Long-term Effect of Sodic Water for Irrigation on Soil Quality and Wheat Yield in Rice-Wheat Cropping System

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Abstract
Increasing scarcity of good quality water in many arid and semi-arid regions necessitates the use of poor quality groundwater for irrigation. Soil degradation resulting from alkali water irrigation has become a serious threat to soil health. In the present study, we conducted an investigation (2021-22) on the physicochemical properties (soil organic carbon, available Na, and available K) of sandy loam soil under a semi-controlled lysimeter. Wheat was grown as an experimental crop, which was irrigated with synthetic alkali waters having similar salts (total electrolyte concentration, TEC = 30 me L⁻¹) and sodium adsorption ratio (SARiw 10 mmol L⁻¹) but varying in residual sodium carbonate (RSC) are being continuously applied since 2004 (20 years). Five types of irrigation water having different levels of residual sodium carbonate comprised. (T₁) best available groundwater, (T₂) residual sodium carbonate water 1 (RSC 5 me L⁻¹), (T₃) RSC water 2 (RSC 10 me L⁻¹), (T₄) RSC water 3 [RSC 10 treated with gypsum (RSC 10 neutralized to RSC 5 me L⁻¹ with gypsum)] and (T₅) RSC water 4 [RSC 10 treated with sulphur (RSC 10 neutralized to RSC 5 me L⁻¹ with sulphur)]. Soil samples were collected after harvesting two wheat varieties (KRL 210 and HD 3226). Long-term irrigations with alkali water increased the available Na and K in the soil. Furthermore, soil organic carbon (SOC) decreased significantly with increasing alkalinity of irrigation water. Continuous irrigation with alkali water reduced grain yield of wheat by 31.7% over BA W. Moreover, the addition of gypsum and sulphuric acid has shown some capacity to partially restore soil properties, although not to the level of BA W. The majority of soil parameters under both crop cultivars showed a similar trend. The study’s findings led to the conclusion that continuous applications of alkali water drastically degrade soil physicochemical properties. Partial neutralization of alkali water did not allow for the sustained existence of soil physicochemical properties. Consequently, it is recommended that the rate at which amendments are added to alkali water be adjusted to restore the decline in soil physicochemical properties.

Keywords: Sodic water, Irrigation, Soil properties, Wheat yield

Introduction
Poor quality aquifers have been utilized for irrigation to maintain food production and retain the nutritional and economic security of humankind all over the world (Singh et al., 2022a; Minhas et al., 2021). Global agricultural productivity is severely constrained by the lack of fresh water available for irrigation (Makarana et al., 2023). One-fourth of the world’s groundwater is consumed by India, one of the countries with the highest per capita consumption (230 km³ per year) (Fagodiya et al., 2023). Alkalinity has an adverse effect on groundwater quality in many Indian states, including Punjab, Haryana, Uttar Pradesh, Rajasthan, Andhra Pradesh, and Tamil Nadu (Choudhary and Bajwa, 2012). In arid and semi-arid regions, many farmers use poor quality groundwater to meet the crop water requirements due to inadequate availability of good quality water and insufficient rainfall. India is by far no different from other countries with 6.74 million hectares (m ha) of salt affected lands (Mandal et al., 2009), losing 16.8 million tonnes of farm production valued approximately US$ 3.5 billion per annum (Sharma et al., 2015). The problem would be more acute in the north-western India where ~2.7 m ha of barren sodic soils area is underlain with saline/alkali water (32–84%) in different states.
Wheat is the most common field crop grown in winter on 6 m ha of Indo-Gangetic Plain (Chhuneja et al., 2005). Continuous and indiscriminate use of sodic water, however, poses a serious threat to soil health and crop productivity, mainly through increased pH, sodium saturation of soil, and associated deterioration of soil physical properties (Choudhary and Bajwa, 2021; Minhas et al., 2021; Sheoran et al., 2021b, c). Since microbial activities in soils regulate ecological function and soil fertility, salinity has a significant impact on soil microbial populations and their activity (Rietz and Haynes, 2003; Chowdhury et al., 2011). Soil microflora contributes greatly to maintaining or improving soil quality by regulating degradation of organic matter, nutrient availability, and promoting the development of macro-aggregates (Singh et al., 2018). Microbial parameters are sensitive indicators of soil quality changes in response to management strategies or environmental stress, (Wang et al., 2008; Setia et al., 2010) such as soil type, amendment application, crop cultivars as well as different growth stages. The effects of irrigation with alkali water and amendments on soil microbial activity, as well as the mechanisms behind these altered activities, are consequently of major interest (Singh et al., 2015).

