

**EVALUATION OF SOME NEW CHEMICAL AND
ORGANIC AMENDMENTS IN RICE-WHEAT
SYSTEM UNDER SODIC WATER IRRIGATION**

Thesis

**Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

in

SOIL SCIENCE

(Minor Subject: Chemistry)

By

**Harjot Kaur
(L-2019-A-132-M)**

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2022

CERTIFICATE I

This is to certify that the thesis entitled, “**Evaluation of some new chemical and organic amendments in rice-wheat system under sodic water irrigation**” submitted for the degree of **Master of Science**, in the subject of **Soil Science** (Minor subject: **Chemistry**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Ms. Harjot Kaur (L-2019-A-132-M)** under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE – II

This is to certify that the thesis entitled, " **Evaluation of some new chemical and organic amendments in rice-wheat system under sodic water irrigation**" submitted by **Ms. Harjot Kaur (L-2019-A-132-M)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of **Master of Science** in the subject of **Soil Science** (Minor subject: **Chemistry**) has been approved by the Student's Advisory Committee along with External Examiner after an oral examination on the same.

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ABSTRACT

Persistent and continuous use of sodic water for irrigation in south-western regions of Punjab has led to the development of sodicity in soils which severely impacts the physical, chemical and biological properties. The deteriorated soil health proves futile to plant growth causing yield losses and lower farm income. The problems caused by the irrigation-induced sodicity can be rectified by the amelioration of the soils using amendments. Gypsum has been popular among farmers as a source to ameliorate sodic water irrigated soils but the issue with its availability and quality has propelled the scientific community to explore the potential of some others resources such as yellow gypsum, a by-product of steel industry which can help sustain growth in sodic soil environment. Organic amendments such as farm yard manure (FYM) has been studied extensively while others like rice straw compost, rice straw (RS) and biochar (BC) are presently getting attention in terms of their utility in restoring sodic soils. A pot experiment was conducted to collate the effect of application of inorganic (yellow; YG and grey gypsum; GG) and organic amendments (FYM, rice straw compost, RS and BC) on properties of soils (loamy sand; ls and sandy clay loam; scl) irrigated with sodic water and biomass yield of crops. Soils were irrigated with different levels of RSC of irrigation water i.e. RSC 0, 5, 7.5 and 10 meq L⁻¹. Organic amendments, FYM @ 15 t ha⁻¹, Rice straw compost @ 6 t ha⁻¹, RS 6 t ha⁻¹ and BC @ 4 t ha⁻¹ were applied once before sowing of wheat whereas gypsum (both types) @ 50%GR was applied on soil basis and later with each irrigation to neutralize sodicity of water. Individual effect of these amendments was studied through 56 treatment combinations in completely randomized design replicated three times. Results revealed decrease in biomass yield, photosynthetic activity, stomatal conductance and uptake of Ca, Mg and K on irrigation with sodic water in wheat and rice crop whereas uptake of Na and proline content increased. With regard to soil properties, irrigation with sodic water increased pH, sodium adsorption ratio (SAR) (higher in scl), exchangeable sodium percentage (ESP) (higher in ls), and bulk density (BD) but decreased microbial biomass carbon (MBC) and mean weight diameter (MWD). Upon application of gypsum (both types), decrease in pH, SAR and ESP was observed along with significant improvement in biomass yield and other soil properties such as MBC and MWD. Among the organic amendments, BC reduced uptake of Na whereas rice straw compost and FYM gave promising results in restoration of soil properties and biomass yield in both the crops. Further, field studies need to be conducted to evaluate the restorative effect of yellow gypsum vis-à-vis grey (mined) gypsum and its combined application along with the organic amendments in soils receiving sodic water irrigation.

Keywords: Biochar, farmyard manure, gypsum, rice straw, rice straw compost, sodic water irrigation

Signature of Major Advisor

Signature of the Student

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CHAPTER I

INTRODUCTION

According to a report by the United Nations, the rise in global population is expected to hit 9.5 billion mark by 2050 (United Nations 2012). This generates the urgent need to boost the food production by 60% to meet the demands of the soaring population (FAO 2013). The major bottleneck to this huge task is, however, the degradation of land induced by the use of contaminated water resources. On the global scale, the land degradation has taken a toll on nearly 434 million ha of land in the world (FAO 2008). The Indo-Gangetic basin in India presents a serious issue of inherent sodicity and/or irrigation induced alkalization for 1.37 m ha of the area (Minhas *et al* 2019; Sheoran *et al* 2021). Moreover, the increasing competition for water due to rapid urbanization and industrialization is a major impediment to more allocation of fresh water supplies for irrigated agriculture in developing countries. India, harbouring 17.5% of the world human population with mere availability of 2.3% of the total world land area and 4% of global water resources, faces a gigantic task of feeding its population. The shortage of fresh water resources and the need to feed the ever increasing population is leading farmers to irrigate their fields with marginal quality (saline or alkaline) underground water.

The irrigated area in India accounts for 34% of the net sown area which provides 60% of the food production. However, one fourth of the groundwater resources in India are brackish in nature. The areas facing water scarcity are generally underlain with poor-quality ground water (Minhas and Tyagi 1998). In India, the irrigation potential of sodic and/or saline groundwater holds considerable portion (32-84%) of the total irrigation potential of groundwaters surveyed in different states (Minhas and Bajwa 2001). In Punjab, 42% of ground waters are of poor quality, of which 25% are saline, 69% are sodic and 6% are saline-sodic in nature (PRSC 2010). In general, semi-arid areas receiving annual rainfall of 500-700 mm suffer from the prevalence of groundwater sodicity. Consequently, persistent and continuous use of poor-quality waters for irrigation results in build-up of soil sodicity adversely affecting its physico-chemical properties (Grattan and Oster 2003) leading to poor soil health and low crop yields (Choudhary *et al* 2011b; Minhas 2012).

Presence of excess sodium on exchange sites presents a physical challenge to the soil leading to its slaking and swelling. This coupled with dispersion of clay particles causes clogging of soil pores and thus poor air and water movement (low permeability). The sodic soils have alkali soil reaction ($\text{pH}_s > 9.5$), higher exchangeable sodium percentage ($\text{ESP} > 15\%$) and sodium adsorption ratio ($\text{SAR} > 13.0$), low organic carbon content and poor physical properties and poor fertility of soils. These soils form a crust on drying, as a consequence of which seed germination and root penetration is restricted. Reduction in the uptake of K^+ , Ca^{2+}

and Mg^{2+} is evident as a direct result of ionic imbalance in plant cells due to the excess accumulation of Na^+ and Cl^- (Tester and Davenport 2003). The soil productivity of salt-affected soils is reduced due to nutrient imbalance, reduction in water and nutrient availability or water uptake by plant roots causing reduction in crop yield and quality (Ayers and Westcot 1985). However, proper and specific management of sodic groundwaters can make these a valuable irrigation resource for augmenting fresh water supplies for supporting the vision of achieving higher crop productivity. Crop production in soils receiving sodic waters can become sustainable if soil quality (physical, chemical and biological) is improved through reversing the build-up of sodicity in the soil.

Various methods are in vogue to ameliorate the deleterious effects of sodic-water irrigation on soils. Among the amendments, gypsum is the most commonly and effectively used chemical amendment for sodic soil and water reclamation due to its abundant availability and low cost. Gypsum is calcium sulphate ($CaSO_4 \cdot 2H_2O$) that widely occurs as natural deposits. It must be processed through grinding into coarse or fine powder before its application. Reclamation of sodic soils takes time as soil structural restoration is a slow process. Also, gypsum dissolution on application is dependent on pH, partial pressure of CO_2 , and hydrolysis reaction in soil solution (Li and Keren 2009). However, of late, the quality of gypsum being supplied to the farmers has been inconsistent and therefore, the gypsum excavated from natural deposits is not showing the same level of effectiveness in reclaiming sodic soils at several places. Under such scenario, using yellow gypsum, a by-product of the iron and steel industry could be a viable alternative and cheap source of calcium for ameliorating sodic environments. Yellow gypsum (value added gypsum) is synthesized from 60 mesh size slag by acid leaching. The yellow colour is imparted by the iron present in the by-product. Steel industry manufactures near about 125 kg of steel slag per tonne of steel produced through Linz-Donawitz (LD) process. The significance of its use lies in the fact that it reduces the reliability on natural gypsum. However, the use of yellow gypsum in agriculture to reclaim sodic environment remains largely unexplored.

There is no doubt that gypsum effectively reclaims sodic soils but in some cases it cannot substantially bring improvements in some physical and biological properties of the soil. To serve the purpose, the use of organic amendments seems an amiable option. Application of organic manures to sodic soils adds organic matter promoting microbial growth as well diversity and nutrients besides enhancing infiltration rate facilitating sodium leaching, reduces ESP, and enhances water-holding capacity (El-Shakweer *et al* 1998; Naeni and Cook 2000). The native $CaCO_3$ is dissolved by evolution of H^+ on decomposition of organic matter which reclaims sodic environment (Ghafoor *et al* 2008). However, the rate of reclamation is slow upon the addition of organic manures. Organic colloids contribute largely to the CEC of the soil which determines the magnitude of net surface charge on soil particles

and improves the retention of ions on adsorption complex in soils (Oorts *et al* 2003). Various organic amendments such as composts, farm yard manure, biochar and crop residues can be used for restoration of physical, chemical and biological parameters in a sodic soil environment.

Termorshuizen *et al* (2004) concluded compost to be the most stable sources of organic matter. Composts are prepared by biological or microbial decomposition of organic materials. Composts contain nutrient elements which upon mineralization enrich soils and provide cations responsible for replacing and leaching of sodium ions from the exchange complex. Farm yard manure (FYM) is a type of compost containing dung and farm wastes. When applied to sodic soils, FYM enhances nutrient availability and also helps in binding of soil particles leading to better soil aggregation and improvement in physical soil properties. Walker and Bernal (2008) indicated that incorporation of such organic amendments increases the cation exchange capacity (CEC), saturating the exchange sites with flocculating ions such as Ca^{2+} , Mg^{2+} and keeping Na^+ away from the exchange sites.

Crop residues are generated every year in surplus amounts due to increased production under intensively irrigated RW systems in South Asia. The narrow time window between harvesting of rice crop and sowing of the next wheat crop along with limited uses of rice straw as fodder due to its high silica (10-15%) prompts the farmers to resort to burning of residues left in the field. Burning of crop residues not only destroys organic matter but also deprives the soils of essential nutrients, particularly, nitrogen, phosphorus and sulphur (Yadvinder-Singh *et al* 2008). Studies have claimed that the retention of rice residue as a surface mulch is useful in improving soil water status and regulating soil temperature. This has proven to be beneficial in plants as it increases root growth, plant canopy, wheat yield and water productivity (Jiafu 1996; Sharma and Parmar 1998; Li *et al* 2004; Rahman *et al* 2005; Chakraborty *et al* 2010 and Balwinder-Singh *et al* 2011). Cai *et al* (2019) proposed an increase in organic carbon in the soil and available K compared with the control treatment upon application of rice straw in conjunction with fertilisers. Son *et al* (2017) found rice straw application with gypsum to be useful in reducing EC_e and ESP below the critical limits in saline-sodic soils. Also, conversion of surplus crop residue and manures to biochar with pyrolysis technique can reduce the agricultural waste turning it into a valuable asset.

Biochar is a carbon (C)-rich substrate formed on pyrolysis of organic substances under restricted supply of O_2 and temperatures below 700°C (Lehmann and Joseph 2009). The product is high in ash content, pH, CEC, and surface area. Biochar, as an amendment, is well known to improve nutrient status of soils, inorganic fertilizer efficiency, soil physical properties, base saturation, microbial populations, and is reported to reduce saline and drought stresses (Al-Wabel *et al* 2017; Saifullah *et al* 2017). The ameliorative effects of biochar have been known to arise from three mechanisms alleviating the antagonistic effects

of salinity, including temporary salt adsorption on negatively charged sites on the surface of biochar, reduced osmotic effects in root zone by improving water relations, and reduced uptake of Na by increasing availability of other macronutrients (K, P, Ca, and Mg) (Akhtar *et al* 2015). Furthermore, its application can improve plant growth and yield favourably through cation exchange, surface interactions and water availability processes (Major *et al* 2010; Mavi *et al* 2018). Tapping of beneficial effects of biochar is dependent on its type, application rate, soil type and environmental conditions (Olmo *et al* 2016).

While considering the reclamation of sodic soils, the soil part is generally taken into consideration whereas the plant responses are often neglected. Sodicity negatively influences biochemical responses of plants grown in such soils. Sodicity stress leads to reduction in water potential in leaves, thus affecting the absorption of water and nutrients from the soil through roots. Salinity, immediately and transiently, leads to distressed water relations along with the synthesis of ABA (Munns and Tester 2008). As the stomatal conductance decreases, it directly affects the exchange of gases and respiration rate (Ashraf 2001; Marler and Zozor 1996; Romero-Aranda *et al* 2001). However, every crop species has its salt tolerance mechanism. Some species are capable of accumulating amino acids like proline, alanine, arginine, glycine, serine, leucine, and valine in their tissues that can counterbalance the effect of sodium and chloride ions in the cells (Mansour 2000). Proline is a major amino acid accumulated at a rate higher rate than other amino acids in the plants under salt stress (Abraham *et al* 2003; Torabi *et al* 2010). Ketchum *et al* (1991) proved that proline concentration increased in the cytosol and attained osmotic adjustment. Plants have shown increased adaptation to salt stress through proline accumulation. It works as an indicator molecule signalling the activation of various response mechanisms related to adaptation process. Though the research is being continued towards restoration of soil properties under salt stress, effectiveness of application of amendments in mitigating the negative biochemical responses needs further insight so that the soil-plant-air-continuum works in a balanced configuration in sodic soils.

Objectives

To collate the effects of chemical (grey gypsum and yellow gypsum) and organic amendments (like farm yard manure, rice straw, rice straw compost, biochar) on

- i) Ionic composition and
- ii) Dry matter yield in Rice-Wheat system under sodic water irrigation

CHAPTER II

REVIEW OF LITERATURE

2.1 Effect of sodicity on plant growth

2.2 Effect of sodicity on soil properties

2.3 Role of amendments in reclamation of sodic soils/sodic-water irrigated soils

2.3.1 Effect of application of inorganic and organic amendments on soil physical properties

2.3.2 Effect of inorganic and organic amendment application on soil chemical properties in sodic soils

2.3.3 Effect of application of inorganic and organic amendments on soil biological properties in sodic soils

2.3.4 Role of amendment application on physiological parameters, crop yield and uptake of ions

The world has lost its cultivable land to fast paced degradation in the recent years affecting over one third of the global population. This issue has taken a toll on the productivity of cropped lands worldwide challenging food security and widening the gap between sufficiency and inadequacy. A report by the United Nations (2008) predicts an increase in the world population up to 8.01 thousand million people. The food production to support such a rise in population needs to be increased by 38% till 2025 and 57% by 2050. But the exponential increase in population is outpacing the production of food grains. Moreover, problems related to water use such as depleting water tables, degradation of groundwater quality, diversion of water resources to various industries, urbanization, etc. are making it obvious to find a sustainable alternative to meet the targeted food grain production. In various arid and semi-arid regions, the lack of good quality water resources has forced the farmers to use substandard quality ground waters (Choudhary *et al* 2011b) to irrigate the fields. The problem with the use of poor quality waters in agriculture lies in the presence of NaHCO_3 and other soluble salts in the water (Minhas and Bajwa 2001) which may produce sodicity in soils in the long run. In Punjab, the drier areas lying in south-western parts are facing the problem of degraded water quality. Therefore, to achieve the goal of feeding a hefty population, judicious management of bicarbonate rich waters is necessary in the areas with the constraint of good quality waters keeping in mind the overall ionic composition of irrigation water sources to save soil health from deterioration.

2.1 Effect of sodicity on plant growth

Increasing food production to support a larger population has picked up momentum worldwide and in lieu of this, bringing degraded soils under cultivation becomes an important consideration. Presence of excess sodium on the exchange sites of clay particles results in

degradation of soil physical properties. The dispersive nature of sodium saturated soils makes the land impermeable to air and water and destroys its structure. As a result, dense, impenetrable surface crusts may form with a compact subsoil layer due to migration of dispersed clay particles. This layer hinders the growth and functioning of roots due to poor water and nutrient uptake thus, affecting the growth of plants (Qadir *et al* 2007; Garg and Malhotra 2008). However, vigorous root growth can play a pivotal role in maintaining adequate tilth below the soil surface (Robbins 1986) which in turn is ensured through enhanced soil physical parameters.

Sodium ions present on exchange complex shoot up the pH of soils above 8.2. High pH does not affect the crop directly but highlights toxicities of some ions and limits the availability of others. At very high pH, the concentration of calcium and magnesium decreases with a concomitant increase in sodium. These ions form insoluble calcium and magnesium carbonates by reaction with soluble carbonate of sodium and other ions and results in their deficiency for plant growth. Symptoms of calcium deficiency are visible as whip-like appearance of young emerging leaves, blackheart in celery, blossom end rot in tomato and pepper (Grattan and Grieve 1999). Accumulation of certain elements in plants at toxic levels may result in plant injury or reduced growth and even death (specific ion effects). Elements more commonly toxic in sodic soils at high pH levels include sodium, molybdenum and boron. Typical sodium toxicity symptoms include leaf burn, scorch and dead tissue along the outside edges of the leaves. Sodium toxicity can be reduced if sufficient calcium is made available through the application of organic and inorganic amendments.

