	15.81	(-41.05)
FYM @ 10 t. ha^{-1}	18.20	17.30	16.80	14.29	(-46.71)

of 41.05 % and 46.71 % respectively compared to initial value of SAR.

Among physical properties, soil bulk density (BD) slightly increased (8.02 %) with continuous irrigation of high RSC water, whereas it decreased by all the applied amendments. BD decreased (about 15.32 %) with gypsum application, whereas, H_2SO_4, Guar and FYM showed a reduction of 14.59 %, 10.94 % and 11.67 % respectively (Table 6). On contrary, an opposite trend was observed in case of HC. Upon irrigation with high RSC water a reduction of 11.94 % was noted but at the same time gypsum and H_2SO_4 surpassed the hydraulic conductivity by an increase of 26.86 % and 25.37 % respectively over its initial value (Table 7).

3.2 EFFECT OF HIGH RSC WATER AND AMENDMENTS ON GROWTH AND PADDY YIELD OF RICE

Analysis of four years pooled data showed that use of high RSC water significantly ($p < 0.05$) affected the rice crop growth while simultaneously all the amendments thwarted the detrimental effects of high RSC water (Table 8). As far as plant height of rice crop was concerned

Table 6: Effect of high RSC water and amendments on soil bulk density

Treatments	1st year	2nd year	3rd year	4th year	+% increase or -% decrease over initial value
High RSC water	1.37	1.41	1.46	1.48	(+8.02)
Gypsum @ RSC of water	1.28	1.22	1.19	1.16	(-15.32)
H2SO4 @ RSC of water	1.27	1.24	1.22	1.17	(-14.59)
Green manuring with guar	1.34	1.29	1.26	1.22	(-10.94)
FYM @ 10 t ha^{-1}	1.33	1.29	1.25	1.21	(-11.67)

Table 7: Effect of high RSC water and amendments on soil hydraulic conductivity

Treatments	1st year	2nd year	3rd year	4th year	+% increase or -% decrease over initial value
High RSC water	0.66	0.64	0.60	0.59	(-11.94)
Gypsum @ RSC of water	0.72	0.77	0.81	0.85	(+26.86)
H2SO4 @ RSC of water	0.72	0.76	0.79	0.84	(+25.37)
Green manuring with guar	0.71	0.73	0.75	0.76	(+13.43)
FYM @ 10 t ha^{-1}	0.70	0.73	0.76	0.78	(+16.41)

maximum plant height (135.33 cm) was observed with application of gypsum application on RSC basis followed by sulphuric acid application. Farm yard manure @ 10 t ha^{-1} and green manuring with guar were statistically ($p < 0.05$) non-significant. While, least plant height (124.00 cm) was recorded in treatment where field was irrigated with high RSC water without any amendment. Productive tiller data showed that maximum productive tiller/m^2 (235.33) was observed by H_2SO_4 application followed by gypsum on of RSC basis, however, both amendments were non-significant ($p < 0.05$) from each other (Table 8). High RSC water adversely affected productive tillers and lower numbers of productive tiller were recorded with use of high RSC water (220). Gypsum and H_2SO_4 produced the highest panicle length (16.66 cm) that was statistically ($p < 0.05$) non-significant with other treatments and minimum panicle length was noted in control (Table 8). Paddy yield was also significantly influenced by different treatments, data in Table 9 revealed that amendments had pronounced effect on yield attribute and all the organic and inorganic amendments exhibited an antistress effect against deleterious impact of high RSC water (Table 9). Gypsum application on RSC basis produces significantly ($p < 0.05$) more paddy yield (3.66 t ha^{-1}) which was similar with H_2SO_4 application on the basis of RSC of water (3.62 t ha^{-1}) followed by FYM @ 10 t ha^{-1} (3.35 t ha^{-1}) and green manuring with guar (3.20 t ha^{-1}). High RSC water irrigation without any amendment resulted minimum paddy yield of 2.22 t ha^{-1}. Same trend was recorded for straw yield and 1000 grain mass (Table 9). Gypsum application recorded the highest mean value for straw (7.96 t ha^{-1}) and 1000 grain mass (28.33 g) however, difference was non-significant with H_2SO_4 application. On contrary lower mean value for straw (4.16 t ha^{-1}) and 1000 grain mass (19.66 g) was divulged in control plot irrigated with high RSC water.

