Journal of Soil Salinity and Water Quality 15(1), 1-14, 2023

Advances in Reclamation and Management of Sodic Waters for Irrigation#

OP Choudhary* and MS Mavi

Department of Soil Science, PAU, Ludhiana-141004, Punjab, India
**Corresponding author E-mail: opc_2k@yahoo.com*

Abstract

Sustainable management of water resources is an international priority to meet the demands of future populations for food and fiber. However, increasing demands for freshwater use for municipal and industrial processes coupled with increasing world food needs leaves very less fresh water available for agriculture. Thus, agriculture will either need to reduce acreage under irrigation, which is undesirable since it will reduce food supply, or irrigate with alternative water sources such as saline/sodic ground waters. This is possible but sustained use of poor-quality water requires consideration of their impacts on both crop production and soil health. In different states of India, 32-84% ground waters surveyed are saline and/or sodic. Injudicious use of sodic waters poses grave risks of causing irrigation-induced sodification that is insidious and impacts soil health in terms of deteriorating soil physical, chemical and biological parameters. The development of salinity and sodicity problems not only reduces crop productivity but also limits the choice of crops. It is, therefore, imperative that plans are carefully drawn and executed to sustain crop production, reduce soil sodification and minimize deterioration of soil conditions over the long-term. In this context, it has been observed in many instances that water previously considered unsuitable for irrigation can be used with site-specific and careful management. In Punjab, about 42% ground waters are brackish and about 70% of these are sodic waters having high sodium absorption ration (SAR) as well as residual sodium carbonate (RSC), posing a serious threat to sustainable crop production, especially in the south-western region of the state. To prevent the degradation of the state's land and water resources, emerging technological interventions for optimally using sodic-waters for supplementing irrigated agriculture are of paramount importance. In this context, the long-term research work carried over more than three decades has developed many technologies for judicious use of sodic-waters for sustaining crop productivity and maintaining soil health in these challenging environments. Remedial technologies have been developed at the, root-zone, crop and cropping systems, and field scale. These include conjunctive uses based on available water qualities, chemical amelioration of sodic- soils and irrigation waters, mobilising native calcite through organic amendments, growing tolerant crop cultivars, fertiliser use, and irrigation management technologies. Although the emphasis is placed on managing sodic waters in the Indian context, the developed practices are expected to be helpful to promote irrigation with sodic waters, thereby partly alleviating the forecasted scarcities in water for agriculture in many other arid and semi-arid regions in the world confronting similar challenges.

Key words: Sodic water, Irrigation water quality, Management of sodic environment, Soil health, Crop productivity

Introduction

Sustainability of water resources is a critical issue for fulfilling the rising water demands of various competitive sectors including agriculture, which is the largest water user and consumes over 70% of the abstracted freshwater globally (Singh, 2015). The issue has become more challenging in the light of dwindling resource base due to urbanization, contamination, and climate change impacts. There is a growing realization especially for countries in the arid and semi-arid climatic zones that these countries are approaching full utilization of their surface water resources. Therefore, sustainable development of water resources requires that we respect the hydrological

---

The paper was presented as Lead Paper in 6th National Conference on "Salinity Management for Land Degradation Neutrality and Livelihood Security under Changing Climate" held at Tiruchirappalli, Tamil Nadu in joint collaboration of the Indian Society of Soil Salinity & Water Quality; ICAR-Soil Salinity Research Institute, Karnal: Tamil Nadu Agricultural University; and Indian Council of Agricultural Research during 11-13th October, 2022.

cycle by using the marginal but renewable water resources judiciously to supplement meagre surface water resources and avoid water scarcity through their long-term use.

The Indian National Water Policy in 2012 had clearly enunciated that to meet the required food grain production of 2050, the efficiency of surface water use has to increase to 60% (now 30-40%) and of ground water to 75%. In addition, the poor quality sodic (containing high carbonates of Na) and/or saline ground waters constitute a major portion (32-84%) of the total irrigation potential of ground waters in different states of the country. In Punjab, majority (69%) of the 42% poor quality ground waters are sodic in nature posing serious threat to sustainable crop production especially in the south-western region of the state (Sharma *et al.,* 2010). In this context, the long-term research work conducted at PAU, Ludhiana and ICAR-CSSRI, Karnal focused on managing and developing strategies for safe and judicious use of sodic waters in agriculture for sustaining crop productivity and maintaining soil health in these challenging environments (Choudhary *et al.*, 2004; Choudhary *et al.*, 2011b; Choudhary and Mavi, 2019; Minhas *et al.*, 2021) and these sodic waters can rather become a valuable resource for irrigation.

Chemical Composition of Sodic Irrigation Water

Sodic waters contain high concentration of dissolved carbonates and bicarbonates (CO_3^{2-}+ HCO_3^-) of sodium (Na^+) greater than chlorides and sulphates; and high proportion of Na^+ with respect to $Ca^{2+} + Mg^{2+}$ (United States Salinity Laboratory, 1954). The soluble Na percentage is generally > 75 and the ratio of divalent cations to total cations is < 25 for sodic waters. Residual alkalinity, defined as $[HCO^-_3 + CO_3^{2-}] – [Ca^{2+} + Mg^{2+}]$, determines the potential of irrigation water to create alkalinity hazard in the soil. This has been expressed as residual sodium carbonate (RSC) by Eaton (1950) and is being used as an index of water-suitability for irrigation of crops in the soil testing laboratories of India. In general, sodic waters having high RSC test low in electrical conductivity (EC) but some waters termed as saline-sodic test high in RSC, sodium absorption ration (SAR) and EC. Other parameters for knowing the potential of irrigation waters to create alkalinity/ sodicity hazards are: Sodium Adsorption Ratio [SAR = $(Na)/\sqrt{(Ca + Mg)/2}$], concentrations expressed in $mmol_c\ L^{-1}$ and new adjusted SAR denoted as (adj. RNa). It is defined as $Na/\sqrt{[(Ca_x + Mg)/2}$, where Ca_x represents the Ca in applied water modified due to salinity (ionic strength) and HCO_3^-/Ca^{2+} ratio (Ayers and Westcot, 1985).

Rengasamy and Marchuck (2011) gave the concept of ‘CROSS’ (Cation ratio of soil structural stability) where flocculation values for K relative to Na was 0.56 and that Mg relative to Ca was 0.60 and is expressed as CROSS = $C_{Na} + 0.56C_K/[(C_{Ca} + 0.60C_{Mg})/2]^{0.5}$. However, the use of CROSS in place of SAR is advisable for waters having saline waters having EC < 4 dS m^{-1} and Mg concentration > Ca concentration.

Strategies Managing Sodic Waters for Sustainable Crop Productivity

If the challenges of sustaining global food supplies are met, it is essential that the sodic ground waters are used appropriately to sustain crop production. There are two options to manage and sustain crop productivity in a salt-affected environment:

i) Modifying the environment to suit the plant and,

ii) Modifying the plant to suit the environment.