Salt stress leads to reduced osmotic potential in leaves due to the accumulation of Na^+ ions resulting in decreased water availability to various parts of the plant which interferes in normal functioning of different plant mechanisms including photosynthesis. Akhtar *et al* (2015) conducted a pot experiment in biochar amended soils with wheat receiving saline irrigation (control, 25 mM NaCl and 50 mM NaCl) along with respective controls to study the effect of biochar on mitigating salt stress. They observed that salt treatment had a significant negative impact on photosynthetic rate and stomatal conductance in plants. Biochar addition had a positively significant effect on both the parameters in relation to unamended control at both levels of salinity. Likewise, Sheoran *et al* (2021) reported a decrease in photosynthetic rate (P_n) by 15 and 16% and stomatal conductance (g_s) by 16 and 34% in rice and wheat crops, respectively with a parallel increase in RSC_{iw} from 5 to 7 meq L^{-1} . Apart from lowered photosynthetic activity, reduction in relative water content (RWC) and protein content in leaves is also observed even in the tolerant varieties at pH 9.5 (Nehal *et al* 2018). Tolerant varieties have less accumulation of Na^+ and maintain better level of K^+ at higher sodicity levels while reverse is true in case of sensitive varieties. Under salt stress conditions, protein accumulation in plant tissues is observed which is thought to serve the dual purpose of being

a pool of energy and a moderator of osmotic potential in plants (Mansour 2000). Various studies have reported the accumulation of proline in plants facing a range of unfavourable conditions such as water shortage, salt stress, temperature extremes and high light intensity (Aspinall and Paleg 1981; Delauney and Verna 1993; Hare *et al* 1999; Mansour 2000). It shields the protected protein structures against denaturation, interacts with cell membrane phospholipids strengthening cell integrity, scavenges radicals and may serve as an energy and nitrogen source. In many cases, it plays a major role in osmotic adjustment. In plants, proline ranges from 0.5 (unstressed) to 50 (stressed) $\mu\text{mol g}^{-1}$ fresh weight. Ashraf and Harris (2004) reported high content of soluble proteins in salt tolerant cultivars of rice. Several researches have shown a negative correlation between soluble protein content of leaves and salinity response (Agastian *et al* 2000 and Parida *et al* 2002). Grain yield of rice is reduced as a consequence to the sensitivity of rice crop to salt stress (Gao *et al* 2007; Ismail *et al* 2007). At early seedling stage, rice is extremely sensitive to salt stress (Aslam *et al* 1993) and high yield losses are attributed to high seedling mortality and poor crop establishment. Plants exposed to salt stress show de-novo protein synthesis or over expression in the form of increasing the intensity of certain proteins already present in the plant (Singh *et al* 1987). Proteins which accumulate in plants in response to salinity stress act as a storehouse of nitrogen re-utilized in absence of stress (Akbar *et al* 1972; Akbar and Yabuno 1975; Jha and Singh 1997).

2.2 Effect of sodicity on soil properties

Sodicity presents the problem of dispersion of soils which may lead to formation of surface crusts eventually affecting the emergence of seedlings along with waterlogging caused due to reduced infiltration creating anoxic conditions, impeding root growth with hard setting. With soil deterioration the tillage and other land operations become difficult (Oster and Jaywardane 1998). Slaking upon wetting and thereafter translocation of dispersed clay particles was also reported to be the main cause of limiting infiltration of rainfall water (Shainberg and Letey 1984; Oster *et al* 1999; Sumner *et al* 1998). With simultaneous rise of pH, alkali waters prove more deleterious than those with neutral salts. The heavy-textured soils (Surapaneni and Olsson 2002) and those under rice-wheat systems are prone to infiltration problem when irrigated with sodic/alkali waters (Bajwa *et al* 1983; Minhas and Gupta 1992). Although water movement into the soils is concerning, movement of water through the sodic soils affects salt dynamics. Subsurface soils impregnated with moved-in dispersed clays may develop anoxic conditions with reduced ODRs (oxygen diffusion rates), whereas the reduced unsaturated hydraulic conductivity ($K(\theta)$ relations) would impede the water movement in relation to the root water uptake (Minhas *et al* 1994). Moreover, the dispersion and movement of clay lowers the leaching efficiency by holding back the ions in the dead-end pores formed due to clogging of finer pores. Therefore, more often these soils face a rise in pH upon irrigation with sodic waters (Singh *et al* 1992) and with residual

alkalinity (Sharma and Khosla 1984) making them vulnerable to clay dispersion and a sharp decline in infiltration rates.

Being a dispersive agent, Na^+ ion is directly involved in the fragmentation of aggregates in clayey soils (Pernes-Debuysere and Tessier 2004; Bronick and Lal 2005). This problem aggravates the issue of soil degradation as low water stable aggregates become prone to wind and water erosion. At the soil surface, thin and densely packed seal of dispersed soil particles results from the dispersive and beating action of rain drops or flooding on the soils with high ESP which on drying forms hard crusts. Tillage of such soils results in formation of hard clods and seed germination becomes difficult. Thus more farm power is required to bring soil to adequate till to ensure good contact between seeds and the soil for normal seed germination. To maintain soil physical health for a long run, conditions conducive to root and crop growth need to be maintained so that water and air permeability and their further redistribution within the soil is retained.

The negative impact of higher ESP is dependent on hydration and balance between attractive and repulsive forces among clay sized colloids (Quirk 1986; Sumner 1993). Repulsive forces among clay surfaces increase under high ESP. Dispersion occurs when repulsive forces overpower attractive forces resulting in imbibition of water by clay particles and forces the soils to swell. In this way, radius of soil pores is reduced (Abu-Sharar *et al* 1987) and due to narrowing of pores, these soils suffer from restricted air and water movement. Water application to soils at a rate higher than infiltration rate may either infiltrate it or accumulate at the surface leading to problem of waterlogging. Magnesium ions in some sodic soils also poses a threat to structural stability because hydrated Mg^{2+} present in soil solution is larger than hydrated Ca^{2+} , which disrupts linkages within the soil aggregates causing dispersion and breakdown of soil aggregates. Hardsetting is also observed in sodic soils in which soils on drying exhibit a massive, compact and hard surface (Mullins *et al* 1990). An important difference between hardsetting and crusting soils is that in hardsetting condition, complete breakdown of aggregates and structural instability is observed in the entire tilled zone, whereas in crusting, clogging of soil pores and formation of hard crust is limited to the top few millimetres of the soil. All these physical and chemical disturbances in alkali soils also hinder the functioning of microbial communities in the soil. These changes affect the microbial communities and their activities negatively (Rietz and Haynes 2003; Sardinha *et al* 2003; Saviozzi *et al* 2011). The microbial activity is hindered due to high salt concentration as observed by the dehydration and lysis of microbial spores or cells due to osmotic stress. Moreover, microbial functions are restricted in poorly aerated where anaerobic microbes grow at the expense of aerobic microbes. Mavi *et al* (2012) observed increased activity of beneficial microbes and dissolved organic carbon in sodic soil during decreased SOM stability whereas Pathak and Rao (1998) stated that sodicity did not affect C

mineralization. In contrast, Setia *et al* (2011) found that sodicity and CO₂ emission were negatively correlated with poor physical conditions of soils. Similarly, as in non-sodic soils, soil respiration decreased with sodicity which was attributed to blockage of soil pores with dispersed clay particles.

2.3 Role of amendments in reclamation of sodic soils/ sodic-water irrigated soils

2.3.1 Effect of application of inorganic and organic amendments on soil physical properties

In order to sustain crop productivity in sodic soils, exchange of sodium on clay complex with calcium ions from different sources and their successive leaching with irrigation water is necessary. Researchers have worked on various chemicals amendments such as calcite, gypsum, pyrite etc. Among all these chemicals, gypsum is most effectively used to enhance calcium ion concentration on exchange complex replacing sodium ions. Gypsum alone or in conjunction with organic amendments is effective in restoration of sodic soils. The farmers in Punjab use gypsum as the primary source for reclamation of such soils. But application of gypsum at the surface only reduces surface pH and the salts leached get accumulated in the sub-surface soil layers. The constraint in the use of other chemical amendments like pyrite and sulphur is that they need aerobic conditions for providing best results. The efficacy of gypsum application is dependent on optimization of the dose to be applied.

The use of organic material has also proven to enhance the physical, chemical and biological properties of sodic soils. The influence of organic material application on such soils is evident from the enhanced soil physical properties due to the added organic matter upon decomposition of such material on soil aggregation which increases porosity and therefore improves infiltration and conductivity of sodic soils. In addition to this, reduction in soil pH due to the production of CO₂ and organic acids upon decomposition solubilize native CaCO₃ and counter-balance alkalinity (Ansari 2008; Rai *et al* 2010; Rahman and Nath 2013). Organic acids formed during decomposition also lead to dissolution of insoluble compounds and boosts the availability of N, P and K in soils (Bhandari *et al* 1992; Rahman and Nath 2013). Choudhary *et al* (2011a) observed an increase in exchangeable sodium percentage (ESP) and soil pH with the continuous use of sodic water for irrigation. Over a span of 7-9 years, the application of organic manures increased rice and wheat grain yields which were otherwise dormant during the initial years. Interestingly, organic manure addition and ultimately their decomposition helped in mobilization of Ca²⁺ from CaCO₃. The positive effect of organic amendments was confirmed to reduce the requirement of inorganic amendments in controlling the lethal effects of sodic water irrigation on soil properties.

Prolonged use of sodic waters as irrigation affect the water dynamics in the soil and this is evident from reduced hydraulic conductivity in soils receiving them. The main

mechanism working behind this is the swelling of clays constricting pores in clayey soils (Bhardwaj *et al* 2008) and pore blockage due to dispersion and downward movement of clay particles in coarse soils (Shainberg and Letey 1984). Application of organic amendments results in build-up of aggregates in the long run via 2 dominant mechanisms of soil aggregation: (i) a quick top-down aggregate formation (~31 days) in less decomposed organic amendments with low C quality; and (ii) a slow bottom-up formation of aggregate hierarchy (≥ 90 days) in more decomposed high C-quality organic amendments.

Chaganti *et al* (2015) evaluated the amelioration potential of biochar, biosolids co-compost, green waste compost (all applied @ 75 t ha^{-1}) alone or in combination with gypsum (50% soil GR) through a leaching experiment in saline-sodic soil irrigated with moderate SAR irrigation water. The study proposed an increase in aggregate stability by an average of 58, 56 and 61% with the use of biosolids compost, green waste compost and biochar respectively over initial values. Gypsum also showed an increase in aggregate stability by 37% over the initial stability measurements. On the same note, Herath *et al* (2013) explained the increase in aggregate stability on biocharred corn stover applied soils by linking it with the duration of incubation experiment. He suggested the release of microbial exudates which help in coercing soil particles forming macro aggregates. This finding was confirmed upon visualizing fungal hyphae and microbial products within biochar pores under scanning electron microscope (SEM). Moreover, biochar addition results in the reduction of bulk density (BD) which is a result of dilution of mineral matter with the consequent increase in organic matter percentage and improvement in soil porosity and thus, soil aeration (Verheijen *et al* 2019). As BD is reduced upon biochar addition, the soil volume increases and may uniquely influence water storage (Atkinson 2018) and associated soil processes and activities (e.g. microbial activity and nutrient uptake). Verheijen *et al* (2019) showed the effectiveness of biochar in water storage under both sandy and sandy loam soil conditions.

Dao *et al* (2019) conducted a field experiment using gypsum at two different rates (6.8 and 10 t ha^{-1}) to ameliorate soils receiving sodic alkaline industrial wastewater with maize and spinach as experimental crops. They concluded that gypsum treated soils showed reduced pH (below 8) and ESP (below 18%). There was a significant reduction in sodium absorption ratio from 14.0 to 7.9 and an increase in aggregate stability from 44.2 to 51.2%. They also reported an increase in Ca:Mg from 3.5 to 7.8 which helped in restoring the cation balance in soils and showed 80% reduction in Na concentration in plant tissues significantly increasing root length density (RLD).

Ibrahim *et al* (2020), in a pot experiment, showed a significant increase in mean weight diameter (MWD) values of 168% and 184% with the addition of 12 and 24 t ha^{-1} WTR (water treatment residuals) and an increase of 164% and 180% with the addition of 12 and 24 t ha^{-1} RC (rice straw compost) to the soil, respectively. The soil bulk density (BD)

decreased significantly with the addition of WTR or RC as well as mixtures. The BD value of the soil decreased from 1.52 g cm^{-3} in untreated soil to 1.22 g cm^{-3} in the treatment RC 24 t ha^{-1} .

Minhas *et al* (2021) conducted a lysimeter experiment with varying levels of residual sodium carbonate of irrigation water to report a decrease in the proportion of water-stable macro-aggregates (8.0-4.75 mm and 4.75-2.0 mm size) from 0.11 with GQW (good quality water) to 0.093 and 0.07 with AW1 (RSC 5 meq L^{-1}) and AW2 (RSC 10 meq L^{-1}), respectively, while some improvement was observed with the use of amendments as under AW2 + SA (sulphuric acid) and AW2 + Gyp (0.084 and 0.074, respectively). The MWDs (mean weight diameters) under GQW, AW1 and AW2 were 0.76, 0.68 and 0.53 mm respectively, which increased to 0.61-0.68 mm with the use of amendments, though the differences were not significant due to large variation.

Fang *et al* (2021), in an incubation study involving the application of different organic and inorganic amendments on their effect on aggregate stability and mean weight diameters of soil, observed that combined application of organic amendments such as sorghum stubble or sugarcane baggase, gypsum, with or without other nutrients increased the proportion of macro- and meso-aggregates (0.25-6 mm) by 80-110% and micro-aggregates (0.05-0.25 mm) by 10-35%. Moreover, the wet mean weight diameter (MWD) increased from an average of 0.25 mm in control soil to 0.49-1.04 mm after the application of organic amendments. Singh *et al* (2016) concluded that application of gypsum at 50% of GR is highly efficient to restore physic-chemical properties of alkali soils. Yet, gypsum alone cannot improve soil physical and biological properties. Several researches conducted at different levels have also complied with the same verdict. Therefore, shifting to the use of organic amendments in combination seems a sustainable option.

2.3.2 Effect of inorganic and organic amendment application on soil chemical properties in sodic soils

Sodic soils are characterised by the presence of excess sodium in the soils along with anions such as carbonates and bicarbonates. Sodium has a pronounced effect on soil physico-chemical and nutritional properties of soil. These soils have an exchangeable sodium percentage of 15 or above with pH of saturation extract ranging between 8.2 and 10.5 which renders many essential nutrients unavailable. The excess sodium present on clay complexes creates conditions dispersive enough to dissolve organic matter giving these soils a dark colour and thus the name, black alkali soils. One of the options for management of such soils requires the replacement of excess exchangeable sodium with suitable cations like Ca^{2+} which can be provided by the application of chemical amendments such as gypsum, calcium chloride, and iron pyrite etc. or organic amendments like farm yard manure, straw residues, composts, etc. Chaudhary *et al* (2004) reported that the soils irrigated with saline-sodic water

could be ameliorated with gypsum at 50% of GR in two split doses using saline-sodic irrigation water in short time. However, such soils were found to be low in cation exchange capacity ($6\text{-}10\text{ cmol kg}^{-1}$) as considerable amount of Ca^{2+} ions leached down without replacing Na^+ ions.

Yazdanpanah *et al* (2011), in a leaching experiment, observed that application of 50 t ha^{-1} of cattle manure and pistachio residues was more effective than application of gypsum in reducing adverse effects of salts in calcareous saline-sodic soils ($\text{EC}_e = 19.8\text{ dS m}^{-1}$, $\text{SAR} = 32.2$) because the high native calcium carbonate (20.7%) in these soils hampered the dissolution of gypsum considerably. Similarly, Abdel-Fattah (2012) evaluated the efficacy of two types of composts namely water hyacinth compost and rice straw compost on reclamation of clayey saline-sodic soils using leaching columns. They concluded that the organic amendments lowered soil EC, pH and ESP compared with unamended soil with rice straw compost displaying a relatively greater effect on decrease in ESP by 19% vs 6.5% in hyacinth compost.

Tazeh *et al* (2013) concluded that cow manure and compost can be used efficiently in sodic soil remediation without any need of chemical sources. They also proved that on application of these materials the amount of soluble cations first increased and then decreased on leaching. Results showed that the application of manure and compost decreased soil EC by 75% and 65.2% and soil SAR by 44% and 38.9% with respect to initial soil in an incubation experiment conducted for four months with three stages of leaching indicating that saline and sodic soils can be reclaimed without the use of any chemical calcium source. Singh *et al* (2017) also reported a decrease in soil pH from 9.8 to 8.8 and ESP from 78% to 28% on application of compost to sodic soil under rice-wheat cropping system and further noted the build-up of organic C and nutrients. Improvement in bulk density and infiltration was also recorded.

Chaganti *et al* (2015) stated that composts restored soil CEC and pH values apart from recovering soil structure particularly hydraulic conductivity. This positive influence was linked to the facilitation of the divalent cations (Ca^{2+} and Mg^{2+}) by decomposing composts used in the experiment. Moreover, synergistic effect of gypsum and organic amendment application in remediating sodic soil cannot be neglected.

Murtaza *et al* (2017) evaluated the use of gypsum at 100% gypsum requirement, farm manure @ 10 t ha^{-1} and wheat straw mulch @ 10 t ha^{-1} with lysimeter experiment on its various properties. They observed that apart from decreasing pH_s , electrical conductivity (EC_e) of saturation paste and SAR, applied amendments were also effective in salt removal of 3008 , 4965 , and 5048 kg ha^{-1} with leaching fraction of 0.75, 0.77 and 0.78 in loamy sand, silty clay loam, and sandy clay loam soils, respectively.

Singh *et al* (2019) conducted a field experiment with 13 treatments combinations

involving organic (vermicompost, municipal solid waste compost, pressmud and farmyard manure) and inorganic amendments in rice-wheat system under sodic soils. Application of Vermicompost @ 10 t ha⁻¹ + 100%RDN of fertilizers decreased BD, pH, EC, ESP and Na content by 2.0, 4.2, 26.5, 42.8, 56.6%, respectively. Due to significant improvement in soil microbial biomass carbon, nitrogen, and phosphorus and in overall fertility, significant increase in crop growth, growth indices, and grain yields in rice and wheat crops was also recorded. They also recommended the combined use of VC or MSW compost @ 10 t ha⁻¹ in combination with 75% RDN of inorganic fertilizers in restoration of sodic soil properties and improving crop productivity.

Pawar *et al* (2020) concluded that gypsum was more efficient in enhancing soil properties in salt affected soils in comparison to green manuring although both were equally efficient in the same way that of gypsum in terms of crop yield of cotton. Application of gypsum @ 2.5 t ha⁻¹ reduced ESP to low levels and associated high values for soluble cations such as Mg²⁺ (4.72 meq L⁻¹), K⁺ (0.90 meq L⁻¹) and lowest value for sodium (3.10 meq L⁻¹) in saturated paste extract than GM. It was quite evident from this study that gypsum has much faster reclamation rate in soil than organic amendments.

Cation exchange capacity (CEC) is a reliable indicator of soil stability, in conjunction with the organic matter content and the kinds of the exchangeable cation (especially K⁺ and Na⁺) present on exchange complex. Long-term FYM/manure addition has shown an increase in CEC due to the colloidal nature of organic matter. Significant increase in CEC was linked to the availability of nutrients in a balanced and integrated form.