3.3 EFFECT OF HIGH RSC WATER AND AMENDMENTS ON GROWTH AND YIELD OF MUSTARD

Information in Table 10 & 11 showed that use of amendment relieves the drastic effects of high RSC water on growth and yield of mustard crop. An obvious increased in plant height of mustard was observed with use of amendments (Table 10). Maximum plant height (155 cm) and number of branches/plant (26.66) were observed with gypsum application; however, values were at par ($p < 0.05$) with H_2SO_4 followed by green manuring with guar. While minimum plant height (119.33 cm) and number of branches/plant (17.33) were observed in con-

Table 8: Effect of high RSC water and amendments on rice growth (Average of four seasons)

Treatments	Plant height (cm)	Number of productive tillers (m^{-2})	Panicle length (cm)
High RSC water	124.00 D	220.00 C	12.66 B
Gypsum @ RSC of water	135.33 A	232.67 A	16.66 A
H_2SO_4 @ RSC of water	133.00 B	235.33 A	16.66 A
Green manuring with guar	128.33 C	227.00 B	15.33 A
FYM @ 10 t ha^{-1}	129.33 C	225.00 B	14.66 AB

Different letters in the same column indicate significant differences by LSD at p ≤ 0.05

Table 9: Effect of high RSC water on and amendments rice growth (Average of four seasons)

Treatments	Paddy yield (t ha^{-1})	Straw yield (t ha^{-1})	1000-grain mass (g)
High RSC water	2.22 C	4.16 D	19.66 D
Gypsum @ RSC of water	3.66 A	7.96 A	28.33 A
H2SO4 @ RSC of water	3.62 A	7.70 AB	27.00 AB
Green manuring with guar	3.20 B	6.93 C	23.66 C
FYM @ 10 t ha^{-1}	3.35 B	7.03 BC	24.66 BC

Different letters in the same column indicate significant differences by LSD at $p \leq 0.05$

trol. Similarly, the highest pods $plant^{-1}$ (258) and grains $pods^{-1}$ (13) were produced with gypsum application while, irrigation with high RSC water negatively affected these attributes and recorded minimum pods $plant^{-1}$ (227.33) and grains $pods^{-1}$ (7.33). Data showed (Table 11) that the highest grain yield (1.70 t ha^{-1}) and 1000-grain mass (8.81 g) was recorded with gypsum application on RSC basis which was statistically ($p < 0.05$) at par with H_2SO_4 application on RSC basis followed by FYM @ 10 t ha^{-1}, which was at par with green manuring with guar. While minimum grain yield (1.0 t ha^{-1}) and 1000-grain weight (6.06 g) were recorded in control (brackish water).

4 DISCUSSION

4.1 EFFECT OF HIGH RSC WATER ON SOIL PROPERTIES

Fresh water resources of the country are not enough to meet the agricultural requirements because of increased cropping intensity and drought condition. Therefore, use of unconventional water resources in addition to fresh water resources is necessary and ground water pumping is need of the time. However, underground water is generally inferior to canal water and may vary in quality depending upon type and quantity of dissolved salts. So, there is need for development and adoption of such technologies that can ensure the safe utilization of low-quality water and prevent the salt deposition. Therefore, an attempt has been made to study the harmful effects of high RSC water and efficiency of different amendments on physico-chemical properties of soil for rice-mustard rotation.

Continuous use of high RSC water without any amendment slightly increased the electrical conductivity, it was obvious effect of dissolved salts in high RSC water that accumulated in top soil due to lack of leaching and upward movement caused by soil evaporation and induces secondary salinization (Huo et al., 2017; Yang et al., 2019; Wang et al., 2019). A build of salt load in surface soil was also reported by Arora et al. (2018) in rice-wheat cropping system when irrigated with saline

Table 10: Effect of high RSC water and amendments on mustard growth (Average of four seasons)

Treatments	Plant height (cm)	Number of branches plant^{-1}	Number of pods plant^{-1}
High RSC water	119.33 C	17.33 C	227.33 D
Gypsum @ RSC of water	155.00 A	26.66 A	258.00 A
H2SO4 @ RSC of water	153.33 A	24.33 AB	250.00 AB
Green manuring with guar	137.67 B	21.33 BC	240.67 C
FYM @ 10 t ha^{-1}	135.00 B	20.66 BC	248.33 BC

Different letters in the same column indicate significant differences by LSD at $p \leq 0.05$

Table 11: Effect of high RSC water and amendments on mustard growth (Average of four seasons)