Therefore, in order to understand the impacts of long-term irrigation of poor quality water with high RSC on soil quality parameters and yields of wheat (*Triticum aestivum*) the current study was aimed to ascertain the impact of alkali water irrigation on soil quality parameters (available potassium, sodium, and soil organic carbon) as well as wheat grain yield. Additionally, the study sought to ascertain the correlation between soil properties and microbial biomass carbon and dehydrogenase activity, as well as the relationship between wheat yield and soil quality parameters.

**Material and Methods**

This investigation was carried out at ICAR–Central Soil Salinity Research Institute, Karnal (Haryana) India in 20 lysimeters of 2 m$^3$ size. The initial soils belonged to sandy loam texture having exchangeable sodium percentage value of 5.3, soil pH (1:2) 7.8 and electrical conductivity of saturation extract 0.7 dS m$^{-1}$. Factor one had five treatments of irrigation water quality which included T$_1$: best available water (BAW), T$_2$: RSC 5, T$_3$: RSC 10, T$_4$: RSC 10 (T3) neutralized to RSC 5 with application of gypsum (RSC 10 + gypsum), and T$_5$: RSC 10 (T3) neutralized to RSC 5 with application of sulphuric acid (RSC 10+ sulfuric acid). RSC was calculated by the equation:

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

Five quality of irrigation water were applied in respective plots and two different wheat varieties namely KRL 210 and HD 3226 were sown (2021-22) in each plot adopting the recommended agronomic packages of practices. First irrigation was applied @ 100 L per plot before sowing, using respective RSC water. Afterward, five irrigations of 200 L (each plot) per plot were applied according to the critical growth stages of wheat.

After wheat harvest, soil samples were collected from 0-15 cm soil depth and fresh samples were sieved using a 2 mm sieve and kept at 4°C for analysis of microbial parameters. Soil organic carbon, available Na and K, exchangeable sodium percentage, sodium adsorption ratio, pHs, were estimated and their correlation with microbial properties and wheat yield was determined. Both varieties of wheat were harvested in the first fortnight of April, 2022. The grain yield of wheat was determined by weighing and expressing the harvested wheat grains from each plot in terms of metric tons per hectare (t ha$^{-1}$) after the threshing and sorting processes. The analysis of variance (ANOVA) was done for treatment comparison in randomized complete block design using SAS (9.4) (SAS, 2013) at $P \leq 0.05$ significance.

**Results and Discussion**

**Changes in Soil Organic Carbon, Available Na and K**

A significant decline in soil organic carbon was observed due to irrigation with alkali water as compared to BAW (Fig.1a). The reduction in SOC values was greater in the treatments having higher RSC. The lowest OC (3.23 g kg$^{-1}$) was recorded in RSC 10 applied irrigation water followed by BAW,
RSC 5, RSC 10 + gypsum, RSC 10 + sulphuric acid (4.58, 3.79, 3.75, and 3.71 g kg$^{-1}$). There was no significant difference in OC under two different wheat varieties. The depletion of organic matter under alkali water irrigation may be attributed to lower inputs of organic matter from plants due to severe reduction in crop growth, especially the stunted root growth caused by sodicity stress that was the main source of organic biomass in root zone (Singh et al., 2022 a).

Irrigation with RSC 10 water increased available K (23.95 me L$^{-1}$) by 138% over BAW, although available K was comparable among RSC 5 me L$^{-1}$ treatments, viz. RSC 5, RSC 10 + Sulfuric acid and RSC 10 + Gypsum (14.16, 14.91, and 11.32 me L$^{-1}$) (Fig.1c). It might be the result of lower removal of potassium through restricted growth and lesser bioass reduction (Singh et al., 2022a). As a result, inadequate root growth and development hindered their ability to explore a larger area of soil in search of nutrients to be absorbed (Bhardwaj, 2021).

Available Na exhibited significant variation (ranging from 5.06 to 33.96 me L$^{-1}$) among the different treatments (Fig.1b). Higher concentration of Na$^+$ ions (33.96 me L$^{-1}$) was recorded in soils irrigated with ALKW2 (Alkali water type 2 having RSC 10), while soils irrigated with good quality water showed the lowest available Na concentration (5.06 me L$^{-1}$), followed by RSC 5 (25.99 me L$^{-1}$), RSC 10+Gypsum (29.27 me L$^{-1}$), and RSC 10+Sulfuric acid (31.45 me L$^{-1}$). Although there was no significant difference in available Na concentrations between the two wheat varieties. The HD 3226 had 24.90 me L$^{-1}$ and KRL 210 had 25.40 me L$^{-1}$ Na concentrations.