Walker and Bernal (2008) performed a pot experiment with highly saline calcareous clay loam soil under glasshouse conditions concluding that the application of mature compost (40 t ha⁻¹) and poultry manure (50 t ha⁻¹) proved beneficial in increasing CEC as compared to the unamended soils.

Jalali and Ranjbar (2009) observed increased adsorption of cations such as Ca²⁺, Mg²⁺ and K⁺ more than Na⁺ and hence improved CEC upon application of sheep and poultry manure to soils. Moreover, organic amendments when applied with adequate irrigation leads to increased Na⁺ leaching and lower ESP in soils. Application of compost favours aggregation and improves CEC (Luo *et al* 2017) and nutrient retention (Soinne *et al* 2014). The cations such as Ca²⁺, Mg²⁺ and K⁺ are produced during decomposition of compost (Abdel-Fattah 2012). Humic acid, a major component of compost and other functional groups such as carboxyl groups can bind positively charged multivalent ions such as Ca²⁺, Mg²⁺, Fe²⁺ and trace elements, i.e. Cd²⁺ and Pb²⁺ (Pedra *et al* 2008).

Chaganti and Crohn (2015) through a leaching experiment showed that application of greenwaste and biosolids compost to saline-sodic soils increased the cation exchange capacities by 19 and 23% respectively, relative to the control soils after leaching. Post

leaching CEC's were also higher for biosolids and greenwaste compost by 25 and 21% respectively, when compared to their initial soil CEC's. The increase in CEC on compost addition is attributed to the higher exchange capacity of these amendments. Other studies have also reported significantly higher soil CEC when organic amendments such as composts were incorporated into soils (Aggelides and Londra 2000; Bulluck *et al* 2002).

Jat and Singh (2017) concluded from their results that the CEC of the soil increased significantly due to the application of organic manures in combination with chemical fertilizers. However, some researchers have also shown the negative effects of the application of such composts. Some of these have proved that the integrated use of inorganic and organic amendments improves the conditions of sodic soils effectively and sustainably in the long run.

Murtaza *et al* (2019) conducted a pot experiment assessing the effects of application of farm yard manure (FYM), municipal solid waste (MSW) composts and gypsum application on various soil properties and crop yield under rice-wheat system. They observed a dip in soil pH (6.95% and 8.77%), electrical conductivity (EC) (48.13% and 51.04%), and sodium adsorption ratio (SAR) (40.27% and 45.98%) with an-aerobically decomposed MSW compost during rice and wheat, respectively. With the application of MSW compost, organic matter (OM) (93.55% and 121.51%) and cation exchange capacity (CEC) (19.31% and 31.79%) were the highest as compared with control treatment during rice and wheat, respectively. Further, the study suggested that MSW compost can be an effective solution for waste disposal, thence in improving chemical properties of soil and crop productivity from saline sodic soils.

Nguyen *et al* (2018) studied the interactive effects of biochar (rice-husk and rice-straw) and cow manure on properties of salt affected soils and rice growth. They observed that addition of biochar increased CEC significantly over control. The CEC with the application of rice-husk ($29.0 \text{ cmol}_c \text{ kg}^{-1}$) and rice-straw ($28.8 \text{ cmol}_c \text{ kg}^{-1}$) was significantly higher than no-biochar treatment ($25.6 \text{ cmol}_c \text{ kg}^{-1}$). Moreover, the aboveground biomass increased by $0.79 \text{ g dry matter pot}^{-1}$ for every one cmol_c of CEC. Furthermore, biochar addition improved soil available P concentration, exchangeable K, especially the concentration of EC_cNa due to enhanced adsorption of flocculating ions on exchange complex which can possibly account for the increased rice growth. However, the study did not report a reduction in exchangeable Na concentration in soils upon the addition of biochar and manure. Therefore, as the reason explaining reduced exchangeable Na^+ ions in soil after addition of amendments is not clear and needs further study. Kim *et al* (2016) provided with a possible explanation which made total negative surface charges from the amendments to be responsible for increase in exchangeable Na and thus its concentration in soil solution. If this was to be the case then it may be concluded that the application rate of biochar used in the

study was not sufficiently high to provide for the appropriate amount of total negative surfaces which would hold the exchangeable Na^+ in soil by adsorption. This mechanism needs further insight for clarity of thoughts.

Biochar has proven to be effective in remediation of acidic and saline-sodic soils. However, its restorative potential in soils supplied with sodic water irrigation is unclear. Biochar application has been proven to affect the exchangeable Na concentration in two contrasting ways. On the positive side, Wu *et al* (2014), on the basis of a four month incubation experiment, indicated that biochar addition reduced soil ESP significantly. Similarly, Sappor *et al* (2017) also reported a reduction in amount of exchangeable Na ions as a result of saw-dust biochar addition. On the negative side, Chan *et al* (2007) found a positive correlation between exchangeable Na^+ ions and biochar application rates. In contrast to it, Sappor *et al* (2017) reported non-significant effect of biochar on soil exchangeable Na^+ concentration as compared to the control.

Schultz *et al* (2017) have proven consistent results of biochar addition on soil physico-chemical properties and respiration. Schultz *et al* (2017); Lentz and Ippolito (2012) observed that soil pH was negligibly affected upon biochar application to calcareous soils. However, Chaganti *et al* (2015) working on composts and biochar stated that former recovered soil CEC and pH values but the latter could not. Both the amendments were efficient in contributing flocculating cations (Ca^{2+} and Mg^{2+}) to the soil that hastened the Na^+ - Ca^{2+} exchange reaction on clay complex. Haefele *et al* (2011) suggested that the effectiveness of rice straw biochar application on soil fertility and crop yield is dependent on site-specific conditions. On the positive side, OC content increased from application of the biochar which indicated the high stability of organic carbon in biochar. High OC in soils amended with biochar were also reported by (Novak *et al* 2009; Abebe *et al* 2012; Mukherjee and Lal 2013). This increased availability of OC in sodic soils ensures restoration of degraded soil structure. Besides this, use of biochar as an organic amendment has been proven to effectively improve soil physical and chemical properties in previous studies regarding non-salt affected soils (Gwenzi *et al* 2016; Singh and Mavi 2018). Likewise, Bhullar *et al* (2019), in agreement with Lashari *et al* (2013), demonstrated the decrease in soil pH and exchangeable Na^+ ions which was ascribed to adsorption of Na^+ on negative surfaces of functional groups in the biochar (Mukherjee *et al* 2019). Consequently, incubation experiments with biochar confirm the release of soluble salts (Ca^{2+} , Mg^{2+} , K^+) that may have led to recuperation of sodic soils by increasing structural stability with the formation of cross-linked organic polymers making them resistant to microbial attack (Oades 1988). Yu *et al* (2010) reported increased EC due to the availability of carbonates of Mg^{2+} and Ca^{2+} with variable amounts of other impurities. It has been proven that pH and SAR values in biochar amended soils improve but this improvement is non-significant. Therefore, it cannot be concluded that biochar plays a major

role in alleviating the sodicity stress.

2.3.3 Effect of application of inorganic and organic amendments on soil biological properties in sodic soils

Microorganisms are of prime importance considering their role in soil organic matter mineralization and cycling of nutrients. Managing many biochemical processes, the microbial communities help stabilize agro-ecosystem functioning and thus regulate crop productivity. It is well established that organic material addition to salt-affected soils enhances structural stability and water infiltration (Wang *et al* 2014), improve WHC, aggregate stability (Makoi and Ndakidemi 2007; Yazdanpanah, Mahmoodabadi, and Cerdà 2016), soil microbial biomass, and enzymatic activities (Chahal *et al* 2017). Microbial biomass carbon (MBC) forms an important component of soil organic matter comprising 1-3% of total organic carbon (Jenkinson and Ladd 1981; Nieder *et al* 2008). This form of carbon has a rapid turnover rate which makes it a suitable indicator of changes in biological conditions caused by soil management practices.

Kaur *et al* (2008) proposed that long-term irrigation with SW significantly decreased MBC compared to CW irrigation. The decline in MBC can be attributed to decrease in microbial populations and their activity under increase in ESP and pH and degradation of physical quality of the soil. Significantly higher values of MBC (105-156 mg kg⁻¹) were recorded when organic manures were added to the soils compared to the unamended control (49 mg kg⁻¹). The order of the increase followed the trend of green manure > farm yard manure > wheat straw. Moreover, application of organic manures as amendments resulted in increase in soil organic carbon content with the maximum increase in farm yard manure (0.71%) followed by green manure (0.51%). Organic amendments led to an increase in organic carbon content by 68% compared to the unamended plots. The corresponding increase in plots applied with green manure and wheat straw was 21 and 19% respectively.

Choudhary *et al* (2013) studied the effect of application of sodic water amended with gypsum with or without the use of organic amendments including farmyard manure (FYM), green manure (GM) and wheat straw (WS) through a 14-year long-term experiment with rice-wheat system. They observed that long-term irrigation with sodic water (SW) significantly reduced microbial biomass carbon in plots treated with or without amendments as compared to control (canal water irrigation). The application of organic amendments showed increase in MBC values which presented the following order of increase: GM > FYM > WS.

Shirale *et al* (2018) recorded maximum improvement in dehydrogenase activity (DHA) (90.79 and 90.79 µg g⁻¹) and SMBC (soil microbial biomass carbon) (174.97 and 171.29 mg C kg⁻¹) for dhaincha and sunhemp as compared to gypsum (48.93 µg g⁻¹ and 119.19 mg C kg⁻¹). The increase in DHA and SMBC was linked to a reduction in pH and ESP of soil in relation to the addition of organic matter (Kaur *et al* 2008; Wong *et al* 2009;

Choudhary *et al* 2011a). The potential of different organic amendments in improving biological properties of soils followed the sequence as dhaincha> sunhemp> Leucaena loppings> cowpea> green gram> composted cotton stalk> biomulch> gypsum. The potential was attributed to the ease of availability of carbonaceous materials and substrates such as sugar, amino acids, and organic acids to soil from the decomposing organic materials and decay of roots under the plant canopy, which are important source of energy for the microbial population.

Bhullar *et al* (2019), through an incubation study, examined a decrease in MBC concentration in sodic soil, decrease being higher in SAR20 (32%) and SAR30 (13%) than non-sodic soil at the end of incubation. A positive linear relation of MBC was observed with the increase in rate of biochar addition in all soils. Increasing the rate of biochar application favours microbial activity by providing the microbes with labile organic compounds (Singh and Cowie 2014). On 56th day of incubation, they observed that compared with unamended non-sodic soil, biochar addition at 2% increased MBC concentration by 20% at SAR30, but it remained lower by only 6% at SAR20 (from 32% in unamended sodic soil). Further, application of biochar to soil at different rates (1-4%) significantly reduced pH (0.06-0.21 units) and SAR (0.14-2.23 units) at SAR20 and by 0.10-0.27 units (pH) and 0.45-2.50 units (SAR) at SAR30, respectively. Moreover, across all soils, EC values increased with increasing rates of biochar application. At the end of incubation, biochar application (1-4%) increased EC values by 0.81-3.09 units in non-sodic, 0.98-3.37 units at SAR 20 and 0.95-4.87 units at SAR30 soil, respectively. Lin *et al* (2012) confirmed experimentally that biochar addition can momentarily increase the amount of loosely connected low molecular weight humic acids in the soil formed by coupling of lignin and cellulose fibres during pyrolysis. With time this fraction of C is utilized by microbes and only stable C persists in the soil (Jin 2010). In addition to this, Luo *et al* (2016) concluded that micro-aggregates within the biochar protect and stabilize the DOC and nutrients to support microbial growth. This marks the utility of biochar as a source of long-term C sequestration in the degraded soils. Rather, slow availability of recalcitrant substances from biochar acts as a substrate to the microbial community to reverse the negative effects of high salt stress.

Basak *et al* (2021) proposed that gypsum and pressmud (Gyp or PM) applied either alone or in conjunction with each other (Gyp+PM) decreased soil pH, ESP and BD than control. Furthermore, they were effective in increasing MBC by 67% in Gyp+PM to 71% in PM treatments in comparison to unamended control. Moreover, Gypsum supplying soluble Ca²⁺ and Gyp+PM mobilizing native CaCO₃ improved total organic carbon (TOC; 32 and 64%) over unamended soils.

2.3.4 Role of amendment application on physiological parameters, crop yield and uptake of ions

Studies in plants under stress conditions have shown the accumulation of reactive oxygen species (ROS) and salts in leaf cells affecting its basic functions like photosynthesis, cell turgidity and various metabolic pathways (Gill and Tuteja, 2010; L'aucli and Grattan, 2012). Such structural and functional changes hamper uptake of water and nutrients by plants due to permeability of plasma membrane and ion leakage. Salt tolerant varieties are better adapted to stress conditions as they are capable of accumulating osmolytes, maintaining integrity of chloroplasts in the leaves and ability to exclude Na^+ ions while building affinity for accumulation of K^+ ions helping in maintaining the water balance equilibrium and osmoticum (higher RWC). These varieties are equipped to protect the cells from radical damage (lower MII), maintain gaseous exchange (higher photosynthetic rate, Pn ; stomatal conductance, gS and transpiration rate, E) and reduced Na/K ratio in shoot and root with increasing induced salt stress through high RSC_{iw} (Rhodes *et al* 2002; Perez-Lopez *et al* 2009; Atiq-ur-Rahman *et al* 2014; El-Hendawy *et al* 2017; Mann *et al* 2019).

Niamat *et al* (2019) compared the potential of Ca-based fertilizer industry waste (Ca-FW) and Ca-fortified compost (Ca-FC) to increase growth and yield of maize under saline-sodic conditions. They observed that individual application of compost increased Pn by 19%, 11% and 6% at EC levels of 1.6, 5, and 10 dS m^{-1} with respect to control, respectively. The maximum increase in Pn was recorded with the application of Ca-FC by 67%, 43% and 35% at EC levels of 1.6, 5 and 10 dS m^{-1} as compared to control, respectively. Likewise, the maximum increase in gS was observed with the application of Ca-FC by 56.16%, 42.39% and 34.11% at EC levels of 1.6, 5 and 10 dS m^{-1} with respect to control, respectively.

Sheoran *et al* (2021) marked an improvement in physiological traits of rice and wheat crops with the use of gypsum and pressmud in soils irrigated with high RSC irrigation water through significant improvement in their relative water content (RWC) by 6 and 10%; photosynthetic efficiency (Pn) by 40 and 36%; stomatal conductance (gS) by 46 and 52% and transpiration rate (E) by 72 and 45% along with lowered Na^+/K^+ ratio in shoot (NaK_S ; 37 and 45%) and root (NaK_R); 41 and 46%) in comparison to the control. Also, combined application of gypsum and pressmud produced highest yield in rice (3.42 t ha^{-1}) and wheat (4.30 t ha^{-1}) with nearly 25% yield advantage over unamended control. This increase was attributed to enhanced availability of essential macronutrients like Ca and Mg following application of amendments.

Potassium plays a major role in maintaining osmotic balance in various tissues in plants cells controlling cell expansion and turgor-related motions. It is key transporter of water and nutrients in plants. By being involved in regulation of opening and closing of stomata, it balances processes like photosynthesis and protein synthesis. Since it is essential

for root growth, it provides drought tolerance of plants. Potassium is taken up as K^+ ions and its concentration in plant tissues varies from 1 to 5%. Plants lacking in potassium often face a reduced supply of NO_3^- , Ca^{2+} , Mg^{2+} and amino acids. Being a competitor to sodium, its content in plants decreases with increase in ESP of soils. Sodium present in excess amounts in growth medium reduces the uptake of K^+ under the dominance of CO_3^{2-} and HCO_3^- ions in sodic soils and Cl^- and SO_4^{2-} in saline soils (Mor and Manchanda 1992; Qadar and Zake 2007). Calcium is another macronutrient important in the growth of meristematic tissues and functioning of root tips. There are a wide array of factors affecting the uptake of Ca^{2+} by crop plants, some of which include, concentration of soluble Ca^{2+} , soil pH, Ca:Na ratio, ions interactions, precipitation in sodic soils and crop species (Marschner 1995; Fageria *et al* 1997). Increase in pH decreases the solubility of inherent $CaCO_3$ rendering Ca insufficiently available to fulfil the plant needs. Furthermore, Na has a negative relation to Ca absorption by plants. But in highly sodic soils, and in sensitive crops, accumulation of toxic levels of Na in plant tissues is chiefly responsible for poor plant growth and low yields. All these factors reduce the activity of Ca^{2+} in solution thereby decreasing Ca^{2+} availability to plants (Cramer *et al* 1986; Grattan and Grieve 1999).

Jin *et al* (2018) conducted a pot experiment to evaluate the effects of biochar application at different rates (NK-control, T1-15g, T2-30g and T3-45g biochar) on sodium ion accumulation, yield and quality of rice in saline-sodic soil. The results pointed at significant decrease in sodium accumulation in rice plant parts, increased rice dry biomass, grain yield and improved rice quality. The accumulation of sodium in different plant parts was significantly different from control but insignificant among the biochar levels inferring that the application of biochar application reduces sodium uptake by rice plants. The results were in tune with the findings of Chaganti and Crohn (2015). The reduced uptake of sodium under biochar application was attributed to temporary binding of sodium ions on exchange sites of biochar due to its high adsorption capacity and due to the release of nutrients into the soil solution (Akhtar *et al* 2015; Melas *et al* 2017).

He *et al* (2020) observed that application of biochar at 2.0 and 2.5% reduced Na^+ concentration though not significantly over control in the leaf sap of *Miscanthus*. On the other hand, the concentration of K^+ in the cell sap showed significant increase, which significantly uplifted K^+/Na^+ ratio in biochar treatments relative to the control. They concluded that Na^+ uptake decreases with the application of biochar, while simultaneously increasing K^+ absorption and translocation in *Miscanthus* plants in the saline-alkali soil. Similarly, Cao *et al* (2019) reported an increase in Na^+ but decrease of K^+ and Ca^{2+} in the plant tissues, which led to reduction in both K^+/Na^+ and Ca^{2+}/Na^+ ratios compared to control. C (control) and G (FGD gypsum) treatments alone overrode the negative effects of salt stress in the chosen plants.

Mali *et al* (2020) performed a field experiment at Bihar to analyse the effect of

treatments T1-control, T2-Gypsum @ 100%GR, T3-Gypsum @ 50%GR + Biocompost @ 2.5 t ha⁻¹ and T4-Biocompost @5 t ha⁻¹ on the uptake of macronutrients in ten genotypes of rice in sub plots under sodic soils. They reported higher uptake of N, P and K in straw samples of CSR 36 followed by CSR 27 and CR 3884-244-8-5-6-1-1 when gypsum was applied at 50%GR and biocompost @2.5 t ha⁻¹.