Both these approaches have been used, either individually or in combination. Practical options for the safe use of poor-quality waters for sustainable crop production should focus on improving the physical and chemical properties of soils receiving sodic waters and controlling the buildup of sodicity in the soil. Such an approach will not only add an additional water source in arid and semi-arid areas, but also can minimize the problem of rising water tables in shallow water table canal command areas.

Management strategies to sustain productivity using sodic waters include crop selection, irrigation management strategies, chemical/

organic amend-ments, and fertility management. No single management practice is able to control sodicity of irrigated soils in itself but rather a combination of practices is required. Nevertheless, each manage-ment option is described separately for better understanding in the following sections.

Laser Leveling of the Land and Rain Water Harvesting

Suitable land leveling and provision of 30-40 cm high strong bunds for capturing and retaining rainwater are the essential prerequisites for managing the land irrigated with sodic water. Laser levelling is very important in sodic-water irrigated soil for uniform water application, reducing any micro-relief and micro-depression which ensures uniform leaching of salts and sodium. The surface soil should be protected against the beating action of raindrops, which can be achieved through ploughing the field in between rains. This practice, besides increasing the intake of rainwater helps in controlling the unproductive losses of water through weeds and evaporation. These practices also promote uniform salt leaching and self-reclamation through the rain-induced dissolution of soil calcium carbonate.

Selection of Suitable Crops and Varieties

The guiding principle is to select suitable crops and varieties capable of producing high yields and economic returns under varying levels of soil Na saturation for achieving sustainable high agricultural productivity under sodic irrigation system. This is because crops differ in tolerance to soil salinity and sodicity/alkalinity (Mass and Hoffman, 1977; Ayers and Westcot, 1985), which may form the basis of selection of crops for growing on soils irrigated with varying levels of sodicity in water. Most of the crops, however, show varying levels of sensitivity to increasing levels of sodicity in the soil at different growth stages (germination, early seedling development, and reproductive and grain formation).

Rice and wheat are the crops most commonly recommended for growing in salt-affected soils during the reclamation process as both these crops can tolerate higher levels of salinity and sodicity. However, rice is not recommended to be grown with saline and sodic waters as rice and other high-water requiring crops need large number of irrigations (24-28) that can appreciably increase the salt load and Na build-up in the soils and hasten the degradation of the soils through sodification. So, under poor-quality water irrigation, low water requiring crops that are tolerant or semi-tolerant to the salts should be raised wherever possible. Furthermore, the crop grown in the previous season greatly influences the productivity of the crop in the subsequent season. In a monsoonal climate, crops that favour higher retention and *in situ* conservation of rainwater, which is salt-free, result in less sodicity development in the soil profile at the end of the season, providing a better environment for the next crop (Tyagi, 2003). Among three important cropping sequences (rice–wheat, cotton–wheat and sorghum–wheat) under sodic water irrigation, the productivity of the rice–wheat system was higher than the other two systems. In more arid areas, where fresh water during the *rabi* season is scarce, similar trends were observed with mustard, which replaces wheat because of its high salt tolerance and requirement of only one or two post-sowing irrigations compared with four or five irrigations in case of wheat (Tyagi, 2003). However, long-term experiments show a greater reduction in productivity of sodic irrigated wheat grown after high irrigation requiring rice crop as compared with the wheat grown after low irrigation requiring millet and cotton crops (Bajwa and Josan, 1989 a,b).

Adequate information needs to be generated about tolerance and production-efficiency of different crops (varying in rooting-behaviour) in soils undergoing sodification due to long-term sodic water irrigation. Choudhary *et al.* (1996 a,b) reported that tolerant wheat and barley genotypes had penetrative root system and higher spike density than the sensitive ones. Varieties of crops having high yield potential should be preferred over those having lower yield potential. A typical example is that of high yielding wheat cultivar

PBW-343 that should be preferred over other wheat cultivars (PBW 550 and PBW 502) to obtain acceptable yield levels without any loss in grain quality in soils irrigated with sodic waters with RSC > 5 me L^{-1} (Choudhary *et al.*, 2007, 2012a). Further, wheat cultivar PBW 658 performed better under high RSC and EC water irrigation than HD 2967 and PBW 621 (Pawittar *et al.*, 2018). Sodicity tolerance of crop plants also depends upon the ability of plant-roots to exclude Na and absorb nutritionally adequate amounts of Ca (otherwise deficient (below 2 meL^{-1}) under sodic environment). Crops having higher tolerance to soil Na saturation have also been reported to maintain relatively higher Ca/Na and lower Na/K ratios in shoots by restricting Na absorption (Choudhary *et al.*, 1996b; Singh *et al.* 2018).

Growth and yield of three cotton cultivars were adversely affected by long-term irrigation with sodic waters having RSC of 5, 10 and 15 me L^{-1} (Choudhary *et al.,* 2001). Compared with canal water irrigation, relative seed-cotton yield under ESP build-up of 56.2 was 69% in F-846, 49% in LD-327 and only 29% in F-505. Cultivar F-846 produced larger bolls than the other two cultivars under irrigation with higher RSC waters. The harmful effects of high RSC water on fibre quality (2.5% span length and bundle strength) were also not observed in the tolerant cultivar F-846. Among Bt cotton hybrids, RCH 134 was observed to perform better than MRC 6301 and MRC 6304 (Choudhary *et al.,* 2012b) because of its early vigour during emergence and seedling stage.

Concerted efforts over the past four decades have resulted in the development of promising salt-tolerant varieties in rice, wheat and mustard. However, there is a growing realization that the development of multiple stress-tolerant crop genotypes must be prioritized by integrating molecular and genomics tools with conventional breeding approaches (Sharma and Singh, 2015). In spite of that, only a few have become popular among the farmers. Major reasons behind limited adoption of such lines by the farmers are low level of salt tolerance relative to the locally adapted landraces and poor grain quality (Singh *et al.,* 2010). Choudhary *et al.* (2010) found that highly salt tolerant tomato cultivar, *Edkawi* performed poorly compared with the performance of locally developed cultivar, *Punjab Chuhara* under sodic-water irrigation both under drip and furrow irrigation. The recent trends in the development of salt-tolerant rice cultivars include greater emphasis on quantitative trait loci (QTL) mapping and marker-assisted breeding for introgression of markers tightly linked to the submergence tolerance gene (SUB1) and QTL for sodicity tolerance at the seedling stage (qSAL-TOL) in the background of high-yielding cultivars (Singh *et al.,* 2010).