**Correlations of Soil Biological Properties with Soil Alkalinity Parameters**

Dehydrogenase and microbial biomass carbon were negatively associated with soil pH, ESP and SAR (Fig.2 a-f). It indicated the adverse effect of soil alkalinity on the microbial activities of soil. Higher coefficient of determination ($R^2 = 0.49-0.85$) was observed for DHA than MBC ($R^2 = 0.54-0.68$) indicating that DHA is one of the most important indicators of overall soil microbial activity (Singh et al., 2018), because these occur intracellular in all living microbial cells.

**Correlation among Wheat Grain Yield, Soil Biological and Alkalinity Parameters**

Pearson's correlation statistic ($p \leq 0.05$) (Fig. 3) among grain yield, soil biological and alkalinity parameters of wheat crop, showed that grain yield had a strong and positive relationship with OC ($r = 0.92$), DHA ($r = 0.91$), MBC ($r = 0.75$); and moderate positive correlation with Ca+Mg ($r = 0.25$). However, ESP ($r = -0.98$), Na ($r = -0.96$), SAR ($r = -0.93$) and pHs ($r = -0.92$) exhibited negative association with wheat grain yield. A relationship study among different parameters of wheat crop revealed that organic carbon (OC) had a strong and positive correlation with DHA ($r = 0.97$), MBC ($r = 0.95$) and negatively interacted with ESP ($r = -0.98$). ESP showed a strong negative relationship with microbial enzyme activity, i.e., DHA ($r = -0.96$), MBC ($r = -0.86$). The effect of soil biological attributes on grain was determined by performing principal component analysis (PCA) (Fig.4). The first two principal components (PC1: 87.28%, PC2: 10.29%) accounted for nearly 97% of the cumulative
Fig. 2 Relationship of microbial biomass carbon (MBC) and dehydrogenase activity (DHA) with some soil properties. (a), (b) and (c) show relationships of DHA with soil pHs, exchangeable sodium percentage and sodium adsorption ratio, respectively; (d), (e) and (f) show relationships of MBC with soil pHs, exchangeable sodium percentage and sodium adsorption ratio.

Fig. 3 Pearson's correlation coefficients among grain yield, soil biological and alkalinity parameters under different quality of irrigation water. The color of the boxes reflects the strength of the correlation. The correlation coefficients represent mean value of pooled measurements of soil parameters and microbial activities. DHA; dehydrogenase, MBC; microbial biomass carbon, ESP; exchangeable sodium percentage, OC; organic carbon, pHs; negative logarithm of hydrogen ion activity in saturated soil, Na; available sodium, Ca+Mg; available calcium and magnesium, SAR; sodium adsorption ratio, grain yield.
variation. Treatments with BAW (control) irrigation water clustered in the first quadrant. Na and grain yield showed unique separation and laid on the opposite quadrant in the PCA biplot. Grain yield along with DHA, MBC, OC and Ca+Mg laid in one quadrant while Na and alkalinity parameters (ESP, SAR and pHs) laid in the opposite quadrant.

Conclusion
The long-term effects of residual irrigation water alkalinity resulted in decreased organic carbon content of the soil, increased available Na and K content, soil chemical & biological properties, and significantly decreased wheat grain yield. The effect was increased with the increment in the alkalinity of the applied irrigation water and highest in the RSC 10 water. The neutralization alkalinity (5RSC units) of irrigation water with gypsum or sulfuric acid was marginally better than the pure RSC 5 alkalinity water in terms of wheat yield and alkalinity buildup in the soil. The dehydrogenase and microbial biomass carbon were found negatively correlated with the soil alkalinity parameters pHs, ESP and SAR. The pearson’s correlation coefficients and PCA validated the positive association of OC and DHA MBC with wheat yield and negative association with soil alkalinity with the increased RSC of irrigation water. The study concluded that the irrigation water alkalinity had a negative effect on soil biological properties and OC, hence wheat yield. The neutralization of RSC with gypsum or sulfuric acid is an effective technique to utilize high RSC water for wheat production and reverting the alkalinity buildup in the soil.

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