Ashraf *et al* (2017) reported decrease in soil EC by 54%, SAR by 43% and shoot Na⁺ by 57% with conjunctive increase in soil organic matter by 166%, shoot K⁺ by 360% , photosynthetic rate by 102% compared to saline-sodic water irrigation without K and/or FYM. Sunflower was chosen as the test crop receiving saline-sodic water irrigation treated with potassium @ 100 and 200 mg kg⁻¹ K₂O soil) and farm yard manure @ 5 and 10% of soil, w/w). Also, lowest proline content of 4.4 µmol g⁻¹ FW found in the control was found to increase by 86.3% with saline-sodic water irrigation without any amendment. When K and FYM were applied with SSW irrigation, proline content decreased by 29.2% with K100, 20.7% with FYM-1 (5% FYM of soil, w/w) and 25.6% with FYM-2 (10% FYM of soil, w/w) compared with the SSW irrigation without any amendment.

Many studies have observed decline in yield and related growth parameters such as plant height, number of tillers, test weight etc. in various crops grown under salt stressed conditions. In one such study, Phogat *et al* (2010) observed the decrease in yield of potato, tomato, brinjal and cluster bean grown in sequence on sandy loam soil when irrigated with alkali water (RSC 11.6 meq L⁻¹; SAR 14.0) in a long term experiment. The average yield of 3 years was found to be 13.41, 1.65, 0.30 and 0.06 Mg ha⁻¹ which improved to 21.0, 23.6, 16.7 and 9.6 Mg ha⁻¹, respectively with the application of gypsum @ 50%GR and further to 21.3, 31.6, 22.9 and 10.5 Mg ha⁻¹ with gypsum applied at 100%GR.

Choudhary *et al* (2011b), in a long term experiment, monitored the effects of farm yard manure and green manuring on soil properties and crop yields in sodic water irrigated soils. Yield of rice and wheat crop increased by 38% and 26% with FYM, respectively over those receiving sodic water without amendment application (RSC 10 and 12.5 meq L⁻¹). The corresponding increase with gypsum application @ 50%GR was 18% and 19%. Likewise, green manure and wheat straw application resulted in 22% and 17% higher yields in rice whereas the impact was similar on wheat (20%).

Rasouli *et al* (2013) conducted a field experiment with two sizes of gypsum granules (1-10mm and < 1mm) applied either through mixing with irrigation water or added to the soil at three different level of neutralisation of RSC i.e. 50, 75 and 100% GR. The total biomass of wheat crop was 5970 kg ha⁻¹ at 50%GR, 6830 kg ha⁻¹ and 7080 kg ha⁻¹ at 75 and 100% GR with fine gypsum application; 6590, 7370, and 7710 kg ha⁻¹ at the corresponding levels of 50, 75 and 100 % GR in coarse gypsum applied soils respectively. The increase was significant for each level of gypsum applied. Moreover, gypsum application increased Ca:Na in wheat

leaf tissue from 0.18 in SW plots to 1.21 in F50 and C50. It further increased to 2.47 and 2.75 in F100 and C100.

Murtaza *et al* (2015) proposed that a coarse-textured salt-affected soil can be restored with the use of saline-sodic water (EC 3.94 dS m⁻¹ SAR 18.2) in conjunction with gypsum. The improvement in grain yield of wheat was observed by 9%, 42% and 75% when gypsum was applied at 50 and 100%GR and to neutralise 100% RSC of irrigation water, respectively.

Singh *et al* (2016) observed an improvement in all growth parameters (plant height, numbers of tillers, dry matter accumulation, number of leaves/hill, leaf weight/hill and leaf area index), yield parameters and yield with increasing dose of gypsum (control, 15, 25 and 50% GR) in a field experiment on highly sodic (pH 10.5, ESP 89.0%) loamy soil. The increase in plant height was 50.3, 58.1 and 67.8 % at 15, 25 and 50 % GR doses as compared with control, respectively. Moreover, significant increase in dry matter accumulation (61.8g/hill) was observed at 50% GR at harvest of crop though the results were at par with that of 25% GR.

In the bigger picture, chemical and organic amendments work effectively alone as well as in synergism with each other in non-salt affected soils but further studies are still needed to understand the effectiveness of these amendments under present cropping sequences in Punjab irrigated with sub-standard quality waters or groundwater contaminated with excessive salts. The study will help us evaluate the pros and cons of application of different amendments under sodic water irrigation and their potential to restore the properties of soils irrigated with such waters. Furthermore, the best suited chemical or organic amendments could be recommended to farmers who have no choice but to put the poor quality irrigation water to use.

CHAPTER III

MATERIALS AND METHODS

The methodology for the present investigation has been discussed under the following headings:

3.1 Preparation of experimental soil

3.2 Experiment details

3.3 Observations recorded

3.4 Statistical analysis

3.1 Preparation of experimental soil

Two bulk soil samples (loamy sand and sandy clay loam) from the surface layer (0-15 cm) were collected from two different sites at the research farm of Punjab Agricultural University, Ludhiana (30°56'N, 75°52'E), India. Soil samples were collected from 4 spots within the plots using a shovel, and collected sub-samples were mixed thoroughly to make a composite sample. The soil samples were air dried and sieved through 2 mm sieve and stored at room temperature before the start of pot experiment. The properties of experimental soils are enlisted in Table 3.1.

Table 3.1 Properties of the experimental soils

Properties	Loamy sand	Sandy clay loam
% Sand	78	56
% Silt	8	23
% Clay	14	21
Bulk density (Mg m^{-3})	1.57	1.50
pH _(1:2)	7.5	7.7
EC _(1:2) (dS m^{-1})	0.231	0.380
Total C (g kg^{-1})	1.5	6.3
CEC (cmol kg^{-1})	3.8	6.9
Oxidizable Organic C (g kg^{-1})	1.6	3.2
Sodium adsorption ratio	2.5	3.2
Exchangeable sodium percentage	3.3	2.2
CaCO ₃ (%)	2.28	1.93

3.2 Experiment details

3.2.1 Experiment No. 1

To compare the effects of chemical (grey gypsum and yellow gypsum) and organic amendments (farm yard manure, rice straw, rice straw compost and biochar) on ionic composition and dry matter yield in rice-wheat system under sodic water irrigation.

3.2.1.1 Treatment details

1. **Soil texture:** Loamy sand (ls) and sandy clay loam (scl) soil

2. **RSC levels:** 0 (control), 5, 7.5 and 10 meq L⁻¹

3. Amendments

- Control
- Farm yard manure (FYM) - 15 t ha⁻¹
- Rice straw (RS) - 6 t ha⁻¹
- Rice straw compost - 6 t ha⁻¹
- Biochar (BC) - 4 t ha⁻¹
- Yellow gypsum (YG) @ 50%GR
- Grey gypsum (GG) @ 50%GR

Treatments: 2×4×7×3 = 168

The experimental soil was treated with 3 types of sodic water having residual sodium carbonate (RSC) of 5, 7.5, 10 meq L⁻¹ and one non-sodic good quality water (RSC 0). Three levels of RSC (5, 7.5 and 10 meq L⁻¹) in irrigation water were created by dissolving 0.42, 0.63 and 0.84 g of NaHCO₃ per litre in good quality water, respectively. Experimental soil was divided into 6 different heaps (2 quintal each according to levels of RSC of irrigation water and texture of soil) and irrigated with 30 litres of respective sodic water. Soils were tested after each irrigation for pH, SAR and ESP and irrigated 5-6 times in total to achieve the desired SAR and ESP values (control amendment). Pots were then filled with the respective treated soils and various organic amendments were applied once 15 days before the start of experiment. Chemical amendments (yellow and grey gypsum) were applied on soil test basis @ 50% GR at the start of the experiment and later applied with each irrigation to neutralize the sodicity of the water applied. The properties of the applied organic amendments and both types of gypsum are given in Table 3.2 and 3.3.

Table 3.2 Properties of organic amendments used in the study

Property	Farm yard manure (FYM)	Rice straw (RS)	Rice straw compost	Biochar (BC)
pH _(1:5)	7.9	7.6	7.8	9.0
EC _(1:5) (dS m ⁻¹)	4.8	3.6	5.0	12.2
Total Carbon (g kg ⁻¹)	280.0	380.5	390.0	420.0
Total Nitrogen (g kg ⁻¹)	11.0	3.6	5.8	10.0
Total Phosphorus (g kg ⁻¹)	6.0	1.4	4.2	7.0
Total Potassium (g kg ⁻¹)	19.0	12.0	25.2	22.0
Total Calcium (g kg ⁻¹)	3.0	3.5	7.5	4.0
Total Magnesium (g kg ⁻¹)	3.2	2.0	4.0	2.5
Total Sodium (g kg ⁻¹)	5.4	4.4	1.2	1.6

Table 3.3 Properties of grey and yellow gypsum used in the study

Composition	Units	Grey gypsum	Yellow gypsum
CaSO ₄	%	60-70	80-90
Ca		16	21
K		0.17	0.04
Mg		0.70	0.67
S		18.6	23.5
Fe		1.41	6.67
Zn	mg kg ⁻¹	222.2	3252.4
Mn		365.52	829.27
Cu		17.93	28.80
Pb		24.64	32.49
Ni		16.06	30.07
As		4.18	2.27
Cd		0.38	0.86
Cr		38.30	205.56

3.2.2 Pot Experiment

The pot experiment was conducted at screen house of the Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab during *Rabi* (wheat) and *Kharif* (rice) season.

3.2.2.1 Treatments and fertilizer application

Plastic pots of 12'' diameter and 12'' height were filled with seven kg of treated soil passed through 2 mm sieve. The organic amendments were applied at recommended rates (FYM @15 t ha⁻¹, RS @6 t ha⁻¹, Rice straw compost @6 t ha⁻¹ and BC @4 t ha⁻¹) by mixing it into the soil before the start of the experiment whereas gypsums were applied on soil test basis at the start of experiment and later with each respective sodic water irrigation. Each treatment was replicated three times and arranged in CRD (Completely Randomized Design) on a raised platform in the greenhouse. The pots were watered regularly with water of designated RSC levels as per the crop requirements and depending on the prevailing weather conditions. Ten seeds of wheat (*Triticum aestivum*), cultivar *Unnat* PBW 343 were sown in 168 pots on 28th November 2020. Later, 15 days after sowing, seedlings were thinned to five-six plants per pot. After wheat harvest, five-six plants of rice (*Oryza sativa*) (PR 126) were transplanted in the same pots with standing water on 15th June, 2021. Both the crops were harvested after 2 months for biomass. Both the crops were protected from effect of direct rain by using polythene sheets. Fertilizers were applied for rice and wheat crops as per the

recommendations of Punjab Agricultural University (PAU), Ludhiana. All fertilizers were applied after dissolving in water.

3.2.2.2 Harvesting, collection and processing of shoot samples

After harvest of each crop, the plant shoots were harvested with a stainless-steel blade just one centimetre above ground level. Later, the samples were air-dried and then kept in paper bags and placed at 60°C in oven for drying. The shoot samples were first weighed for dry matter yield and then analyzed for mineral ions such as Ca, Mg, Na and K. These samples were digested in 3:1 (HNO₃: HClO₄) di-acid mixture after proper washing and then drying in oven. Samples were placed overnight for proper decomposition of plant material and then digested on a hot plate. After making volume these samples were analyzed for Na and K on flame photometer and Ca and Mg through titration.

3.2.2.3 Post harvest soil sampling

After harvest of both the crops, composite soil samples from each pot were taken with stainless steel tube auger. The collected soil samples were air dried in shade, sieved through 2 mm sieve and analyzed.

3.3 Observations recorded

Photosynthetic rate, stomatal conductance and plant height were measured before the harvest of the crop and dry biomass was recorded after drying the samples to constant weight at 60°C.

The following observations were recorded for soil samples after harvest of both wheat and rice crops in the experiment.

3.3.1 Soil pH

The soil pH was determined using a 1:2 soil-water suspensions using a glass electrode pH meter (Jackson 1973).

3.3.2 Soil EC

The electrical conductivity of the samples was determined in 1:2 soil: water supernatant solution equilibrated for 24 hours using conductivity meter (Richards 1954).

3.3.3 Organic carbon

Organic carbon of the soil was determined by Walkley and Black's rapid titration method (Walkley and Black 1934).

3.3.4 Cation exchange capacity

Soil samples were saturated by 1N sodium acetate, and then washed with alcohol to get rid of water soluble Na fraction. Then soil samples were equilibrated with 1N ammonium acetate to bring back Na in the solution from exchange complex. The sodium so obtained is measured for CEC by the method outlined in USDA Handbook No. 60 (Richards 1954).

3.3.5 Exchangeable sodium percentage (ESP)

It was calculated as (exchangeable sodium/cation exchange capacity) ×100

3.3.6 Calcium and magnesium in soil solution

The $\text{Ca}^{2+} + \text{Mg}^{2+}$ in soil solution was determined by versenate (disodium dihydrogen ethylene diamine tetra acetic acid) method (Richards 1954).

3.3.7 Sodium in soil solution

The soil samples were extracted with water (1:2 soil water ratio) after shaking for 1 hour and subsequent centrifugation (2000 rpm for 20 minutes) suspension was filtered and filtrate was analyzed for water soluble Na by flame photometer (Richards 1954).

3.3.8 Sodium adsorption ratio

It is calculated as $\text{Na}^+ / (\text{Ca}^{2+} + \text{Mg}^{2+} / 2)^{1/2}$, all ions in meq L^{-1} .

3.3.9 Exchangeable cations ($\text{Ca}^{2+} + \text{Mg}^{2+}$, Na^+ , K^+)

Exchangeable cations were measured by giving repeated washings with neutral normal solution of ammonium acetate with final volume 100 ml. Cations such as Na^+ and K^+ were determined on flame photometer whereas Ca^{2+} and Mg^{2+} in soil solution was determined by versenate (disodium dihydrogen ethylene diamine tetra acetic acid) method.

3.3.10 Soluble CO_3^{2-} , HCO_3^- and Cl^-

The soil samples were extracted with water (1:2 soil:water suspension) after shaking for 1 hour and subsequent centrifugation (2000 rpm for 20 minutes) suspension was filtered. The filtrate was analysed for carbonates and bicarbonates by titrating a known volume of soil solution against standard 0.1N sulphuric acid using phenolphthalein and methyl red as indicators. Chlorides were determined by titrating a known volume against standard 0.025N silver nitrate solution using potassium chromate as indicator.

3.3.11 Sulphates

The soil samples were extracted with 0.15% calcium chloride solution (1:5 soil: CaCl_2 solution) and filtered after shaking for half an hour. The filtrate was treated with barium chloride in the presence of gum acacia solution. The turbidity produced due to precipitation of sulphate as barium sulphate was measured with colorimeter at 420 nm.

3.3.12 Bulk density

The soil samples for determination of soil bulk density were taken out in undisturbed metallic core with a known volume. The dry weight of soil was recorded after drying it at 105°C for 24 hrs.

$$\text{Bulk density of soil (Mg m}^{-3}\text{)} = W/V$$

Where W = dry wt. of soil (g); V = Volume (g cc^{-1}) of metallic core with internal diameter 5.5 cm and height of 4 cm

3.3.13 Aggregate stability

Aggregate stability was measured by wet sieving method (Yoder 1936).

3.3.14 Proline

Proline was determined by acid ninhydrin method as described by Bates *et al* (1973).

3.3.15 Uptake of sodium, potassium, calcium and magnesium

Uptake of nutrients (g pot^{-1}) = nutrient concentration (%) * dry biomass yield (g pot^{-1})/100

3.3.16 Microbial biomass carbon

Microbial biomass carbon (MBC) was determined by the fumigation-extraction method (Vance *et al* 1987).

3.3.16.1 Fumigation

Two sets of moist incubated soil containing 5 g soil (60% water holding capacity) from each treatment were taken and one set was extracted immediately with 20 ml of 0.5 M K_2SO_4 which served as control (unfumigated). The other set was fumigated in a desiccator containing about 25 ml ethanol free chloroform in a small beaker. The desiccators were evacuated until chloroform has boiled for 2 minutes and placed in dark at 25°C. After 24hr, beaker of chloroform was removed and residual chloroform vapours in soil removed by repeated evacuation before extraction.

3.3.16.2 Extraction

For extraction, soil was transferred to a 100 ml plastic bottle, 20 ml of 0.5 M K_2SO_4 added and the bottles were shaken on an oscillating shaker for 30 min. and the suspension was filtered through Whatman No. 42. To the filtrate (4 ml), add 66.7 mM $\text{K}_2\text{Cr}_2\text{O}_7$ (1 ml) and 5 ml conc. H_2SO_4 . The mixture was allowed to cool and diluted with 20 ml distilled water added through the condenser as a rinse. The excess dichromate was determined by back titration with ferrous ammonium sulphate (33.3 mM) in 0.4 M H_2SO_4 using few drops of o-phenanthroline monohydrate indicator.

After titration, extractable C was calculated assuming that 1 ml of 66.6 mM $\text{K}_2\text{Cr}_2\text{O}_7$ is equivalent to 1200 microgram C and biomass C from relationship:

$$\text{Biomass} = 2.64 \text{ Ec}$$

Ec is the difference between C extracted from fumigated and non-fumigated soil.

3.4 Statistical analysis

The experimental data was analysed using two-way (RSC levels x amendments) analysis of variance (ANOVA) with Genstat v12.0. The Duncan Multiple Range test (DMRT) was used to determine significant differences at 5% level of significance.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Effect of application of various chemical and organic amendments on soil properties and plant parameters

4.1.1 Wheat crop

4.1.2 Rice crop

4.1.1 Wheat crop

4.1.1.1. Biomass yield

The effect of sodic-water irrigation and application of various amendments on above ground biomass in loamy sand and sandy clay loam soil is depicted in Figure 4.1. The biomass yield decreased with increase in sodicity of irrigation water. The magnitude of decrease, irrespective of amendments, was significantly higher in sandy clay loam soil (scl, 13.1 and 34.7%) than loamy sand soil (ls, 4.7 and 13.3%) at RSC 5 and 7.5 level of sodic water irrigation, respectively compared with RSC 0. It occurred due to more retention of sodium ions in soil solution and thus, higher SAR and ESP values in scl. Among the amendments, application of both types of gypsum increased the biomass yield significantly over the respective controls for RSC 5 and 7.5 levels of sodic-water irrigation which was at par with farm yard manure (FYM) and rice straw compost application in both the soils. Rasouli *et al* (2013), in a field experiment reported that grain yield of wheat increased with the application of gypsum with sodic irrigation water from 1.5 to 4.5 % in different years of experiment as compared with control. The increase in yield could be attributed to the decrease in ESP and SAR values and improvement in nutritional balance upon gypsum application. Choudhary *et al* (2011a) reported higher yield of rice and wheat crops under sodic-water irrigation with the use of FYM than green manure (GM) and wheat straw (WS) to ameliorate sodic irrigation effects in a calcareous soil. The increase in yield was partly accredited to increase in organic carbon content (6.38 compared with 3.27 g kg⁻¹ in the unamended treatment). In the present study, data for soils irrigated with sodic-water of RSC 10 was not presented as no plant survived except where gypsum was applied as an amendment. Nevertheless, the interactive effect of amendment application at various levels of RSC on biomass yield was significant. Significant increase in biomass yield was observed with gypsum (both types), FYM and rice straw compost application at both RSC levels (RSC 5 and 7.5) of sodic-water irrigation. Gypsum amended RSC 5 treatment was at par with RSC 0 treatment in ls.