Use of Amendments to Alleviate Impacts of Sodic Irrigation Water

Chemical amendments

The adverse effects of alkali water irrigation on physico-chemical properties of soils can be mitigated by the application of chemical amendments that provide soluble calcium to knock out exchangeable sodium adsorbed on clay surfaces. There are two main types of amendments: those that add calcium directly to the soil and those that dissolve calcium from calcium carbonate ($CaCO_3$) already present in the soil. Calcium containing amendments include gypsum (hydrated calcium sulfate) and calcium chloride. Gypsum is moderately soluble in water and it is the most commonly used amendment. Acid-forming, or acidic amendments include sulphuric acid, elemental sulphur and pyrite. Sulphuric acid reacts immediately with the native calcium carbonate in the soil to release soluble calcium for exchange with sodium. However, elemental sulphur and pyrite must be oxidized by soil bacteria and react with water to form sulfuric acid to reclaim sodic soil environment. But it may take several months (Choudhary, 2017).

The need for gypsum application for ameliorating the sodic irrigation effects is of recurring nature in contrast to reclamation of a native sodic or alkali soil. Application of gypsum has earlier been recommended when RSC of irrigation water exceeded 2.5 me L^{-1}. However,

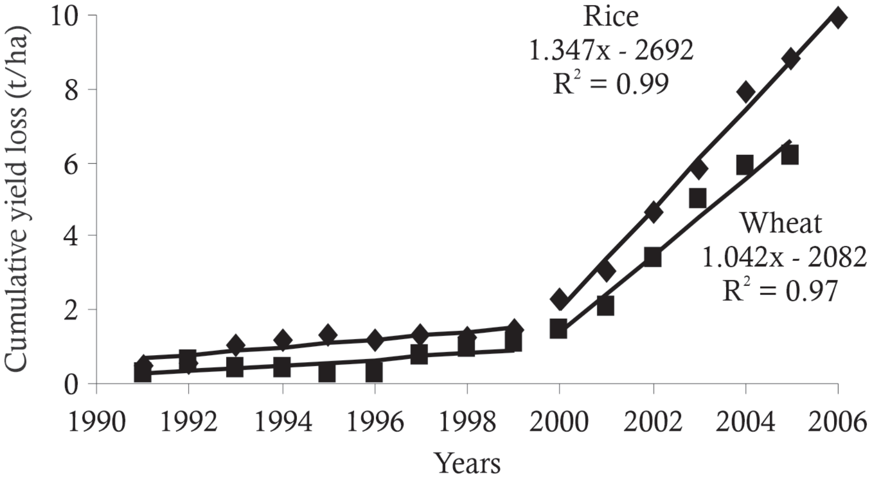

Fig. 1 Cumulative yield loss in response to sodic water irrigation compared to good quality canal water over the years
Source: Choudhary *et al.* (2011a)

later researches have shown that factors such as the level of the deterioration of the soil, cropping intensity, water requirement and sodicity tolerance of crop/s and economic condition of the farmers will ultimately will dictate the amount of gypsum required. Sustainable yields of crops in rice-wheat system, irrigated with alkali water (RSC > 4 me L^{-1}) are possible with occasional application of gypsum and FYM. Gypsum to supply 2.5 and 5.0 me L^{-1} to sodic irrigation water for wheat and rice, respectively, was found to be sufficient for maintenance of higher yields (Bajwa and Josan, 1989a). Gypsum applied with each irrigation or on cumulative basis were observed to be equally effective for wheat crop but in case of rice (requiring large number of irrigations), gypsum applied with each irrigation particularly under high RSC water irrigation showed an edge over its cumulative application. In a long-term experiment (10 years) on sugarcane, Choudhary *et al.* (2004) observed that the beneficial effect of gypsum was pronounced in increasing cane and sugar yield under sodic (30%) compared with saline-sodic water irrigation (13%). In spite of the well-established benefits of gypsum for alkali soils, unassured availability and deterioration in quality of gypsum due to several impurities is forcing researchers to look for some alternative methods for reclaiming the sodic and sodic water irrigated soils.

Organic amendments

It is generally accepted that additions of organic materials ameliorate sodic soil conditions through mobilization of Ca^{2+} from native $CaCO_3$ present in the soil. Choudhary *et al.* (2011a) observed that continual irrigation with sodic water (SW) resulted in the gradual increase in soil pH and ESP in a calcareous soil. Significant harmful effects of SW irrigation were observed after 7-9 years in grain yields of rice and wheat crops irrigated with RSC 12.5 me L^{-1} relative to canal water irrigated crops. Nevertheless, the adverse effects were not pronounced in the initial years when these crops were irrigated with sodic water having RSC 10 me L^{-1} (Fig. 1). It was conclusively found that with mobilization of Ca^{2+} from $CaCO_3$ during decomposition of organic materials such as FYM, green manuring (GM, *Sesbania aculeata*), the need of gypsum required for controlling the harmful effects of sodic water irrigation can be eliminated in rice-wheat cropping system in calcareous soils. In sugarcane crop, FYM was found to be more effective under saline-sodic (38 %) than under SW irrigation (23%) (Choudhary *et al.,* 2004). Complimentary effects of gypsum and FYM in improving sugar yield were observed under sodic irrigation (12.3 t ha^{-1}) but in saline-sodic irrigation, sugar yield under FYM (10.8 t ha^{-1}) was at par with gypsum plus FYM treatment.

Biochar, a carbon-rich, porous product is formed due to thermo-chemical conversion of biomass at temperature around 350-700 °C under low oxygen conditions. Its application to low fertility degraded soils have attracted interest (Amonette and Joseph, 2009; Akhtar *et al*., 2015; Sun *et al*., 2018). In general, biochar has been shown to improve soil physicochemical properties and thus may provide a favourable habitat and nourishment to both plants and soil microbes in degraded soils (Al-Wabel *et al*., 2013, Saifullah *et al*., 2018; Mavi *et al*., 2020). Enhanced soil available nutrients through cation exchange, adsorption of toxic compounds, reduced osmotic effects in root zone by improving water availability and improved soil pH status, all could be an explanation for the positive impacts of biochar application on soil flora and fauna (Chaganti *et al*., 2015, Saifullah *et al*., 2018; Mavi *et al*., 2023b). With this background, long-term field experiments conducted by PAU Soil Salinity Team suggest that biochar (derived from rice straw) holds promising potential as a soil amendment in ameliorating soil functions and promoting plant productivity under saline water irrigated conditions (Chahal *et al*., 2018; Singh *et al*., 2019). Experiment in soil irrigated with saline water but amended with rice straw biochar under cotton-wheat system showed significant improvement in aboveground biomass (both in cotton and wheat), possibly due to its beneficial effects on soil properties such as soil EC, organic carbon, microbial population, water and nutrient availability, bulk density, soil aggregation, and proliferation of roots (Singh *et al*., 2021, 2022). Further, the work also showed that the successive application of rice straw biochar for 5 years doubled the total soil organic C concentration and stocks in plots irrigated by saline water under a cotton-wheat cropping system (Mavi *et al*., 2023a). However, our future work will focus on life-cycle analysis of biochar as soil amendment which would help in understanding the various aspects associated with the overall process of biochar production and benefits in terms of energy utilization, yield improvement and carbon sequestration under sodic environments with different cropping systems.