Treatments	Number of grains pods^{-1}	Grain yield (t ha^{-1})	1000-grain mass (g)
High RSC water	7.33 D	1.00 C	6.06 B
Gypsum @ RSC of water	13.00 A	1.70 A	8.81 A
H2SO4 @ RSC of water	11.33 B	1.68 A	8.79 A
Green manuring with guar	9.00 C	1.35 B	7.01 B
FYM @ 10 t ha^{-1}	9.66 C	1.38 B	7.49 AB

Different letters in the same column indicate significant differences by LSD at $p \leq 0.05$

and alkali water. A rise in pH was also noted in this treatment, a possible reason for this increment was presence of HCO_3^- and Na^+ in applied irrigation water which led to increase in pH (Jalali and Ranjbar 2009; He et al., 2018). Similar results were recorded earlier by Choudhary et al. (2011) that long-term use of high RSC alkali water (12.5 me l^{-1}) increased soil pH by 2.2 units under rice-wheat rotation in Punjab. Similarly (Yang et al., 2020) reported an increase of 0.37 unit in soil pH with irrigation of 12 g l^{-1} brackish water treatment. Nearly similar trend was observed in case of SAR, that increased 35.71 % from its initial value. These results were supported by earlier findings that application of sodic and saline water without any preventive measures increased the sodicity of soil and deteriorate soil physical properties (Bajwa and Choudhary, 2014; Mwubahaman et al., 2024). High residual alkalinityof irrigation water had adverse effect of sodification due to high exchangeable sodium contents as compared to exchangeable calcium and magnesium (Choudhary et al., 2011; Arora et al., 2018). similar results were recorded by Liu et al. (2018) that irrigation with saline water (3 g l^{-1}) increased soil pH value, ESP, and SAR. Adverse effects of low-quality water on chemical properties were directly translated into soil physical properties. Soil bulk density was negatively influenced by continuous use of high RSC water and increased by 8.02 % from its initial value. This increase in bulk density may be attributed to, Na replaces Ca from exchange sites which causes soil dispersion (Qadir and Schubert, 2002; Kahlon et al., 2012; Qadir et al., 2001). HC was negatively related with water sodicity, high Na^+ contents in irrigation water deteriorate soil structure, cause dispersion of soil aggregates and block soil pores thus reducing hydraulic conductivity (Wu and Wang, 2010; Kang et al., 2014).

4.2 EFFECT OF AMENDMENTS ON SOIL PROPERTIES

It is clear from results that addition of amendments counteracted the detrimental effects induced by long term use of low-quality water and prevent the accumulation of salts in upper surface layers. All the amendments substantially improved physico-chemicals properties of soil; however, beneficial effects of gypsum were more visible than all others treatments. Salinity indices pH, EC, and SAR were significantly improved by gypsum application as compared to their initial values. These positives effects of gypsum could be due to that high amount of Ca^{2+} replaces the exchangeable Na^+ on the exchange site and leaching it out from root zone (Sharma and Minhas, 2005). Sufficient leaching of Na^+ leads to lower values of pH, EC, and SAR, furthermore, replacement of hydrated monovalent Na^+ by divalent Ca^{2+}, increased soil aggregation and reorganized soil structure subsequently improved the soil bulk density and hydraulic conductivity. Similar results were reported by Amer and Hashem (2018) that application of only gypsum and along-with with other amendments improved soil physico-chemicals properties like infiltration rate, soil porosity, bulk density, EC and SAR. Gypsum application is a rapid, viable and effective approach for improving pH, EC, and ESP of sodic soils (Koralegedaraa et al., 2019; Yong-gan et al., 2021). Previous studies demonstrated that positive effects of gypsum on soil physico-chemicals properties may remained from 12 to 17 years (Tirado-Corbalá et al., 2019; Zhao et al., 2019). H_2SO_4 also significantly improved soil salinity indices (pH, EC, and SAR), BD and HC. H_2SO_4 is an indirect source of Ca^{2+} in calcareous soils, it reacts with the native $CaCO_3$ and releases Ca^{2+} in the soil solution that probably replaced the Na^+ from exchange sites (Abdelhamid et al.,2013). Consequently, soil phyico-chemical properties were improved after leaching of Na^+ and dissolved salts from the root zone. Comparable outcomes were observed by Qadir et al., (2019) that H_2SO_4 @ 50 % application on RSC basis counteracted negative effects of brackish (5.30 me l^{-1}) water and improved soil properties and cotton-wheat yield. Shaaban, et al. (2013) in a field study also concluded that H_2SO_4 was the best of the amendments for decreasing damaging effects of saline irrigation water and enhancing the productivity and quality of rice crop grown on saline soil. Use of organic amendments like FYM and green manuring is also an effective measure against sodicity build up in soil (Pang et al., 2010). Organic matter after decomposition release CO_2 and organic acids that decreased the precipitation of Ca^{2+}, displace Na^+ on the exchange site, accelerate leaching of soluble salts leading to a decline in pH, EC, and SAR (Liu et al., 2017; Ahmad et al., 2018; Ding et al., 2019). Leaching of larger Na^+ enhanced soil structure stability and improved soil bulk density and hydraulic conductivity (Hammer et al., 2015; Ding et al., 2019). Ding et al. (2019) stated that organic amendments could be successfully used to mitigate the soil salinity and to improve soil physico-chemical properties. Similar results were recorded by Yang et al. (2019) that straw incorporation decreased the BD by 1.6 %–4.7 %, in the 0-30 cm soil layer.