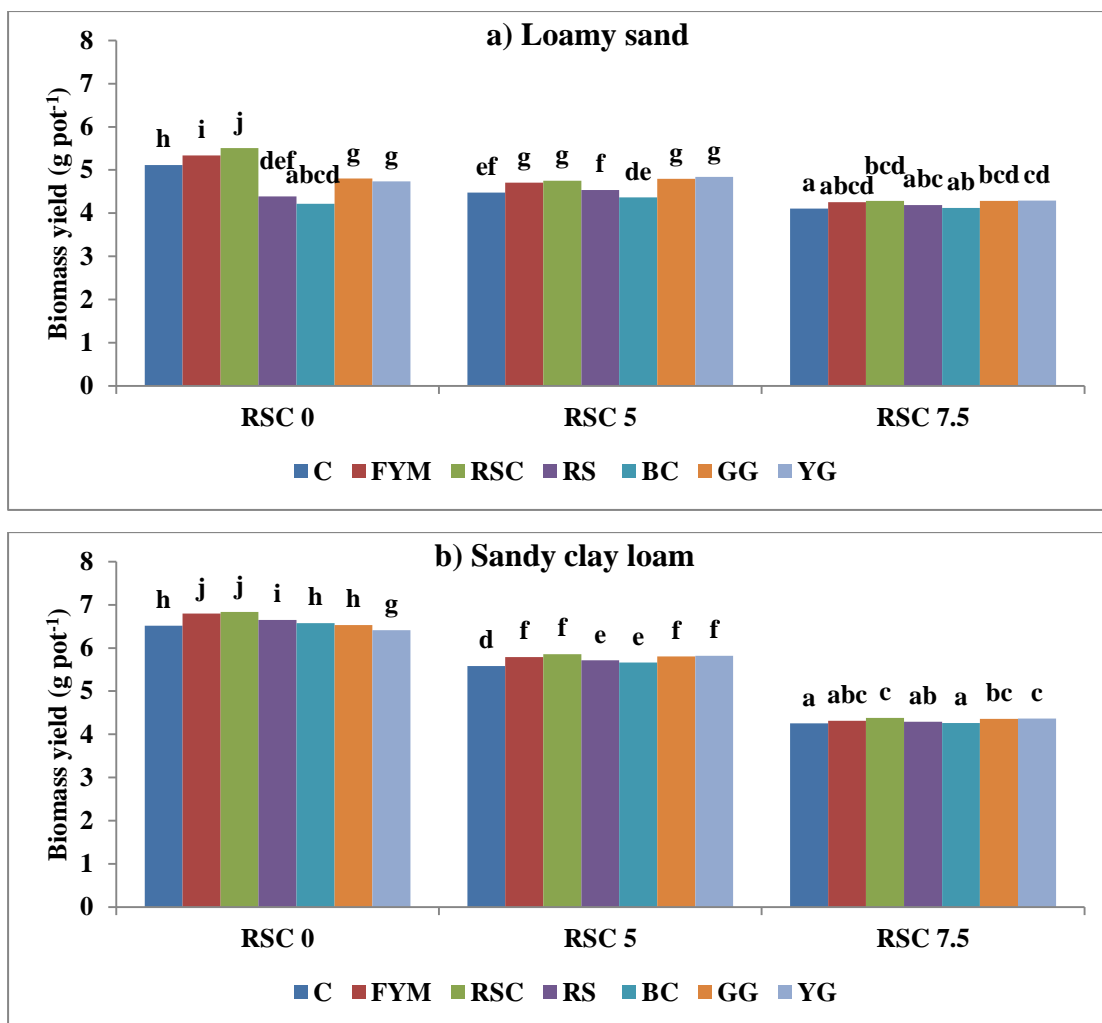


Fig. 4.1 Effect of application of chemical and organic amendments on biomass yield of wheat crop (g pot⁻¹) in a) loamy sand and b) sandy clay loam soil

4.1.1.2 Plant height

With the increase in levels of RSC of irrigation water, irrespective of amendments, plant height decreased significantly in ls (18.5 and 25.8%) and scl (13.3 and 21.9%) at RSC 5 and RSC 7.5 with respect to RSC 0. Plant height was affected due to increase in SAR and excess of sodium to the plant roots itself inhibiting the uptake of Ca and K ion becoming limiting for plant growth (Doodhwal *et al* 2018). Reduction in supply of calcium with subsequent increase in sodium content was shown to hamper the growth of roots and shoots. Such reduction in growth due to restricted supply of Ca under sodium accumulation was ascribed to K leakage (Ben-Hauyyim *et al* 1987). However, application of FYM in ls increased the plant height over the control in RSC 5 and 7.5 soils while FYM was at par with biochar application in RSC 7.5 treatment. In scl, FYM application in RSC 5 soils kept the plant height statistically superior to RSC 0 and at par with biochar (BC) in RSC 7.5 irrigated soil. The soils under RSC 10 level were unable to sustain plants except where gypsum (of any type) was applied as an amendment.

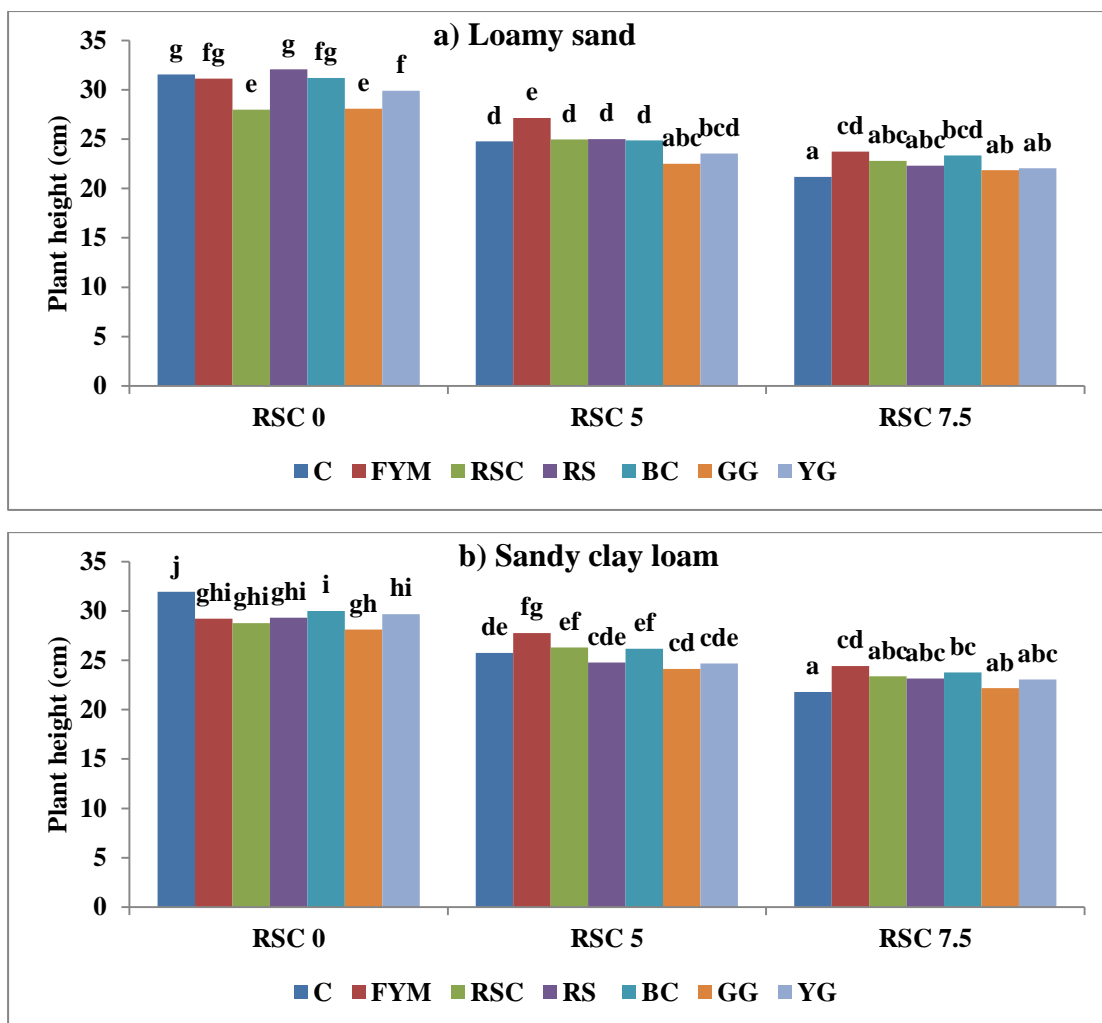


Fig. 4.2 Effect of application of chemical and organic amendments on plant height (cm) of wheat crop in a) loamy sand and b) sandy clay loam soil

4.1.1.3 Uptake of cations (Na, K, Ca and Mg)

The results of effect of sodic-water irrigation and application of various amendments on uptake of sodium, potassium, calcium and magnesium by plants for ls and scl are presented in Figures 4.3 and 4.4, respectively. Uptake of Na, irrespective of amendments, by plants increased with subsequent build-up of sodicity with each irrigation, increase being greater in scl (2.87 and 4.69 times) than ls (1.91 and 4.29 times) soil at RSC 5 and RSC 7.5 level of sodic-water irrigation, respectively over the control (RSC 0). This could be due to more build-up of Na and relatively higher biomass in scl than ls in these two treatments. On the contrary, application of BC alone in soil irrigated with RSC 5 water and with yellow gypsum (YG), grey gypsum (GG) and biochar in RSC 7.5 treatment decreased the uptake of Na significantly over the respective control in ls. In scl, both BC and gypsum (both types) performed at par in reducing the Na uptake at both levels (RSC 5 and 7.5) of sodic water irrigation. The decrease in sodium uptake can be attributed to enhanced supply of calcium and reduced ESP and SAR values in the soils treated with gypsum of any type.

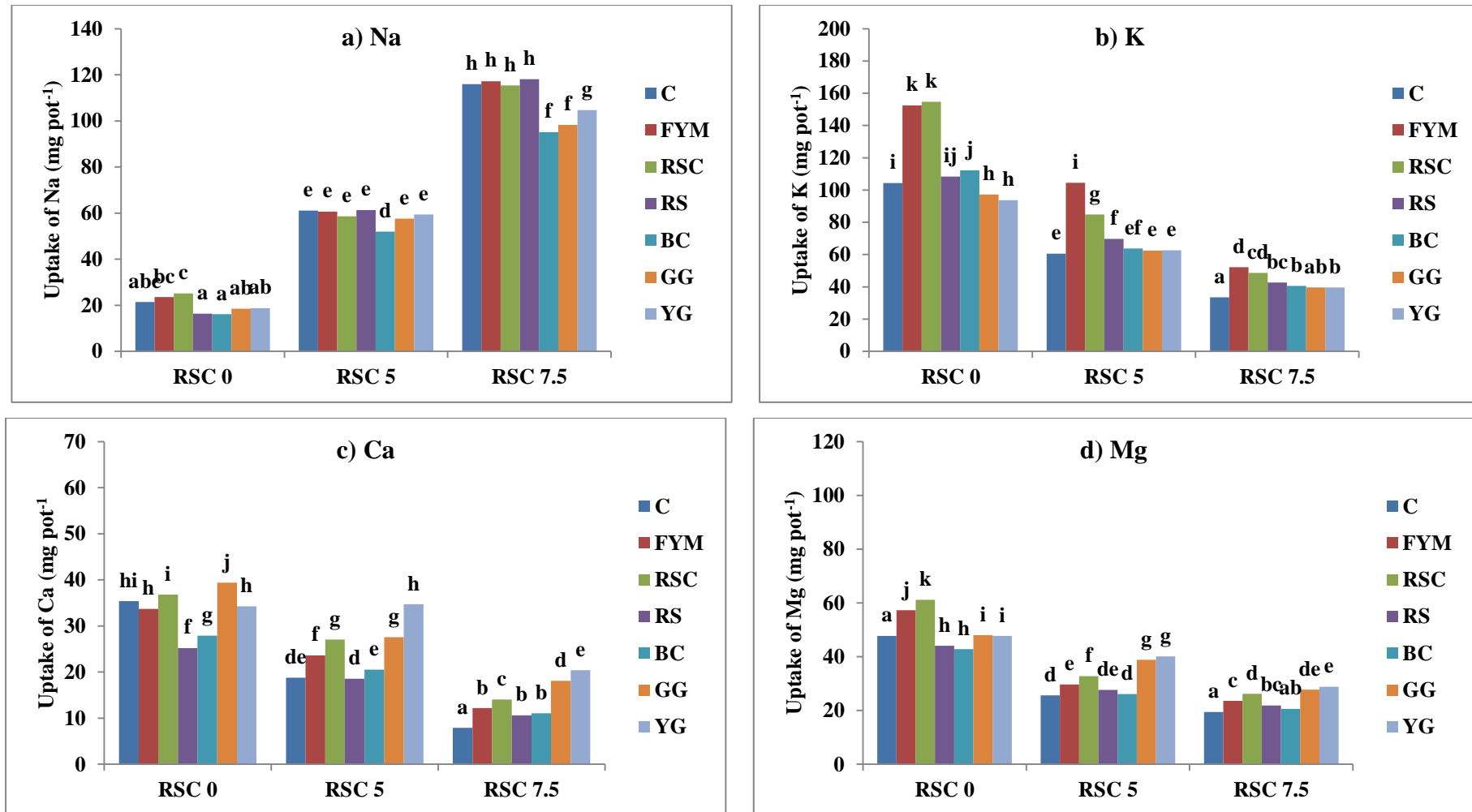


Fig. 4.3 Effect of application of chemical and organic amendments on uptake (mg pot^{-1}) of a) sodium b) potassium c) calcium d) magnesium by wheat plants in loamy sand soil

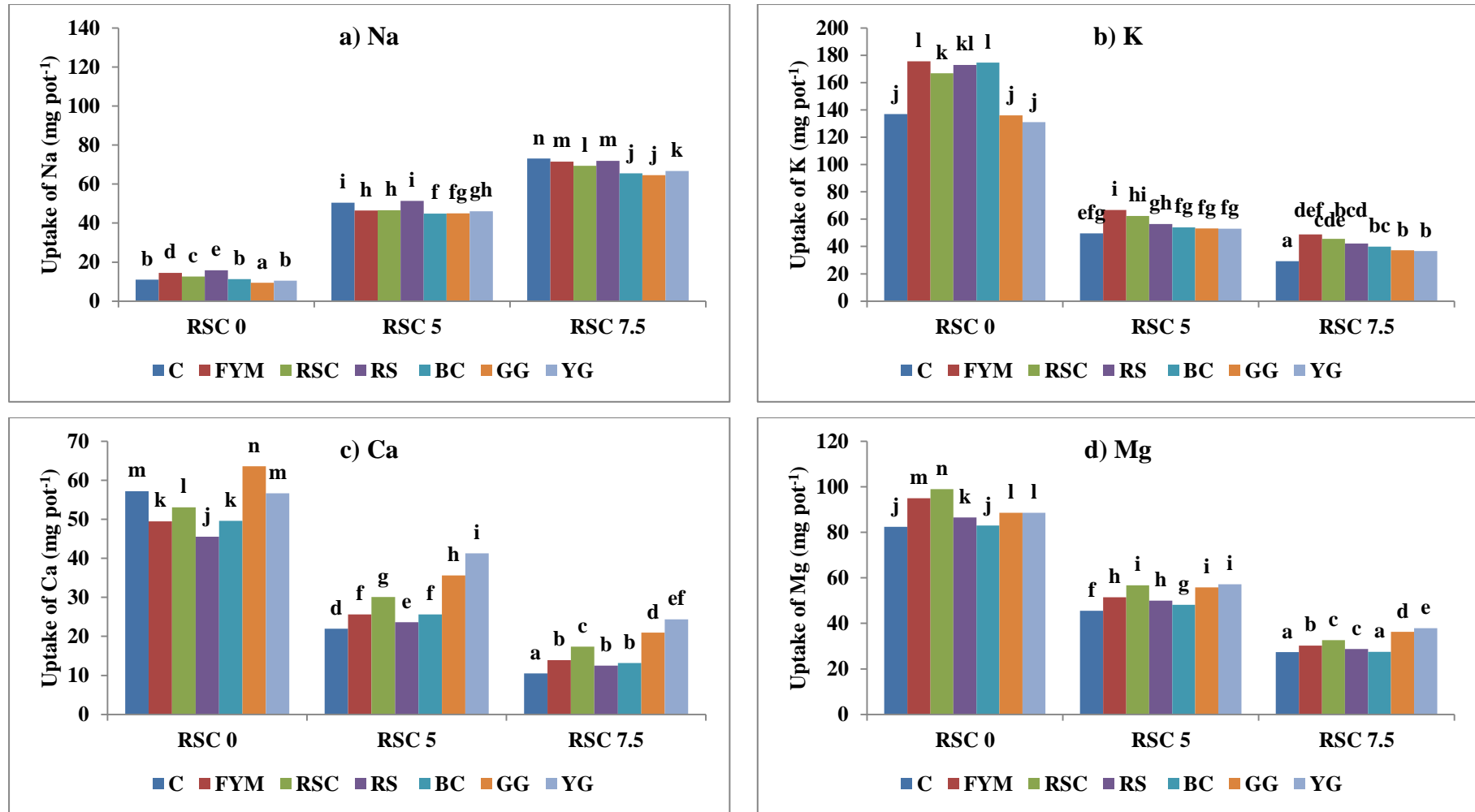


Fig. 4.4 Effect of application of chemical and organic amendments on uptake (mg pot^{-1}) of a) sodium b) potassium c) calcium d) magnesium by wheat plants in sandy clay loam soil

The mode of action for reduced uptake of sodium by plants in biochar treated soils includes transient binding of Na^+ due to its high adsorption capacity and ability to supply mineral nutrients (particularly K^+ , Ca^{2+} , Mg^{2+}) in the soil (Akhtar *et al* 2015, Melas *et al* 2017). The results were also in tune with findings of Jin *et al* (2018) who demonstrated significant decrease in sodium ion accumulation at stem, leaf, sheath and panicle of rice in saline-sodic soil by increasing the rate of biochar addition. Similar results have been previously reported by Chaganti and Crohn (2015).