New Interventions to Ameliorate Sodic Irrigation Effects

Industrial gypsums: Mined gypsum is the most commonly used chemical amendment for sodic soil and water reclamation because of its abundant availability and low cost. Of late, supply and quality of gypsum available to the farmers is not assured/deteriorated and therefore, the supplied gypsum is not showing the same level of effectiveness at several places. Under such scenario, using yellow calcium sulphate available from the iron and steel industry could be an alternative source of calcium for agricultural production for the sodic environment. Thus, the Soil Salinity Team at PAU Ludhiana is working to explore the potential of using yellow gypsum as an indigenous source of calcium in ameliorating sodified soils. Similar, to mined gypsum, yellow gypsum also positively influenced seed cotton and canola yield and reduced pH in soils irrigated with water of high RSC.

In addition, an emerging amendment for reclamation of sodic soils is Flue gas desulfurization gypsum (FGDG) which is a bye-product of scrubbing sulphur from combustion gases in coal-fired power generation plants. FGDG (chemically calcium sulfate dihydrate, $CaSO4_2.H_2O$) has become widely available as a byproduct of forced-oxidation wet scrubbers that are used to reduce sulfur emissions (SOX) from coal-fired power plants using a spray of limestone slurry. FGDG is widely used in building materials (such as wallboard, plaster coatings, and concrete). It has the potential to reclaim sodic soils as an alternative to mined gypsum. Applications of FGDG in cultivated soil improve physicochemical properties, decline nutrients loss, supplement nutrients for soil and improve crop yield; thereby increasing the overall productivity. Recognizing the role of FGDG in the reclamation of sodic soil as an alternative to mine gypsum, CSSRI and NTPC have jointly initiated a collaborative project to study the efficiency of FGDG in the reclamation of sodic soils and monitoring of the heavy metal(s) uptake, crop growth and quality of soil and leachates in FGDG amended soils.

An experiment on reclamation of sodic soils with the application of FGD gypsum showed that the soil pHs declined by 8-11 percent after one year of application of FGDG/mined gypsum in sodic soil at 0-15 cm depth under experimental conditions at ICAR-CSSRI. Similarly, a significant change in pHs was observed at 15-30 cm depth. The decrease in soil sodicity and neutralization of soil alkalinity over the period has improved paddy growth and yield. The paddy grain increased by 30-50% with FGDG/gypsum application compared with unamended control. The wheat grain yield increased by 50-80 with the application of FGDG/gypsum in sodic soil (Basak *et al.*, 2022). The application of FGDG for reclamation of the sodic soils of different regions of the country viz., Haryana, Uttar Pradesh, and Punjab have been executed from kharif season (2021) through participation experiments. Conjunctive use of gypsum with bio-augmented material or municipal city waste compost (Rai *et al.* 2020: Sundha *et al.* 2018, 2020) has also been advocated for reclaiming soil sodicity. However, further experimentation is continued to validate these results with a range of sodicity build-up in the soil and confirm the role of these alternatives on heavy metal build-up, if any, under long-term scenario.

Microorganisms have a great potential to reduce the stress caused by sodic environment. in continued quest to search for alternate sources which not only have capacity to ameliorate sodic-irrigation effects but also are relatively beneficial for soil health. The research efforts have been initiated at PAU, Ludhiana in collaboration with ICAR-CSSRI Regional Centre, Lucknow to evaluate the performance and potential of microbial bio-formulations in improving crop yield and soil functionality under sodic environment. Preliminary results suggest that halophytic microbial bio-formulations can help to reduce the quantity of gypsum required to ameliorate harmful sodic irrigation effects in cotton.

Additionally, after successfully utilizing biochar produced from rice-residue for ameliorating soil salinity and carbon sequestration, work has been initiated at PAU Ludhiana for studying the role of biochar (Bhullar *et al.*, 2019) and sewage sludge as an alternative organic source for ameliorating the soil irrigated with high RSC water.

Fertility Management

Excess salts in the soil solution, high pH and excessive exchangeable Na, and adverse soil physical properties due to long- term use of sodic waterers and sodification influence availability of native and applied fertilizer nutrients (*e.g.* phosphorus) and their losses (aggravation of N losses through NH_3 volatilization). Ammonia volatilization is a major N loss mechanism and it increases with increase in EC, RSC and SAR of irrigation waters. To decrease losses of N and increase N use efficiency, splitting of fertilizer N so as to match crop demands at different growth stages, deep incorporation, slow release N-fertilizers and application of urease inhibitors have been found to be useful. Generally, application of higher dose (25-50%) of N for sodified soils than that for normal soils constitutes one strategy to overcome the adverse effects of salinity. Nevertheless, for improving N use efficiency, a better strategy seems to be to substitute a part of inorganic fertilizer requirements through organic materials. Following the application of N through inorganic fertilizer sources, a large pool of NH_4^+ liable to be lost through volatilization is bound by applied organic matter such as FYM or SPM (Sugarcane press mud) in sodic water irrigates soil, temporarily binding the ammoniacal N and subsequently release N to crops during its growing season (Yaduvanshi and Swarup, 2005). Bajwa and Singh (1992) observed that under flooded alkaline soil conditions, urea, ammonium sulphate and ammonium chloride placed in reduced zone produced similar rice yields whereas nitrate containing fertilizers were appreciably inferior. In case of wheat, effectiveness of fertilizers containing both NH_4^+-N and NO_3^--N was similar. Using sodic water for irrigation leads to lower fertilizer use efficiencies, increased fertilizer loss and decrease in the efficiency of rhizobium nodulation. Moreover, the overall fertiliser use is also low and highly imbalanced, i.e. skewed towards nitrogen only. So, the issues related to appropriate timing and placement of fertilizers, adjustment of the timings of leaching treatment as well choice of slow nutrient release fertilizers require further research (Minhas *et al*., 2022). Further, various site-specific nutrient management (SSNM) tools such as Nutrient Expert, Green Seeker, LCC (leaf colour chart), remote sensing coupled with ICTs etc. should be evaluated for enhancing nutrient use efficiency (NUE) in differential levels of alkalinity developed in soils due to sodic-water irrigations.