4.3 CROPS GROWTH AND YIELD

Parameters like growth and yield of rice and mustard crops were meaningfully influenced by all treatments. Irrigation with high RSC water significantly reduced plant height, grain yield and 1000-grain mass of rice and mustard crop as compared to other treatments. Reduction in growth and yield contributing parameters may be associated with accumulation of salts with constant use of low-quality water that deteriorate the physico-chemical properties of soil. Secondary salinization in root zone reduces absorption of water by crops, results ion toxicity, nutritional imbalance, affect stomatal conductance and photosynthetic activity (Rahm et al., 2018; Wang et al., 2019; Munns and Tester, 2008; Sá et al., 2019). Similar, results were observed by Praxedes et al. (2022) that saline water (4.5 dS m^{-1}) irrigation may reduce grain yield from 26 % to 54 % in cowpea. Alkali water (10.0 me l^{-1}) reduced grain yield of rice up to 87 % in saline soil (Arora et al., 2018). Gypsum application not only counteracted negative effects of high RSC water but also showed the highest value for most of the studied parameters of rice and mustard crops. Better crops growth performance may be corelated with ameliorating gypsum effects on soil properties. Gypsum application increased soil organic matter (Wang et al., 2017), improved nutritional status of soil and microbial activity (Zhao et al., 2019; Ekholm et al., 2024), these factors promote plant growth and subsequently final grain yield. Previous studies also demonstrated the improved yield in barley and rice (Amer and Hashem, 2018) and alfalfa (Yong-gan et al., 2021) with gypsum application in salt-affected soil. H_2SO_4 mobilizes the native $CaCO_3$ of soil and provides Ca in soil solution, which in turn alleviate the ill effect of high RSC water and improved physico-chemical properties. Consequently, crop took the advantages of improved soil conditions in this treatment and produced more yield over control. H_2SO_4 @ 50 % application on RSC basis counteracted negative effects of high RSC (5.30 me l^{-1}) water and improved soil properties and cotton-wheat yield (Qadir et al., 2019). Shaaban, et al. (2013) in a field study also concluded that H_2SO_4 was best of the amendments for decreasing damaging effects of saline irrigation water and enhancing the productivity and quality of rice crop grown on saline soil. Green manuring and FYM application also improved all the yield traits as compared to control. Addition of organic matter also improved microbial activities, soil organic matter and other properties (Urbaniak et al., 2017). Organic matter alleviated the adverse of high RSC water by increasing chelation of toxic Na, water holding capacity of soil and improved soil BD and HC (Liu et al., 2017). Rice and mustard crops were benefited by these positive effects of organic matter on soil environment leading to increased grain yield and other agronomic attributes. Ding et al. (2020) suggested that addition of organic matter is a successful management approach for improving the nutrient uptake and wheat productivity in salt-affected soil which reinforced our findings.

5 CONCLUSION

Findings of the current study highlighted that long-term use of high RSC water could deposit the salts and induce secondary salinity by increasing pH, EC and SAR which adversely affected the growth and yield of rice and mustard crops. Harmful effects of high RSC water were thwarted by all amendments and can be used as preventive measures against salinity-sodicity development. Among all amendments, positive effects of gypsum were more visible that increased growth and yield of rice-mustard crops by promoting soil properties. Efficiency of different amendments to alleviate adverse effects of high RSC water can be arranged as such gypsum> H_2SO_4 > FYM > green manuring with guar. Therefore, it is recommended that farmers should apply gypsum on the basis of RSC of water for safe use of poor-quality high RSC water. In present study we investigated the ameliorative role of each amendment individually; however, a long-term field trial about ameliorative role of different organic and inorganic amendments in combination should be explored in future.

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