The increase in sodicity also decreased the uptake of potassium, substantially more in scl (63.8 and 74.4%) compared with ls (38.2 and 63.9%) at RSC 5 and 7.5 level of sodic water irrigation, respectively. Higher build-up of Na (high ESP & SAR) in scl than ls explained the differences. Upon amelioration, respective significant increases in K uptake at RSC 5 and 7.5 levels over the control was observed with the application of FYM closely followed by rice straw compost in both the soils whereas gypsum proved ineffective in increasing the K uptake. Niamat *et al* (2019) observed maximum uptake of K^+ in maize shoot with the application of calcium-fortified compost (Ca-FC) under saline-sodic soil conditions. This might be due to positive effect of organic amendment application on cation exchange capacity (CEC) which limits the entry of Na^+ on exchange complex leading to better uptake of K^+ (soluble and exchangeable). Moreover, organic matter decomposition releases essential nutrients especially K^+ , Mg^{2+} and Ca^{2+} and help restoring a better nutrient balance in soil solution.

The uptake of calcium by plants decreased significantly in ls (24.4 and 59.2%) and scl (46.0 and 70.0%), respectively at RSC 5 and RSC 7.5 level of sodic water irrigation with respect to control (RSC 0). However, application of yellow gypsum (YG) and grey gypsum (GG) increased the Ca uptake by plants significantly over the control in soils receiving RSC 5 and 7.5 sodic water irrigation whereas among the organic amendments, rice straw compost showed promising results. The uptake of magnesium decreased significantly in ls (37.1 and 52.0%) and scl (41.7 and 64.7%), respectively at RSC 5 and 7.5 with respect to control. Chemical and organic amendments showed significant increase in Mg uptake compared with the unamended control which was similar as observed in case of Ca uptake.

4.1.1.4 Photosynthetic activity

Increase in sodicity of irrigation water caused decline in photosynthetic activity (Pn) in plants over the control in ls (25.1 and 47.6%) and scl (20.9 and 38.9%), respectively at RSC 5 and 7.5 level of sodic water irrigation (Fig. 4.5). The decrease in Pn can be attributed to significant build-up of sodium in soils, its uptake and accumulation within the plants and subsequent interference with plant metabolism under sodic-water irrigation. In contrast, a significant increase in Pn over the respective controls was observed with the application of YG and GG at all levels of sodicity in both the soils. Application of rice straw compost was

significantly better in scl and was statistically at par with FYM application in ls in restoring the Pn of plants. This could be attributed to improvement in soil conditions (pH, SAR and ESP) with the application of chemical and organic amendments.

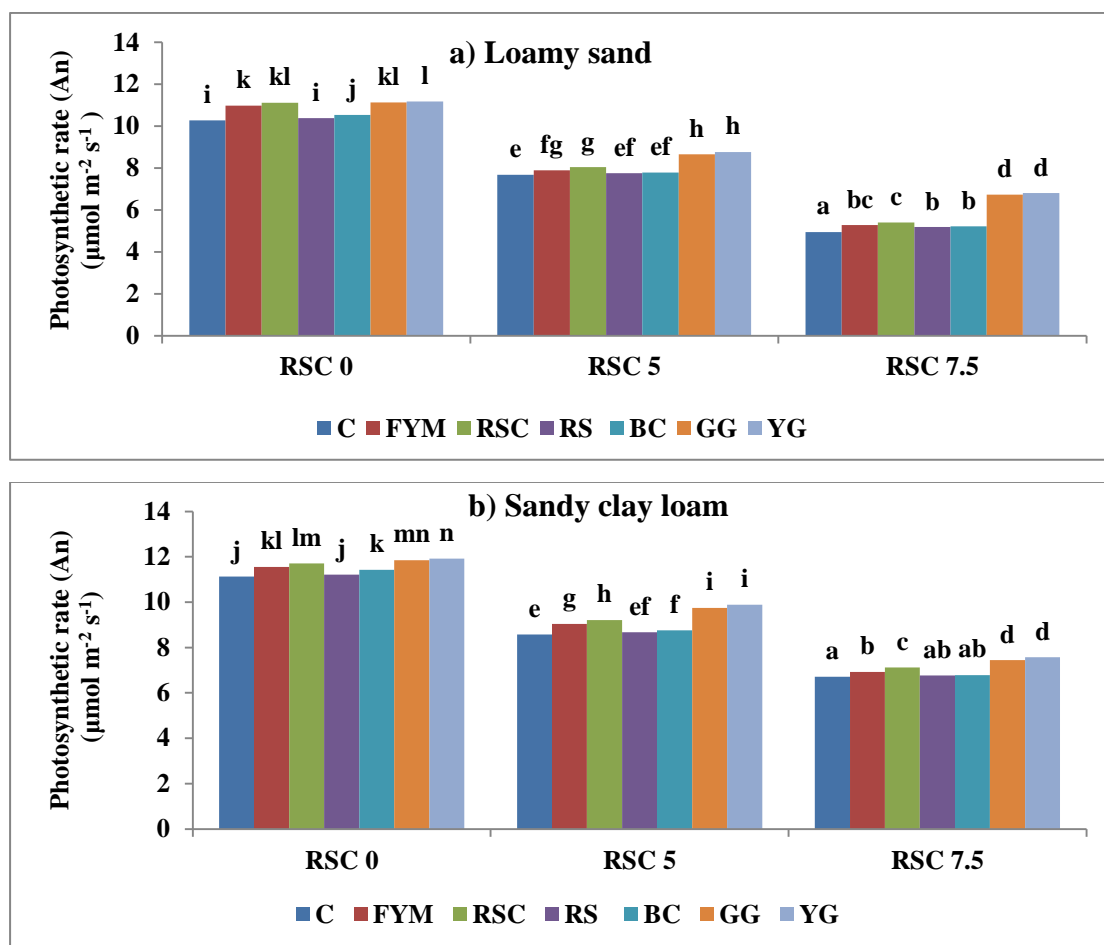


Fig. 4.5 Effect of application of chemical and organic amendments on photosynthetic rate ($\mu\text{mol m}^{-2} \text{s}^{-1}$) of wheat plants in a) loamy sand and b) sandy clay loam soil

4.1.1.5 Stomatal conductance

The results presented in Figure 4.6 pertaining to the effect of sodic water irrigation and application of various amendments on stomatal conductance (gS) by plants revealed that stomatal exchange was negatively impacted with the increase in RSC levels of irrigation water. The decrease in stomatal conductance with sodic-water irrigation can be ascribed to the increase in sodicity stress in plants due to higher uptake and accumulation of sodium in plant tissues and reduced K availability which is mainly responsible for regulating stomatal opening. The decrease was significant over control in ls (24.4 and 39.5%) and scl (10.9 and 37.6%) at RSC 5 and 7.5 level of sodic water irrigation, respectively. However, application of YG was found to be statistically at par with GG in RSC 7.5 irrigation and with rice straw compost in RSC 5 irrigation in increasing gS significantly over the control in ls. Conversely, in scl, YG was the most effective at both levels of RSC of irrigation water. Rice straw compost increased the gS significantly over other organic amendments and the unamended

control. The ameliorative effect of gypsum and rice straw compost application can be attributed to improved soil conditions (pH, SAR and ESP) and better plant growth. Sheoran *et al* (2021) also observed positive association of physiological parameters (Pn and gS) of plant with yield attributing traits resulting in higher rice and wheat yields. They proposed that supplement of calcium ions through gypsum application for displacement of exchangeable Na^+ and mobilization of soil-Ca from native CaCO_3 through application of organic amendments resulted in better soil conditions (clay flocculation and structural stability) and

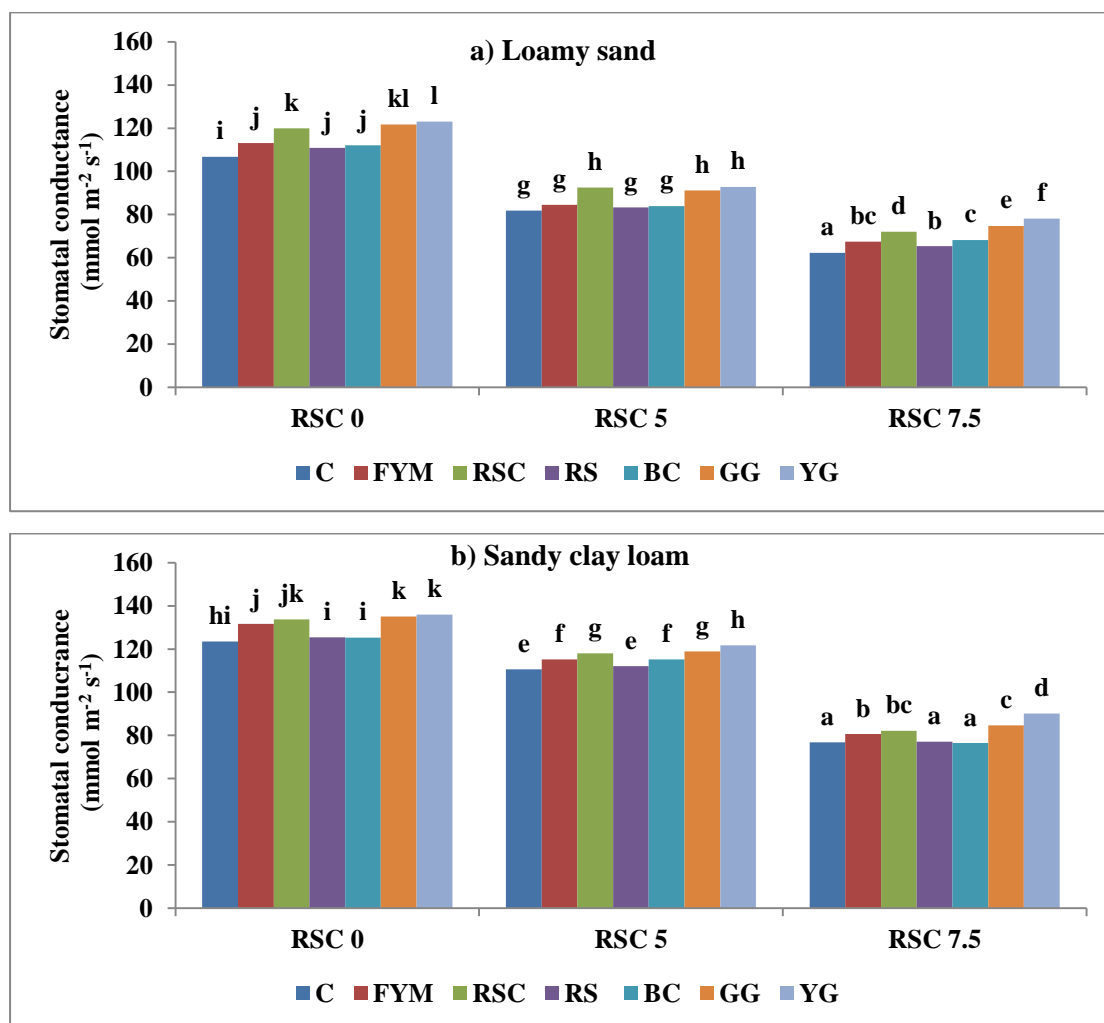


Fig. 4.6 Effect of application of chemical and organic amendments on stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$) of wheat plants in a) loamy sand and b) sandy clay loam soil

enhanced stress tolerance which led to increased biomass production and thus, improved crop yields (Koo *et al* 1990, Gharaibeh *et al* 2011, Dotaniya *et al* 2016).

4.1.1.6 Proline

The data regarding the effect of sodic water irrigations and application of various amendments on proline content in plants presented in Fig. 4.7. It revealed that proline content increased significantly as water alkalinity increased from RSC 0 to 7.5 meq L^{-1} in ls and scl.

Proline accumulation in leaves is linked to the expression of genes encoding key enzymes of proline synthesis ‘pyrroline-5-carboxylate (P5C)’ and low activity of oxidising enzymes (proline dehydrogenase) which are controlled by osmotic and salt stress (Uma *et al* 1995). Significant decrease in proline content over the control was observed with the application of YG followed by GG at all RSC levels in both the soils. Rice straw compost was the most effective organic amendment in significantly reducing the proline content in plants at RSC 5 and 7.5 level of sodic-water irrigation in both the soils. The data for RSC 10 level of sodic water irrigation was not presented due to absence of plants in all treatments except the ones receiving YG and GG. Studies have suggested that both rice and wheat crop with salt stress by regulating ion movement in leaves and shoots (Dadshani *et al* 2019), maintaining lower Na^+/K^+ ratio (El-Hendawy *et al* 2017) and by accumulating osmoprotectants to vouch from reactive oxygen species (Chunthaburee *et al* 2016). Reduction in proline content with gypsum and rice straw compost application is indicative of improved soil conditions ultimately enhancing plant growth and making it more resilient to sodic-water irrigation.

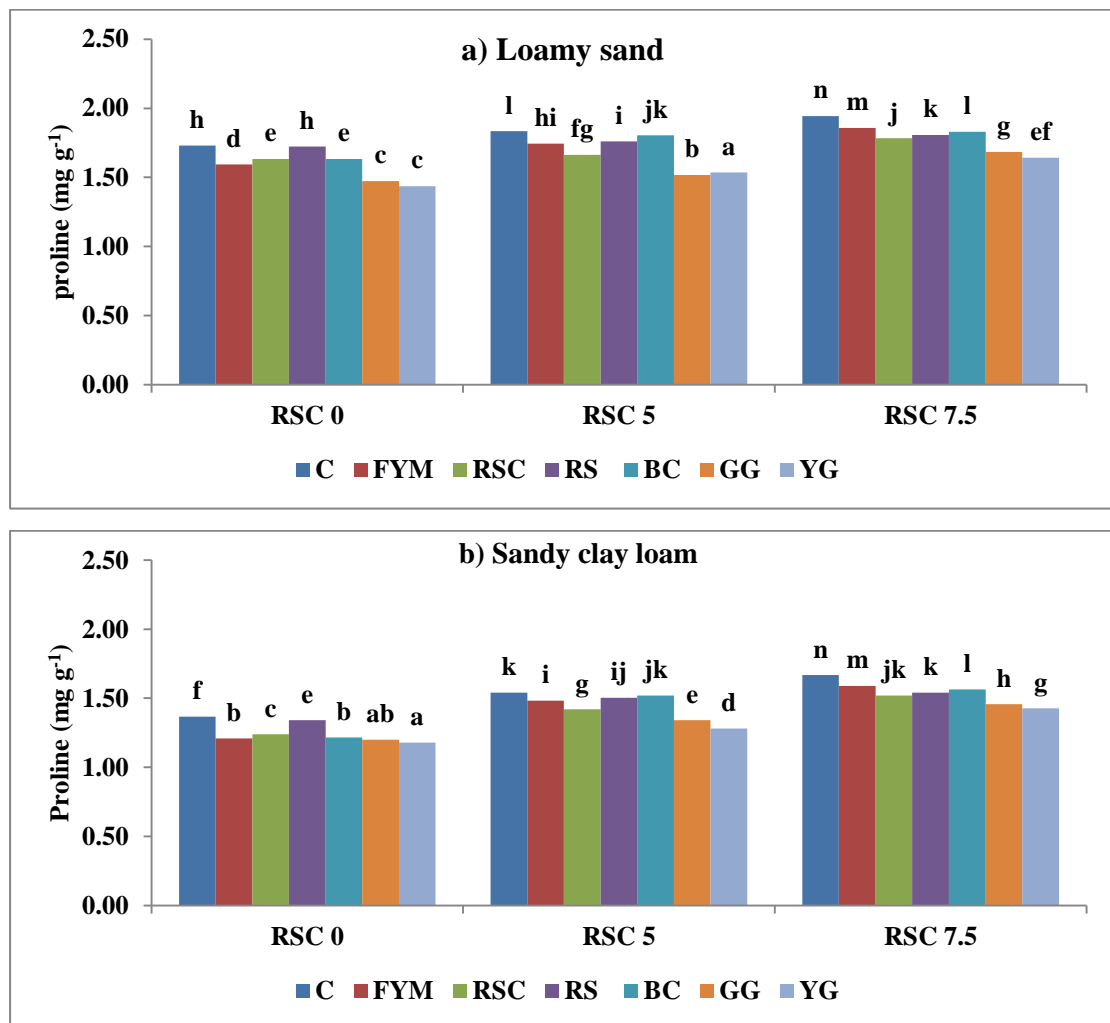


Fig. 4.7 Effect of application of chemical and organic amendments on proline (mg g^{-1}) content in leaves of wheat crop in a) loamy sand and b) sandy clay loam soil

4.1.1.7 Soil reaction (pH) and electrical conductivity (EC)

The increase in sodicity of irrigation water significantly increased the mean pH values in ls (19.7, 29.4 and 40.6%) than scl (10.8, 20.5 and 24.4%) at RSC 5, RSC 7.5 and RSC 10, respectively over RSC 0. Similar study by Choudhary *et al* (2011a) reported a gradual build-up of exchangeable sodium and pH of the soil with repeated irrigations of sodic water in a calcareous soil. On the other hand, application of organic and inorganic amendments decreased the mean pH values significantly with the maximum decrease observed with the application of YG (5.2% in ls and 8.7% in scl) followed by GG (4.6% in ls and 8.4% in scl) compared with the unamended control. Significant decrease in pH with gypsum application is attributed to the release of Ca^{2+} ions on gypsum dissolution which replaced Na^+ from exchange complex of soil resulting in reduced ESP and pH of soil (Ezlit *et al* 2010; Singh and Singh 2014). Among the organic amendments, irrespective of soil texture, the decrease in mean pH values was in the order: rice straw compost > FYM ~ RS (rice straw) > BC. Addition of organic material augments microbial respiration and decreases the pH due to organic acid production during the earlier stages of decomposition and then due to increased pCO_2 later (Chorom and Rengasamy 1997; Nelson and Oades 1998). This enhances the availability of Ca^{2+} and neutralizes HCO_3^- and CO_3^- that would otherwise render Ca^{2+} unavailable due to formation of lime precipitates (Choudhary *et al* 2011a). Decomposition of organic amendments increases pCO_2 and releases organic acids that aid in dissolution of native CaCO_3 (Mubarak and Nortcliff 2010; Qadir *et al* 2007), which hastens the removal of exchangeable sodium and thus, reclamation of calcareous sodic soil. Though the reduction in soil pH and ESP with organic amendments is not substantial initially, but in the long run, it may show a substantial decrease due to their continuous use. The interactive effect of application of various amendments and RSC levels on soil pH was significant. The pH values were significantly higher for ls at all levels of RSC except RSC 0 compared with scl suggesting faster development of sodicity in ls relative to the gradual build-up in scl. It was mainly because of higher CEC in scl soil. Significant reduction in pH values was observed in gypsum treatments (both types) at all levels of RSC in ls and scl; it was significantly greater for YG at RSC 10 in ls. While in scl, pH decrease with GG and YG in RSC 10 was at par with FYM, RSC and RS treatments in RSC 5 indicating faster reclamation with gypsum.