Long term irrigation with sodic water also decreases the availability of micronutrients such as Zn and Fe resulting in deficiency of these nutrients when soils are generally calcareous. Besides being poor in available Zn, the use efficiency and recovery of applied Zn is further adversely affected due to 85-90% fixation of applied Zn (Chauhan *et al*., 1999). Rice crop, though tolerant to soil sodicity, is sensitive to Zn deficiency which may appear 15 to 21 days after transplanting in the form of brown spots on fully matured leaves causing stunted growth and ultimately severe yield reductions. Therefore, application of Zn is an important requirement along with gypsum for optimum crop yields in sodic/sodic-water soils. In a sodic soil amended with 10 to 15 t ha^{-1} of gypsum and 10 to 20 kg $ZnSO_4$ ha^{-1} was enough to meet Zn requirement of crops (Singh and Bajwa, 1987).

Irrigation Management

Conjunctive use

Combined use of canal and sodic waters is a good option for reducing sodicity hazards of irrigation water on soil health and crop productivity. This is particularly true in situations where canal water supplies are either un-assured or inadequate and farmers often pump sodic groundwater for supplemental irrigation.

For efficient use, good quality waters can be used to grow sensitive crops and sodic waters for tolerant crops. In some situations, poor and good quality waters are available either simultaneously or at intervals. The appropriate options include (i) different quality waters can be blended in the supply network making tailor-made water available for each crop and all soil conditions and, (ii) alternating the use of good and poor-quality water (Bajwa and Josan, 1989b; Choudhary *et al.,* 2006; Choudhary, 2017), and (iii) switching these water sources according to critical stage of crop growth during the growing season. Rhoades *et al.* (1992) advocated the adoption of seasonal cyclic use, called 'dual rotation' strategy where non-saline non-sodic water is used for salt/sensitive crops/ initial stages of tolerant crops to leach out the accumulated salts from irrigation with salty waters to previously grown tolerant crops. Sharma and Minhas (2005) reported that this strategy may work better in arid climate with very low rainfall but it is of natural occurrence in the monsoonal climate. Blending is a promising practice in areas where freshwater supplies can be made available on demand. Mixing of sodic and canal water is done in such a proportion so that final SAR/RSC is maintained below threshold limit of the crop to be grown.

The proportion of blending two different water supplies (canal and sodic water) depends on the crops to be grown, extent of sodicity of water and freshwater supplies and economically acceptable yield reductions. Allocation of the two kinds of waters separately, if available on demand, can be done to different fields, seasons or crop growth stages so that salinity/ sodicity stresses are minimized during sensitive growth stages in the crop. Cyclic use of multi-quality waters can be made inter- or intra-seasonal (Minhas *et al*., 2007b). Shelhevet (1994) have opined that cyclic use is more common and offers several advantages over blending. Moreover, mixing of two types of waters also requires the creation of additional facilities. Better quality water can be used for pre-sowing and early stages of crop growth and then switching to sodic water later on when the already established crop is able to tolerate relatively higher sodicity levels. Minhas *et al*. (2007b) observed that sustainability yield index of rice and wheat when sodic and good quality waters were used either by blending or by their alternate inter- or intra seasonal use, ranged from 0.52-0.75 and 0.79-0.95, respectively. Marginal improvements in the yield index over blending indicate a higher sustainability with the cyclic uses.

Bajwa and Josan (1989b) reported reduced crop yields of rice-wheat rotation due to increased pH and ESP and reduced infiltration rate (14%) in a sandy loam soil when put under sodic water (ECw 1.35 dS m^{-1}, RSC 10.1 meq L^{-1}, adj. SAR 26.7) for 6 years. However, when sodic irrigation was applied alternatively with canal irrigation, it resulted in increased yields of both the crops that were maintained at par with canal water except when there were two irrigations with sodic water (CW-2SW) in the cyclic option. In fact, in rice-wheat cropping system, farmers having some access to canal water supplies can sustain crop yields compared with situations where farmers do not have canal waters supplies at all (Minhas *et al.*, 1996). In alternative use, buildup of salt and ESP in the soil should be periodically monitored for better results. For crops sensitive at germination stage, cyclic option involving SW should address problem of seedling emergence due to crusting by ensuring pre-sowing irrigation with good quality canal water. Bajwa and Josan, (1989b), Choudhary *et al*. (2006) and Choudhary and Ghuman (2008) reported that alternating irrigations with canal water (CW) and sodic water (SW) maintained low soil ESP, and helped in sustaining good yields of rice and wheat, sunflower and cotton.

Yearly or seasonal conjunctive use strategy for canal and alkali (RSC 15) waters was evaluated for six years (2003-09) in potato-sunflower–green manure crop rotation (AICRP-SSW, 2010-17). The modes where higher number of canal water (CW) irrigations were applied, gave higher yields compared to the modes with higher number of alkali water (AW) irrigations in both the crops. Averaged over 6 years, the relative yield (RY) of potato was 67, 54, 78 and 61% under year-wise cyclic mode (1yCW : 2yAW, 1yAW : 2yCW, 2yCW : 1yAW and 1yAW : 2yCW) treatments, respectively. Similarly, the relative yield of sunflower was 60, 55, 73 and 56 for respective cyclic modes. In a seasonal cyclic strategy of irrigating potato with alkali water and sunflower with canal water (AWp : CWs), low relative yields (48% for potato and 60% for sunflower) were recorded. The *Sesbania* green manure crop was grown with monsoon rainwater but responded to sodicity buildup associated with previous crops. Higher proportions of SW used in cyclic option can also lower the quality of the harvested product. Reduction in potato grade and weight loss during storage and, smaller seeds and lower oil content in the case of sunflower was observed (Chauhan *et al.*, 2007). In onion, the proportion of 'A' grade bulbs was higher in 1TW : 1AW cyclic mode; at par with good quality water (TW) irrigation (Chauhan and Kaledhonkar, 2018). The proportion of lower grade bulbs (C grade) and weight loss during storage were higher under AW irrigation and the treatments with higher number of AW irrigations in a cyclic mode. Chauhan and Kaledhonkar (2018) also reported higher water use efficiency (WUE) of about 560 kg ha-cm^{-1} in 1TW : 1AW and TW treatments than mixing treatment of 2TW and 1AW (540 kg ha-cm^{-1}) and AW treatment (240 kg ha-cm^{-1}).

It became evident that in cyclic strategy, pre-sowing/first irrigation should be given with canal water. However, this may not happen in many canal commands where canal water supplies progressively decrease from the head reach to the tail reach (Tyagi, 2003) and even may not be available at the time of sowing of a crop. Choudhary and Ghuman (2008) observed greater decline in seed-cotton yield (16.5% $year^{-1}$) than that in wheat yield (5.9% $year^{-1}$). Compared with the SW treatment, yield of cotton and wheat were higher (93-98%) when the irrigation cycle started with CW and involved one SW (2CW:SW, CW:SW). The yields of cotton and wheat also remained higher in an irrigation cycle starting with SW but followed by 2CW irrigation (SW:2CW). But with cycles (SW:CW, 2SW:CW) involving one CW, the decline in seed-cotton yield was relatively greater (18-23%) than in the wheat yield (10%) after six years. Long-term sustainability of

Table 1. Effect of different irrigation cyclic modes on crop yields (t ha^{-1}) under cotton-wheat rotation in different time periods

Irrigation treatments/ Cyclic modes	Wheat				Cotton			
	1996-97 to 2001-02		2002-03 to 07-08		1997 to 2002		2003 to 2008	
	Mean	SYI[#]	Mean	SYI	Mean	SYI	Mean	SYI
CW[@]	5.20f[*]	0.79	5.21d	0.85	1.32d	0.54	2.02d	0.55
SW	4.43a	0.65	4.07a	0.61	0.95a	0.41	1.31a	0.35
2CW:SW[$]	5.10ef	0.77	5.01d	0.83	1.26cd	0.53	1.93cd	0.57
CW:SW	4.95cd	0.75	4.88cd	0.81	1.21bcd	0.51	1.85bcd	0.55
CW:2SW	4.70b	0.72	4.61bc	0.73	1.15bcd	0.49	1.64abcd	0.51
SW:2CW	4.82bcd	0.73	4.88cd	0.81	1.22cd	0.56	1.82bc	0.55
SW:CW	4.70b	0.71	4.63bc	0.73	1.08abc	0.47	1.59abc	0.45
2SW:CW	4.75bc	0.73	4.31ab	0.66	1.02ab	0.42	1.52ab	0.44

[@]CW – Canal water; SW- Sodic water; [$] Cyclic use of 2CW and one SW irrigation
[*]Means sharing the same letter(s) in a column do not differ significantly at $p<0.05$ according to DMRT; [#] SYI – Sustainable yield index,
Source: Choudhary (2017)

2CW:SW, CW:SW and SW:2CW was established during the next 6 years (7-12 years) when optimum wheat and cotton yields (90-96% RY) were achieved (Choudhary, 2017). This trend was also confirmed by sustainable yield index values (Table 1).

The SYI indicating the minimum guaranteed yield as referenced to the maximum observed yield (Y_{max}). It ranged from 0.55-0.57 for cotton and 0.81-0.83 for wheat in 2CW:SW, CW:SW and SW:2CW treatments after 12 years, respectively. The SYI values for these treatments were higher for both crops relative to CW:2SW, SW:CW and 2SW:CW treatments. Lower SYI values for cotton might have resulted due to large variability in seed-cotton than wheat yields in different years. It suggests that although pre-sowing irrigation to cotton should be given always with good quality CW for ensuring better germination of cotton, sustainable seed-cotton yield can also be obtained even with occasional pre-sowing irrigation with SW followed by 2CW irrigations (SW:2CW). It is due to lower buildup of ESP (ESP < 10 in surface 0.3 m soil) in this treatment (similar to that observed in 2CW : SW) that controlled the precipitation of Ca^{2+} as $CaCO_3$. This treatment simulates the situations where availability of CW is not assured at the time of sowing. The proposed strategy offers the additional advantage of integrated water resources management by using low quality water for soil amelioration while saving better-quality water for producing high-value crops.

Irrigation interval

A general recommendation under sodic soil conditions is to apply light and frequent irrigations for overcoming the effects of poor hydraulic properties of soils. Under arid conditions, higher transpiration rates from wetter soils due to frequent saline irrigations may lead to increased soil solution salt concentration (1.5 to 2.0 folds) adjacent to growing roots, thus disapproving the case for a higher irrigation frequency.

In a long-term study, Bajwa *et al.* (1993) reported that crop responses to short irrigation intervals involving sodic and saline-sodic waters depended upon the season in which the crop was grown and its relative salt and Na tolerance. Frequent irrigation schedules during the summer season moderated the soil temperature and thus, increased crop yield over the long irrigation intervals.

Irrigation method

The distribution of water and salts vary with the method of irrigation. The surface irrigation methods such as border strips check basins and furrows are the oldest and are most commonly practiced in India. However, these irrigation methods generally result in excessive irrigation and non-uniformity in water applications.

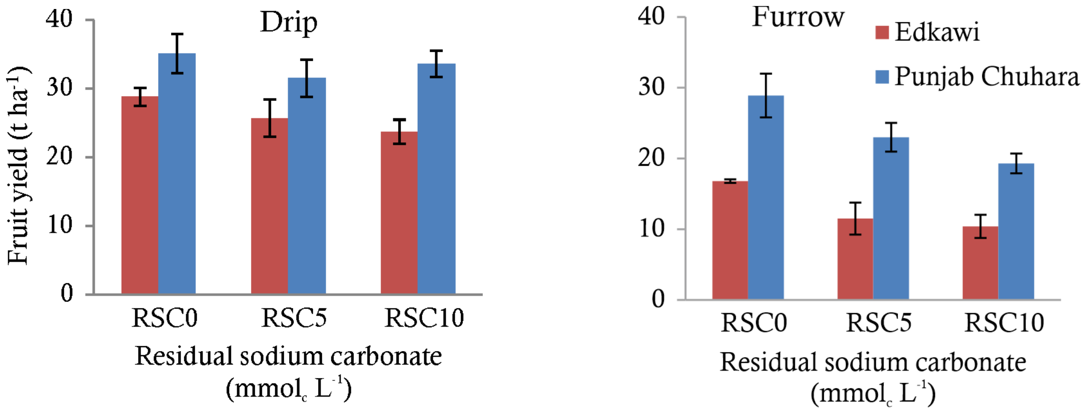

Fig. 2 Tomato fruit yields (t ha^{-1}) as influenced by RSC of irrigation water under drip and furrow irrigation (after three years in 2003-04)
Source: Choudhary *et al.* (2010)

Consequently, on-farm irrigation efficiency is low (50-60%). Drip irrigation has revolutionized the production of some high-value crops. Due to the formation of the wetting front by the movement of water due to regular and frequent water supply in drip irrigation, salts are pushed away towards the periphery of the front. Thus, drip irrigation has the potential to enhance the threshold limits of crop salt and Na tolerance by modifying the pattern of salt distribution.

While irrigating tomato crop with sodic waters high in bicarbonates, Choudhary *et al.* (2010) observed that effects on soil physical and chemical properties can be more severe in furrow than in drip-irrigation. On the other hand, better soil moisture conditions and lesser deterioration in soil properties when irrigated with medium and high RSC water under drip irrigation can lead to higher tomato yields than under furrow irrigation (Fig. 2).