A significant increase in mean values of EC was observed with the increase in sodicity of irrigation water. Mean EC values were higher in case of scl compared with ls due to more retention of sodium ions through irrigation with sodic water due to presence of large proportion of finer clay particles in scl. The increase in EC with the addition of gypsum can be attributed to the release of salts into the soil solution upon gypsum dissolution (Amrhein and Suarez, 1987). The mean EC values increased by 7.2 and 10.1% and 8.9 and 13.3% on application of GG and YG compared with the unamended control in ls and scl, respectively.

Rasouli *et al* (2013) observed increase in salinity with application of gypsum. Similarly, Ahmed *et al* (2006) reported an increase of 28.3% in EC of a sodic soil with application of gypsum when applied at the rate of 50% GR in wheat-rice cropping system. Furthermore, Zia *et al* (2006) also recorded a slight increase in EC_e in field trials. Rice straw compost and BC application in both the soils was statistically at par with RS application in ls leading to small decrease in mean EC values over the unamended control. Significant interaction between applied amendments and RSC of irrigation water revealed that YG followed by GG increased EC values at all levels of RSC except for GG at RSC 10 in ls. The EC values were significantly lower for RS at RSC 5 and 7.5 and rice straw compost at RSC 10 in ls while in scl, rice straw compost at all RSC levels was significant in reducing the EC values.

Table 4.1 Effect of application of chemical and organic amendments on soil pH and EC in loamy sand and sandy clay loam soil after wheat harvest

pH										
Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	7.42	9.01	9.80	10.57	9.20	7.75	8.76	9.68	10.18	9.09
FYM	7.40	8.87	9.68	10.49	9.11	7.68	8.57	9.45	10.14	8.96
RSC	7.32	8.81	9.54	10.48	9.04	7.75	8.53	9.37	9.93	8.89
RS	7.43	8.91	9.65	10.52	9.13	7.72	8.66	9.54	9.86	8.95
BC	7.50	8.93	9.69	10.56	9.17	7.77	8.72	9.61	9.96	9.01
GG	7.26	8.61	9.20	10.04	8.78	7.67	8.32	8.72	8.58	8.32
YG	7.23	8.58	9.19	9.89	8.72	7.69	8.30	8.70	8.52	8.30
Mean	7.37	8.82	9.54	10.36		7.72	8.55	9.30	9.60	
LSD (5%)	RSC level = 0.029, amendments = 0.029, interaction = 0.068					RSC level = 0.026, amendments = 0.038, interaction = 0.086				
EC (dS m ⁻¹)										
	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.674	0.944	1.520	2.433	1.393	0.690	1.232	2.450	3.757	2.032
FYM	0.756	1.180	1.657	2.523	1.529	0.847	1.286	2.577	4.037	2.187
RSC	0.819	0.876	1.447	2.250	1.348	0.923	1.149	2.347	3.173	1.898
RS	0.642	0.817	1.414	2.400	1.318	0.706	1.259	2.383	4.050	2.100
BC	0.589	0.906	1.457	2.337	1.322	0.690	1.214	2.410	3.397	1.928
GG	0.786	0.972	1.844	2.357	1.490	0.788	1.332	2.783	3.933	2.209
YG	0.756	1.014	1.903	2.450	1.531	0.807	1.355	2.860	4.187	2.302
Mean	0.717	0.958	1.606	2.393		0.779	1.261	2.544	3.790	
LSD (5%)	RSC level = 0.04, amendment = 0.05, interaction = 0.09					RSC level = 0.070, amendment = 0.093, interaction = 0.186				

4.1.1.8 Soil organic carbon

The mean organic carbon (OC) was double in scl than ls and it decreased significantly over control with increase in sodicity of irrigation water upto RSC 7.5 only. Increase in RSC of irrigation water and high soils ESP increases C mineralization and leads to dispersion of soil organic matter (Dendooven *et al* 2010). Similar decrease in OC of soil was observed by Basak *et al* (2021) with continued irrigation with high RSC water for prolonged time. Application of organic amendments led to significant increase in OC in the following order: FYM > BC > rice straw compost > RS in ls whereas, in scl, the trend was similar except that rice straw compost and BC were statistically at par. Organic matter due to its cation exchange capacity (CEC) impacts the selectivity of exchange sites for Ca²⁺ over Na⁺, and its ability to donate protons. As a result, organic matter may inhibit the degree to which a soil becomes saline-sodic or sodic under the influence of brackish water, or it may reduce salinity when added to salt-affected soils (Murtaza *et al* 2015). Although the increase in OC was significant upon application of both types of gypsum (GG and YG) in ls, yet the increase was smaller compared with organic amendments except RS. However in scl, gypsum application did not increase OC over the control. The interactive effect of different levels of sodic water irrigation and application of amendments had a significant effect on OC content in both soils. Application of FYM and BC followed by rice straw compost showed higher OC values in RSC 5, RSC 7.5 and RSC 10 compared with the unamended control (RSC 0) in both soils. The only exception was RSC 7.5 treatment in scl for rice straw compost.

Table 4.2 Effect of application of chemical and organic amendments on organic carbon in loamy sand and sandy clay loam soil after wheat harvest

OC (%)										
Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.29	0.27	0.23	0.21	0.25	0.61	0.59	0.54	0.50	0.56
FYM	0.38	0.40	0.39	0.37	0.39	0.74	0.80	0.77	0.71	0.75
RSC	0.40	0.35	0.31	0.30	0.34	0.68	0.67	0.56	0.63	0.63
RS	0.32	0.31	0.27	0.25	0.29	0.61	0.63	0.60	0.58	0.60
BC	0.39	0.36	0.34	0.31	0.35	0.63	0.66	0.61	0.64	0.63
GG	0.31	0.32	0.26	0.25	0.29	0.60	0.60	0.53	0.52	0.56
YG	0.32	0.33	0.25	0.26	0.29	0.61	0.61	0.54	0.53	0.57
Mean	0.34	0.33	0.29	0.29		0.64	0.65	0.59	0.59	
LSD (5%)	RSC level = 0.01, amendment = 0.01, interaction = 0.02					RSC level = 0.01, amendments = 0.01, interaction = 0.02				

4.1.1.9 Soluble cations

The detrimental effect of irrigation water sodicity and restorative effect of amendments on soluble cations in ls and scl can be observed respectively from the Tables 4.3 and 4.4. Soluble Na increased significantly to more than double in scl (7.63, 8.66 and 12.73 times) than ls (3.84, 5.64 and 10.71 times) at RSC 5, RSC 7.5 and RSC 10 levels, respectively over RSC 0. However, application of both types of gypsum decreased the mean soluble Na content significantly by 12.5-12.8% in ls and 22.2-23.3% in scl over the control respectively at different levels of RSC in irrigation water. Among the organic amendments, rice straw compost application in both the soils resulted in the maximum and significant decrease in mean soluble Na compared with the unamended control. Significant interaction between RSC levels and applied amendments was observed. At RSC 7.5 and RSC 10 in ls, both types of gypsum significantly decrease soluble Na over the respective unamended treatments while organic amendments except FYM could significantly decrease soluble Na only at RSC 7.5 treatment. While in scl, GG at RSC 5, YG and GG at RSC 7.5 and 10 brought about maximum decrease in soluble sodium.

Soluble calcium and magnesium (Ca+Mg) declined significantly by 50, 55 and 63% in ls with corresponding decrease of 39, 52 and 60% in scl soil, respectively at RSC 5, RSC 7.5 and RSC 10 compared with RSC 0. Lower values of Ca+Mg in sodic- water irrigated soils can be attributed to antagonistic effect of Na and precipitating effect of anions such as carbonates and bicarbonates on Ca+Mg in the soil. On the other hand, significant increases in mean soluble Ca+Mg ions were recorded with YG (55%) and GG (49%) application in ls whereas in scl soil, application of both types of gypsum proved to be equally effective (49-52%). Application of rice straw compost resulted in the maximum increase in mean Ca+Mg compared with other organic amendments in ls (37%) and scl (28%) soil being at par with RS and FYM in both the soils with BC registering the minimum yet significant increase only in scl. Significant interaction in ls revealed that YG followed by GG were able to maintain higher Ca+Mg in soil solution at all levels of RSC. Rather at RSC 10, these two amendments had significantly higher soluble Ca+Mg compared with unamended RSC 5 treatment. In scl, gypsum (both types) presented maximum increase in soluble Ca+Mg content at RSC 5; being at par with FYM at RSC 7.5 and 10 and rice straw compost at RSC 7.5 proved valuable in increasing soluble calcium and magnesium content in scl. Further all amendments except BC were able to maintain significantly higher soluble Ca+Mg at RSC 10 compared with the unamended RSC 5 treatment in scl. Gypsum (both types) produced promising results in increasing soluble Ca+Mg at all levels of RSC compared with the respective controls and other amendments in ls. However, YG at RSC 10 proved superior to GG and out valued the soluble Ca+Mg content in unamended control, FYM while it was at par with rice straw

Table 4.3 Effect of application of chemical and organic amendments on soluble cations (meq L⁻¹) in loamy sand soil after wheat harvest

Amendments	Soluble Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	2.15	9.91	15.60	24.01	12.92
FYM	2.49	10.22	16.20	25.28	13.55
RSC	1.96	9.06	12.76	23.41	11.80
RS	1.84	9.75	13.47	24.20	12.31
BC	1.78	9.67	12.89	23.51	11.96
GG	1.97	9.74	11.23	22.30	11.31
YG	1.83	9.86	11.31	22.04	11.26
Mean	2.01	9.74	13.35	23.53	
LSD (5%)	RSC level = 0.48, amendments = 0.64, interaction = 1.28				
	Soluble Ca+Mg				
C	7.20	2.53	1.60	1.33	3.17
FYM	6.00	3.07	2.77	2.13	3.49
RSC	7.87	3.73	3.07	2.70	4.34
RS	5.73	2.67	2.87	2.57	3.46
BC	5.47	2.40	2.37	2.23	3.12
GG	7.33	4.40	4.10	3.07	4.73
YG	7.43	4.60	4.20	3.47	4.93
Mean	6.72	3.34	3.00	2.50	
LSD (5%)	RSC level = 0.14, amendment= 0.18, interaction = 0.36				
	Soluble K				
C	0.74	0.64	0.53	0.17	0.52
FYM	1.60	1.49	1.35	0.57	1.25
RSC	1.13	0.92	0.81	0.33	0.80
RS	1.24	1.12	0.77	0.33	0.87
BC	1.31	1.22	0.76	0.42	0.92
GG	0.63	0.61	0.58	0.24	0.51
YG	0.69	0.63	0.59	0.26	0.54
Mean	1.05	0.95	0.77	0.33	
LSD (5%)	RSC level = 0.04, amendment = 0.05, interaction = 0.11				

Table 4.4 Effect of application of chemical and organic amendments on soluble cations (meq L⁻¹) in sandy clay loam soil after wheat harvest

Amendments	Soluble Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	2.48	25.75	35.57	47.61	27.85
FYM	3.63	26.94	32.30	45.19	27.02
RSC	3.55	27.41	29.11	41.06	25.28
RS	3.50	29.98	30.11	42.23	26.45
BC	3.24	26.56	28.64	45.63	26.02
GG	2.56	23.77	26.02	37.97	22.58
YG	2.48	24.42	25.26	34.47	21.66
Mean	3.06	26.40	29.57	42.02	
LSD (5%)	RSC level = 0.72, amendments = 0.95, interaction = 1.89				
	Soluble Ca+Mg				
C	8.27	3.23	2.77	2.23	4.13
FYM	8.00	3.93	4.53	4.20	5.17
RSC	8.07	4.80	4.73	3.60	5.30
RS	8.80	4.00	3.93	3.87	5.15
BC	8.80	3.73	3.27	2.80	4.65
GG	8.57	8.23	4.40	3.47	6.17
YG	8.60	8.30	4.60	3.60	6.28
Mean	8.44	5.18	4.03	3.40	
LSD (5%)	RSC level = 0.17, amendment = 0.23, interaction = 0.46				
	Soluble K				
C	1.73	0.89	0.65	0.37	0.91
FYM	1.48	2.15	1.77	1.39	1.70
RSC	0.93	0.81	0.73	0.61	0.77
RS	0.95	0.90	0.86	0.54	0.81
BC	0.95	0.85	0.83	0.77	0.85
GG	1.67	0.83	0.69	0.38	0.89
YG	1.69	0.81	0.58	0.36	0.86
Mean	1.34	1.03	0.87	0.63	
LSD (5%)	RSC level = 0.03, amendment = 0.04, interaction = 0.09				

compost at RSC 5 level which suggested dominance of gypsum application over other amendments in steady supply of calcium ions at higher RSC levels.

Soluble K presents a declining trend with increasing sodicity of irrigation water in both the soils. The magnitude of decrease was greater in scl (20.15, 32.6 and 51.9%) than ls (9.5, 26.7 and 68.6%), respectively at RSC 5, RSC 7.5 and RSC 10 levels of sodic-water irrigation. The soluble K content in gypsum treated soils remained at par with the unamended control in both the soils. However, maximum increase in soluble K content over the control was observed with the application of FYM (1.40 times in ls and 0.87 times in scl). In both the soils, rest of the organic amendments presented the following order in increasing soluble K: BC > RS > rice straw compost. Significant interaction between RSC levels and applied amendments revealed an increase in soluble K with FYM at all levels of RSC in ls and scl; value at RSC 10 amended with FYM was at par with control for RSC 7.5 in ls. The soluble K was significantly higher in scl compared to ls at all levels of RSC irrespective of amendment application.

4.1.1.10 Sodium adsorption ratio

The data presented in Table 4.5 revealed that relative to RSC 0 increase in the Na and HCO_3^- bicarbonate content of irrigation water led to a significant rise in mean sodium adsorption ratio (SAR) values; more in scl (10.7, 13.3 and 21.1 times) than ls (6.0, 9.4 and 18.8 times) at RSC 5, 7.5 and 10 levels of sodic-water irrigation. The SAR values in scl were comparatively higher than ls due to double the amount of soluble Na but only slightly higher soluble Ca+Mg in this soil. Moreover, sodic-water irrigation led to rise in Na^+ content with subsequent decrease in Ca+Mg content of soils, thereby increasing SAR values with increase in RSC levels. In a similar study by Singh and Bajwa (1991), an increase in SAR was observed with increase in sodicity of irrigation water. Nonetheless, application of GG and YG proved to be most effective in reducing the SAR values in both soils. In ls, mean SAR values were close to 8 in gypsum amended treatments. However, in case of scl, YG decreased mean SAR value 42.7% more effectively than GG (38.6%) relative to control; lowering it down to critical value of SAR for sodic soil i.e. 13. Upon dissolution, gypsum provides calcium to the soil solution which narrowed the gap between soluble Ca+Mg and Na thus lowering the SAR values in the given treatments. Shaaban *et al* (2013) also concluded that gypsum alone decreased SAR by 47% (13.9) compared with that in control (26.6) which is above the critical level as described by US Salinity Laboratory. The interactive effect of increasing level of sodic-water irrigation and application of amendments on SAR was significant. The SAR values were considerably higher in scl than ls at all levels of RSC; the values remained well below the threshold level up to RSC 7.5 in all the amended treatments. Furthermore, SAR

values in ls even at RSC 10 in gypsum treatments were similar to those obtained in scl at lower RSC (RSC 7.5) implying a lower sodium build-up coupled with better amelioration efficiency of amendments particularly of gypsum. While in scl, even gypsum application could not keep SAR below 13 beyond RSC 5 treatment.

Table 4.5 Effect of application of chemical and organic amendments on SAR in loamy sand and sandy clay loam soil after wheat harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	1.13	8.83	17.44	29.47	14.22	1.22	20.28	30.29	45.08	24.22
FYM	1.44	8.26	13.78	24.51	12.00	1.82	19.21	21.50	31.19	18.43
RSC	0.99	6.63	10.33	20.19	9.54	1.77	17.71	18.94	30.63	17.26
RS	1.09	8.45	11.24	21.37	10.54	1.67	21.24	21.47	30.40	18.70
BC	1.08	8.85	11.86	22.24	11.01	1.54	19.44	22.41	38.65	20.51
GG	1.03	6.57	7.84	18.02	8.37	1.24	11.71	17.58	28.93	14.87
YG	0.95	6.50	7.80	16.80	8.01	1.20	11.99	16.66	25.69	13.89
Mean	1.10	7.73	11.47	21.80		1.49	17.37	21.26	32.94	
LSD (5%)	RSC level = 0.54, amendment = 0.71, interaction = 1.43					RSC level = 0.70, amendment = 0.93, interaction = 1.85				

4.1.1.11 Soluble anions

The data presented in Tables 4.6 and 4.7 reveals increase in CO_3^{2-} and HCO_3^- content in both soils with increase in sodicity of irrigation water though the CO_3^{2-} build-up remained higher in scl. The CO_3^{2-} in different treatments was not detected in both the soils receiving non-sodic irrigation water implying that these were free of carbonates. The significant increase in mean soluble HCO_3^- values was 0.84, 1.71 and 3.30 times and by 0.84, 1.54 and 3.20 times at RSC 5, 7.5 and 10 levels over the control in ls and scl, respectively. The maximum decrease in CO_3^{2-} and HCO_3^- content was observed with the application of GG followed closely by YG and distantly by rice straw compost in both the soils and at all levels of sodic-water irrigation. The interactive effect of RSC levels and amendment application on HCO_3^- content was significant in both the soils. YG lowered the HCO_3^- considerably over GG and other amendments at RSC 7.5 and 10 in ls. Bicarbonate content with YG at RSC 10 decreased considerably below the value at RSC 7.5 in ls implying faster reclamation with YG at higher RSC levels.