Leaching requirement

The first requisite for crop production in saline soils is to lower salinity to acceptable limits, which is accomplished through the process of leaching. The extent of leaching required during reclamation depends upon initial salinity, salt tolerance of crops to be grown, and depth of the water table. One recommendation is the application of excessive water to meet the leaching requirement (LR) and maintain a desirable salt and water balance in the soil having adequate drainage. The concept of LR for achieving salt balance holds good for situations with very low rainfall. But it is of natural occurrence in monsoonal type climate where rains are concentrated in 2-3 months. In general, LR increases with the salinity of the water supply and the salt sensitivity of the crop. However, 30-50% higher salinity build up even in light-textured soil was observed when 50% extra saline water was applied to meet the leaching requirement and so was true when applying 50% extra sodic water under rice-wheat and maize-wheat systems (Minhas and Bajwa, 2001; Choudhary *et al.*, 2011b). The general strategy to use the monsoon rainwater to take care of LR and to maintain low salt build-up in the root zone soil seems to be more helpful.

Conclusions and Future Research Needs

Recent trends suggest that the use of sodic waters for irrigation for crop production will increase in the future. But indiscriminate and unmindful use of these sodic waters can, directly and indirectly, affect the soil's physical, chemical, and biological properties and reduce crop growth, yield, and quality. Therefore, adopting site-specific management options is crucial for controlling the build-up of salts in soils ensuring their safe use for the sustainability of crop production. Selection of crops, cropping patterns, and crop varieties that produce satisfactory yields under Na-rich environments are important. Conjunctive use options of available water qualities, appropriate irrigation methods, and leaching strategies are crucial and critical to reduce Na and salt build-up in soil and maintain crop yields. The optimal use of chemical amendments and fertilizers including time and mode of their application and their combined and judicious use along with organic materials will ensure efficient utilization of these inputs to ameliorate the soil and water sodicity.

We believe that the time has come to consider these sodic ground waters as useful resources rather than an environmental burden. Adopting specific systems of management while using these sodic waters should therefore give us an opportunity to shift from subsistence farming to progressive farming. Using alternate sources of gypsum having high purity and assured quality, biochar derived from different biomass and, microbial-mediated calcite dissolution to reduce soil and water sodicity looks promising and should further be explored.

References

Amonette J and Joseph S (2009) Characteristics of biochar: Micro-chemical properties. In: Lehmann J and Joseph S (eds) *Biochar for Environmental Management: Science and Technology*, Earthscan, London, pp 35-52.

Akhtar SS, Andersen MN and Liu F (2015) Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress. *Agriculture Water Management* **158**: 61–68.

Al-Wabel MI, Al-Omran A, El-Naggar AH, Nadeem M and Usman AR (2013) Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. *Bioresource Technology* **131**: 374–379.

Ayers RS and Westcot DW (1985) Water quality for agriculture. *Irrigation Drainage Paper 29*, FAO, Rome, Italy, Rev. 1, p 174.

Bajwa MS and Josan AS (1989a) Effect of gypsum and sodic irrigation water on soil and crop yields under rice-wheat rotation. *Agricultural Water Management* **16**: 53-61.

Bajwa MS and Josan AS (1989b) Effect of alternating sodic and non-sodic irrigations on the build-up of sodium in the soil and on the crop yields in northern India. *Experimental Agriculture* **25**: 199-205.

Bajwa MS and Singh B (1992) Fertilizer nitrogen management for rice and wheat crops grown in alkali soils. *Fertilizer News* **37**: 47-59.

Bajwa MS, Josan AS and Choudhary OP (1993) Effect of frequency of sodic and saline-sodic irrigations and gypsum on the build-up of sodium in soil and crop yields. *Irrigation Science* **14**: 21-26.

Basak N, Rai AK, Sundha P, Meena RL, Bedwal S, Yadav RK and Sharma PC (2022) Assessing soil quality for rehabilitation of salt-affected agroecosystem: *A comprehensive review. Front. Environmental Science* **10**: 935785. doi: 10.3389/fenvs.2022.935785.

Bhullar RS, Mavi MS and Choudhary OP (2019) Adverse impact of sodicity on soil functions can be alleviated through addition of rice straw biochar. *Communications in Soil Science and Plant Analysis* **50**, 19: 2369-2383.

Chahal SS, Choudhary OP and Mavi MS (2017) Organic amendments decomposability influences microbial activity in saline soils. *Archives of Agronomy and Soil* Science **63**: 1-14.

Chahal SS, Choudhary OP and Mavi MS (2018) Microbial activity is constrained by the quality of carbon and nitrogen under long-term saline water irrigation. *Communications in Soil Science and Plant Analysis* **49**, 11: 1266-1280.

Chaganti VN and Crohn DM (2015) Evaluating the relative contribution of physiochemical and biological factors in ameliorating a saline-sodic soil amended with composts and biochar and leached with reclaimed water. *Geoderma* **259**: 45–55.

Chauhan RPS, Singh BB, Singh RK and Singh VP (1999) Strategic nutrient management for sustained rice production in sodic soil. *Fertilizer News* **44**: 13-26.

Choudhary OP and Bajwa MS (2021) *Sodic irrigation waters and their management.* In: Minhas PS *et al* (eds) *Managing Salt-affected Soils in India*. ICAR Publication, New Delhi, India. *pp 485-513*

Choudhary OP, Josan AS, Bajwa MS and Kapur ML (2004) Effect of sustained sodic and saline-sodic irrigations and application of gypsum and farmyard manure on yield and quality of sugarcane under semi-arid conditions. *Field Crops Research* **87**: 103-116.

Choudhary OP (2017) Long term impact of cyclic use of sodic and canal waters for irrigation on soil properties and crop yields in cotton-wheat rotation in a semi-arid climate. *Agricultural Research* **6**: 267-272.

Choudhary OP and Ghuman BS (2008) Cyclic use of sodic and non-sodic canal waters for irrigation in cotton-wheat cropping system in a semi-arid region. *Journal of Sustainable Agriculture* **32**: 269-286.

Choudhary OP, Brar JS, Saroa GS and Sekhon KS (2012a) Wheat response to increasing levels of residual alkalinity in irrigation water in a semi-arid region. *Journal of Crop Improvement* **26**: 802-815.

Choudhary OP, Brar JS, Sekhon KS and Shankar A (2012b) Response of Bt cotton hybrids to irrigation with sodic waters with high residual alkalinity in semi-arid region. *In: Proc National Seminar on Development in Soil Science – 2012*, 77th Annual Conv. Indian Society of Soil Science, Ludhiana. pp 223.

Choudhary OP, Ghuman BS and Saroa GS (2007) Response of 'PBW 343' wheat (*Triticum aestivum*) to increasing levels of residual alkalinity in irrigation water in semi-arid regions. *Indian Journal of Agricultural Science* **77**: 150-153.

Choudhary OP, Ghuman BS, Dhaliwal MS and Chawla N (2010) Yield and quality of two tomato (*Solanum lycopersicum* L.) cultivars as influenced by drip and furrow irrigation using waters having high residual sodium carbonate. *Irrigation Science* **28**: 513-523.

Choudhary OP, Ghuman BS, Singh B, Buresh RJ, and Thuy N (2011a) Effects of long-term use of sodic water irrigation, amendments and crop residues on soil properties and crop yields in rice-wheat cropping system in a calcareous soil. *Field Crops Research* **121**: 363-372.

Choudhary OP, Ghuman BS, Josan AS and Bajwa MS (2006) Effect of alternating irrigation with sodic and non-sodic waters on soil properties and sunflower yield. *Agricultural Water Management* **85**: 151-156.

Choudhary OP, Grattan SR and Minahs PS (2011b) Sustainable crop production using saline and sodic waters. In: Lichtfouse E (ed) *Alternate Farming Systems, Biotechnology, Drought Stress and Ecological Fertilisation. Sustainable Agriculture Reviews* **6**: 293-318. Springer Dordrecht, New York.

Choudhary OP, Josan AS and Bajwa MS (1996a) Rooting and yield relationships in different barley cultivars grown under increasingly soil sodicity stress conditions. *Crop Improvement* **23**: 1-11.

Choudhary OP, Josan AS and Bajwa MS (1996b) Tolerance of wheat and triticale to sodicity. *Crop Improvement* **23**: 238-246.

Choudhary OP, Josan AS and Bajwa MS (2001) Yield and fibre quality of cotton cultivars as affected by sustained sodic irrigations in semi-arid conditions. *Agricultural Water Management* **49**: 1-9.

Eaton FM (1950) Significance of carbonates in irrigation waters. *Soil Science* **69**: 123-133.

Mavi MS, Singh G, Choudhary OP, Singh A, Vashisht BB, Sekhon KS, Pathania N and Singh BP (2023a) Successive addition of rice straw biochar enhances carbon accumulation in soil irrigated with saline or non-saline water. *Environmental Research* **217**: 114733.

Mavi MS, Singh G, Choudhary OP and Dey D (2023b) Moderation of nitrogen availability through the application of pyrolyzed and unpyrolyzed organic materials in saline water irrigated soil. *Environment Monitoring & Assessment* **195**: 467.

Mavi MS, Bhullar RS and Choudhary OP (2020) Differential ability of pyrolysed biomass derived from diverse feedstocks in alleviating salinity stress. *Biomass Conversion and Bio-refinery* **12**: 5229–5240.

Minhas PS, Dubey SK and Sharma DR (2007) Comparative effects of blending, intra/ inter-seasonal cyclic uses of alkali and good quality waters on soil properties and yields of paddy and wheat. *Agricultural Water Management* **87**: 83–90.

Minhas PS, Sharma DR and Sharma DK (1996) Perspective of sodic water management for paddy wheat cropping system. *Journal of Indian Water Resources Society* **2**: 57- 61.

Minhas PS and Bajwa MS (2001) Use and management of poor-quality waters for the rice-wheat based production system. In: Kataki PK (ed) *The Rice-Wheat Cropping System of South Asia: Efficient Production Management*. Food Products Press, an imprint of The Haworth Press, Inc. pp 273-306.

Minhas PS, Qadir M and Yadav RK (2021) Groundwater irrigation induced soil sodification and response options. *Agricultural Water Management* **215**: 74-85.

Rai AK, Basak N and Sundha P (2020) Alternate reclamation sources of sodic soils. In: Minhas PS et al (eds) *Managing Salt-Affected Soils for Sustainable Agriculture*. ICAR Publication, New Delhi. pp 332–345.

Rengasamy P and Marchuk A (2011) Cation ratio of soil structural stability (CROSS). *Arid Soil Research & Rehabilitation* **49**: 280-285.

Sharma DK and Singh A (2015) Salinity research in India-Achievements, challenges and future prospects. *Water and Energy International* **58**: 35-45.

Sharma PK, Sood A, Setia RK, Singh N, Meenakshi and Verma VK (2010) Groundwater quality for irrigation in Punjab. *Punjab Remote Sensing Center, Ludhiana*. pp 63.

Singh A (2015) Land and water management planning for increasing farm income in irrigated dry areas. *Land Use Policy* **42**: 244–250.

Singh B and Bajwa MS (1987) Ammonia volatilization from salt-affected soils fertilized with urea under submerged conditions. *Journal of the Indian Society of Soil Science* **35**: 358-364.

Singh G, Bundela DS, Sethi M, Lal K and Kamra SK (2010) Remote sensing and geo- graphic information system for appraisal of salt-affected soils in India. *Journal of Environmental Quality* **39**: 5–15.

Singh G, Mavi MS, Choudhary OP, Kaur M and Singh BP (2022) Interaction of pyrolysed and un-pyrolysed organic materials enhances carbon accumulation in soil irrigated with water of variable EC. *Soil & Tillage Research* **215**: 105193.

Singh G, Mavi MS, Choudhary OP, Gupta N and Singh Y (2021) Rice straw biochar application to soil irrigated with saline water in a cotton-wheat system improves crop performance and soil functionality in north-west India. *Journal of Environmental Management* **295**: 113277.

Singh R, Mavi MS and Choudhary OP (2019) Saline soils can be ameliorated by adding biochar generated from rice-residue waste. *Clean Soil, Air, Water* **47**(2): 1700656

Singh P, Choudhary OP and Mavi MS (2018) Irrigation-induced salinization effects on soil chemical and biological properties under cotton-wheat rotation on loamy sand soil in northwest India. *Journal of the Indian Society of Soil Science* **66**: 386-391.

Sun J, Yang R, Li W, Pan Y, Zheng M and Zhang Z (2018) Effect of biochar amendment on water infiltration in a coastal saline soil. *Journal of Soils Sediments* **18**: 3271–3279.

Sundha P, Basak N, Rai AK, Yadav RK and Sharma DK (2018) Utilization of municipal solid waste compost in reclamation of saline-sodic soil irrigated with poor quality water. *Journal of the Indian Society of Soil Science* **66**: 28–39.

Sundha P, Basak N, Rai AK, Yadav RK, Sharma PC and Sharma DK (2020) Can conjunctive use of gypsum, city waste composts and marginal quality water rehabilitate saline-sodic soils? *Soil Tillage Research* **200**: 104608. doi:10.1016/j.still. 2020.104608.

Tyagi NK (2003) Managing saline and alkali water for higher productivity. In: Kijne JW et al (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CABI Publishing, Wallingford, U.K, pp 69-88.

United States Salinity Laboratory Staff (1954) Diagnosis and Improvement of Saline and Alkali Soils, *United States Department of Agriculture*. *Handbook 60*. pp 160.

Yaduvanshi NPS and Swarup A (2005) Effect of continuous use of sodic irrigation water with and without gypsum, farm yard manure, pressmud and fertilizer on soil properties and yields of rice and w-heat in a long-term experiment. *Nutrient Cycling in Agroecosystems* **73**: 111-118.

Received: April 26, 2023: Accepted: June 16, 2023