Table 4.6 Effect of application of chemical and organic amendments on soluble anions (meq L⁻¹) in loamy sand soil after wheat harvest

Amendments	CO ₃ ²⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	ND*	2.10	3.90	5.20	3.73
FYM	ND	3.03	4.20	7.10	4.78
RSC	ND	1.78	3.50	4.77	3.35
RS	ND	1.92	3.80	5.10	3.61
BC	ND	1.84	3.73	5.00	3.52
GG	ND	1.50	3.13	4.27	2.97
YG	ND	1.63	3.20	4.37	3.07
Mean	ND	1.97	3.64	5.11	
LSD (5%)	RSC level = 0.04, amendment = 0.06, interaction = 0.10				
Amendments	HCO ₃ ⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	2.67	5.67	8.00	14.33	7.67
FYM	3.00	6.17	8.50	16.00	8.42
RSC	2.80	5.17	7.50	13.33	7.20
RS	3.13	5.33	7.60	13.67	7.43
BC	3.07	5.50	7.67	13.67	7.48
GG	2.40	4.00	7.00	6.33	4.93
Mean	2.27	3.67	6.17	5.67	4.44
LSD (5%)	2.76	5.07	7.49	11.86	
RSC level = 0.18, amendment = 0.24, interaction = 0.47					
Amendments	Cl ⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	2.50	3.50	4.33	5.50	3.96
FYM	2.80	3.67	5.00	6.13	4.40
RSC	2.87	3.40	4.20	5.40	3.97
RS	3.00	3.57	4.37	5.50	4.11
BC	2.93	3.43	4.27	5.47	4.03
GG	2.40	3.20	4.00	4.33	3.48
YG	2.27	3.00	3.87	4.13	3.32
Mean	2.68	3.40	4.29	5.21	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.16				
Amendments	SO ₄ ²⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	1.23	1.38	1.67	1.93	1.55
FYM	1.32	1.46	1.74	2.04	1.64
RSC	1.35	1.26	1.53	1.84	1.50
RS	1.39	1.29	1.56	1.88	1.53
BC	1.41	1.31	1.59	1.92	1.56
GG	1.16	1.21	1.49	1.78	1.41
YG	1.18	1.23	1.51	1.80	1.43
Mean	1.29	1.31	1.58	1.89	
LSD (5%)	RSC level = 0.009, amendment = 0.011, interaction = 0.02				

*ND - Not detected

Table 4.7 Effect of application of chemical and organic amendments on soluble anions (meq L⁻¹) in sandy clay loam soil after wheat harvest

Amendments	CO ₃ ²⁻				Mean
	RSC 0	RSC 5	RSC 7.5	RSC 10	
C	ND*	3.83	6.63	8.75	6.40
FYM	ND	4.22	6.93	9.37	6.84
RSC	ND	3.17	6.16	7.82	5.71
RS	ND	3.57	6.40	8.32	6.09
BC	ND	3.32	6.32	8.08	5.91
GG	ND	2.87	5.88	7.32	5.36
YG	ND	2.95	5.98	7.43	5.46
Mean	ND	3.42	6.33	8.16	
LSD (5%)	RSC level = 0.07, amendment = 0.103, interaction = 0.18				
	HCO ₃ ⁻				Mean
	RSC 0	RSC 5	RSC 7.5	RSC 10	
C	3.20	6.50	8.73	15.00	8.36
FYM	3.60	6.83	9.00	16.17	8.90
RSC	3.40	6.17	8.53	14.50	8.15
RS	3.47	6.43	8.60	14.73	8.31
BC	3.43	6.47	8.67	14.83	8.35
GG	3.00	5.00	7.50	10.40	6.48
YG	2.80	4.83	7.00	10.27	6.23
Mean	3.27	6.03	8.29	13.70	
LSD (5%)	RSC level = 0.08, amendment = 0.11, interaction = 0.21				
	Cl ⁻				Mean
	RSC 0	RSC 5	RSC 7.5	RSC 10	
C	3.40	4.50	6.00	7.27	5.29
FYM	3.60	5.00	6.33	7.73	5.67
RSC	3.73	4.17	5.43	7.00	5.08
RS	3.80	4.33	5.60	7.53	5.32
BC	3.67	4.27	5.53	7.40	5.22
GG	3.07	3.87	5.27	6.00	4.55
YG	3.00	3.80	5.00	5.67	4.37
Mean	3.47	4.28	5.60	6.94	
LSD (5%)	RSC level = 0.09, amendment = 0.12, interaction = 0.24				
	SO ₄ ²⁻				Mean
	RSC 0	RSC 5	RSC 7.5	RSC 10	
C	1.55	1.79	2.14	2.87	2.09
FYM	1.62	1.87	2.22	2.98	2.17
RSC	1.66	1.63	2.03	2.70	2.01
RS	1.70	1.67	2.07	2.76	2.05
BC	1.68	1.71	2.10	2.79	2.07
GG	1.53	1.58	1.97	2.63	1.93
YG	1.56	1.60	2.01	2.66	1.96
Mean	1.61	1.69	2.08	2.77	
LSD (5%)	RSC level = 0.008, amendment = 0.01, interaction = 0.02				

*ND - Not detected

It is evident from the data that mean Cl^- content increased from 2.68 to 5.21 meq L^{-1} in ls and from 3.47 to 6.94 meq L^{-1} in scl as RSC varied from 0 to 10 meq L^{-1} ; mimicking the trend observed for the content of soluble Na in both the soils. This might have happened because with increased sodicity of irrigation water, poor plant growth was observed which led to lower uptake of Cl^- ions. Thus, most of Cl^- (added through muriate of potash) remained unutilized in soil with increasing sodicity levels. Application of YG followed by GG was effective in significantly reducing the mean values of soluble Cl^- in both the soils. On the other hand, organic amendments could not lower the Cl^- content beyond the control treatment in ls whereas rice straw compost significantly lowered the Cl^- over other amendments in scl. The significant interaction between RSC levels and applied amendments was observed as lowering of Cl^- content with GG at RSC 10 which was comparable to all treatments at RSC 7.5 except FYM in ls. In scl, YG significantly reduced Cl^- content compared to GG except at RSC 5. Rice straw compost, RS and BC at RSC 5 and 7.5 and only rice straw compost at RSC 10 level was effective in reducing Cl^- content compared with the respective controls. The SO_4^{2-} content of soils increased significantly over control in both the soils with increase in sodicity of irrigation water from 1.29 to 1.89 meq L^{-1} and from 1.61 to 2.77 meq L^{-1} as sodicity of irrigation water increased from 0 to 10 meq L^{-1} in ls and scl, respectively. While the maximum decrease in mean SO_4^{2-} content was observed with the application of GG (9.0% in ls and 7.7% in scl) and YG (7.7% in ls and 6.2% in scl). This decrease can be attributed to the formation of sodium sulphate from SO_4^{2-} ions supplied through gypsum and sodium ions present in the soil solution which leaches down below the sampling layer with percolating irrigation water. Rice straw compost and RS in ls and with BC in scl were effective in decreasing mean SO_4^{2-} content among other organic amendments. Significant interaction among RSC levels and applied amendments showed that maximum decrease in SO_4^{2-} content was observed with GG followed by YG, RSC, RS and BC while FYM increased SO_4^{2-} content at all RSC levels in ls and scl.

4.1.1.12 Exchangeable cations

The perusal of data in Table 4.8 and 4.9 revealed that exchangeable Na values increased at all levels of RSC of irrigation water applied in both the soils. The increase was more in scl than ls due to high retention power (CEC) of scl. Application of YG (8.3% in ls and 14.9% in scl) and GG (10.7% in ls and 13.0% in scl) recorded maximum decrease in mean exchangeable Na. The decrease in exchangeable Na upon gypsum application can be ascribed to the release of Ca^{2+} into soil solution upon gypsum dissolution to replace Na^+ ions on the exchange complex. Application of organic amendments was unable to reduce the mean exchangeable Na below that in unamended control in ls whereas in scl, the maximum decrease in exchangeable Na content was observed with the application of rice straw compost that was at par with BC followed by RS and FYM. Sandy soils are naturally low in fertility

Table 4.8 Effect of application of chemical and organic amendments on exchangeable cations (meq 100 g⁻¹) in loamy sand soil after wheat harvest

Amendments	Exch Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.24	3.96	6.20	8.32	4.68
FYM	0.27	3.66	6.37	9.05	4.84
RSC	0.23	3.59	6.33	9.25	4.85
RS	0.21	3.74	6.35	8.96	4.81
BC	0.22	3.77	6.41	8.61	4.75
GG	0.23	3.24	6.13	7.14	4.18
YG	0.20	3.20	6.07	7.71	4.29
Mean	0.23	3.59	6.26	8.43	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.16				
	Exch Ca+Mg				
C	3.87	2.47	0.67	0.12	1.78
FYM	5.17	4.57	1.37	1.33	3.11
RSC	5.27	4.90	1.77	1.63	3.39
RS	4.20	4.03	1.30	1.17	2.68
BC	3.93	3.90	1.40	1.37	2.65
GG	5.53	5.17	3.20	2.47	4.09
YG	5.60	5.20	3.33	2.57	4.18
Mean	4.80	4.32	1.86	1.52	
LSD (5%)	RSC level = 0.10, amendment = 0.13, interaction = 0.26				
	Exch K				
C	0.22	0.21	0.21	0.18	0.21
FYM	0.76	0.66	0.56	0.48	0.62
RSC	0.39	0.33	0.29	0.25	0.31
RS	0.40	0.36	0.31	0.24	0.33
BC	0.48	0.41	0.38	0.33	0.40
GG	0.23	0.19	0.17	0.19	0.19
YG	0.23	0.20	0.17	0.16	0.19
Mean	0.39	0.34	0.30	0.26	
LSD (5%)	RSC level = 0.01, amendments = 0.01, interaction = 0.03				

Table 4.9 Effect of application of chemical and organic amendments on exchangeable cations (meq 100 g⁻¹) in sandy clay loam soil after wheat harvest

Amendments	Exch Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.86	4.51	9.56	12.65	6.90
FYM	0.96	3.62	9.50	12.54	6.66
RSC	0.84	3.51	9.40	11.98	6.43
RS	0.61	3.45	9.49	12.81	6.59
BC	0.85	3.69	9.41	12.75	6.67
GG	0.83	3.41	9.26	10.51	6.00
YG	0.82	3.34	9.21	10.10	5.87
Mean	0.82	3.65	9.40	11.91	
LSD (5%)	RSC level = 0.09, amendment = 0.12, interaction = 0.24				
	Exch Ca+Mg				
C	5.47	4.13	3.87	3.47	4.23
FYM	5.73	4.90	4.77	4.57	4.99
RSC	5.53	5.07	4.90	4.83	5.08
RS	4.33	4.73	4.60	4.53	4.55
BC	4.23	4.50	4.43	4.30	4.37
GG	5.67	5.73	5.47	5.30	5.54
YG	5.70	5.77	5.53	5.43	5.61
Mean	5.24	4.98	4.80	4.63	
LSD (5%)	RSC level = 0.10, amendment = 0.13, interaction = 0.26				
	Exch K				
C	0.31	0.26	0.24	0.22	0.26
FYM	0.59	0.52	0.51	0.44	0.51
RSC	0.41	0.31	0.29	0.31	0.33
RS	0.45	0.34	0.34	0.28	0.35
BC	0.47	0.39	0.38	0.32	0.39
GG	0.29	0.26	0.26	0.23	0.26
YG	0.30	0.29	0.28	0.23	0.28
Mean	0.40	0.34	0.33	0.29	
LSD (5%)	RSC level = 0.01, amendment = 0.01, interaction = 0.02				

and have less microbial activity as compared with clayey soils resulting in lower decomposition of added organic material. The interaction between RSC levels and applied amendments was significant for exchangeable Na. Yellow gypsum was statistically superior at RSC 10 and comparable with GG at RSC 5 and 7.5 in reducing exchangeable sodium in ls and scl.

Increasing sodicity in soils due to irrigation with RSC 5, 7.5 and 10 level of sodic water irrigation significantly decreased the mean values for exchangeable calcium and magnesium (exch. Ca+Mg) by significant margin in ls (10.0, 61.3 and 68.3%) than scl (4.9, 8.4 and 11.64%), respectively over RSC 0. It might be due to lower CEC of ls soils and more proportion of calcium and magnesium being precipitated out due to continuous irrigation with sodic-water irrigation. Upon amelioration, increase in the mean values for exch. Ca+Mg were higher with the application of either type of gypsum in both the soils at all RSC levels. Alcívar *et al* (2018) also observed an increase in exchangeable Ca^{2+} on application of gypsum which was attributed to increase in Ca^{2+} content in soils which facilitated more exchange of Na^+ from soil exchange sites. Also, the organic amendments increased the mean values for exch. Ca+Mg in the following order: rice straw compost > FYM > RS ~ BC in ls soil whereas, in scl soil, the order slightly varied as: rice straw compost ~ FYM > RS > BC. Significant interaction among RSC levels and applied amendments was observed for exch. Ca+Mg. Gypsum (both types) increased the exch. Ca+Mg at all levels of RSC in both the soils. Rice straw compost at all levels of RSC followed by FYM at RSC 5; FYM at par with RS and BC at RSC 7.5 and 10 increased exch. Ca+Mg over the respective controls of RSC levels in ls. In scl, rice straw compost was at par with FYM at RSC 5 and 7.5 levels of irrigation water in increasing the exchangeable calcium and magnesium.

The data also revealed significant reductions in exchangeable K with increasing levels of irrigation water sodicity in both the soils. However, significant increase in mean exchangeable K was observed in YG treated scl only while organic amendments also gave promising results. The order in which these amendments statistically increased mean values of exchangeable potassium is: FYM > BC > RS > rice straw compost in both the soils. The interactive effect of increase in sodicity of irrigation water and application of amendments on exchangeable potassium was significant. Amending with FYM followed by BC was effective in significantly increasing exchangeable K at all levels of RSC in both the soils.

4.1.1.13 Exchangeable sodium percentage

The data in Table 4.10 presents the effect of sodic water irrigation and application of amendments on ESP in sodic-water irrigated ls and scl soils. It is evident that the ESP increased significantly over the control and considerably higher for ls (14.4, 24.6 and 30 times) than scl (3.2, 9.3 and 11.5 times) at RSC 5, 7.5 and 10 level of sodic water irrigation, respectively. Higher magnitude of increase in ESP for ls can be attributed to lower CEC of

these soils. The build-up of ESP in soils under high RSC waters may be attributed to greater supply of sodium bicarbonate and proportionately higher exchange of Na⁺ ions from the soil solution with Ca²⁺ ions on the exchange complex. Upon amelioration, maximum decrease in ESP was observed with the application of GG and YG in both the soils at all levels of sodic water irrigation. Similar decrease in ESP values were observed by Singh *et al* (2016) with the application of gypsum at 50% GR. Ezlit *et al* (2010) and Prapager *et al* (2012) also observed a decrease in ESP upon gypsum application which was attributed to desodification resulting from increased exchangeable efficiency of Ca²⁺ on the exchange complex. Application of rice straw compost was the most effective in reducing ESP over control in scl whereas in ls, all organic amendments were at par. The interaction among RSC levels and applied amendments was significant for ESP in both the soils. Yellow gypsum effectively reduced ESP at RSC 10 while being at par with GG at RSC 5 and 7.5 in ls but could not lower the soil ESP below critical limit of 15. In scl, decrease in ESP was statistically greater for GG at RSC 7.5 and 10 while being at par with YG at RSC 5. Among the organic amendments, FYM and RSC in ls and with RS in scl significantly reduced ESP at RSC 5 while being at par with other amendments at RSC 7.5 and 10 in both the soils.

Table 4.10 Effect of application of chemical and organic amendments on exchangeable sodium percentage in loamy sand and sandy clay loam soil after wheat harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	5.52	59.64	61.51	78.09	51.19	7.42	41.44	60.95	65.17	43.75
FYM	4.56	39.92	61.13	68.25	43.46	8.64	34.02	56.49	57.92	39.27
RSC	3.99	39.59	60.57	69.24	43.35	7.87	33.49	56.65	59.06	39.27
RS	4.48	44.80	63.40	71.63	46.08	6.65	34.74	58.03	61.57	40.25
BC	4.98	45.14	63.81	68.32	45.57	8.19	39.59	56.67	63.67	42.03
GG	3.94	35.23	53.28	55.62	37.02	7.71	30.23	52.78	53.13	35.96
YG	3.29	34.62	52.07	61.63	37.90	7.59	29.43	50.33	50.78	34.53
Mean	4.40	42.71	59.40	67.54		7.72	34.71	55.99	58.76	
LSD (5%)	RSC level = 0.60, amendment = 0.80, interaction = 1.59					RSC level = 0.52, amendment = 0.69, interaction = 1.37				

4.1.1.14 Microbial biomass carbon

Irrigation with sodic water significantly decreased MBC in both the soils (Table 4.11). The mean MBC values were higher for scl than ls soil. It could be due to greater

availability of carbon substrates in these soils as evident from higher oxidisable organic carbon values and may be better environment for thriving of microbes in scl. The mean values of MBC decreased by 16.5, 52.5 and 63.1% and by 18.2%, 51.6% and 62.7% in ls and scl, respectively at RSC 5, 7.5 and 10 level of sodic-water irrigation over the control (RSC 0). Choudhary *et al* (2013) reported a significant reduction in soil MBC upon long-term irrigation with sodic-water. The decrease in MBC was ascribed to the deterioration of soil physical and chemical properties which impacted microbes and their activity in soil. Batra *et al* (1997) also noted a decrease in MBC in sodic environment as a direct consequence to increase in ESP and high pH along with deterioration of physical properties of the soil. However, application of both organic and chemical amendments increased the microbial activity significantly over the control. The organic amendments presented the following order of increasing MBC in both the soils: rice straw compost~RS > FYM > BC. Azmal *et al* (1996) observed an increase in MBC on addition of plant residues in soil. Moreover, readily available C pool from the organic sources increased microbial population in soils (Selvi *et al* 2004). The increase in MBC upon application of organic amendments can be attributed to the availability of additional substrate to the microbial population and also reduces osmotic and pH stress on microorganisms (Pathak and Rao 1998). Significant interaction between RSC levels and amendments revealed that rice straw compost at RSC 5 in ls and scl increased MBC significantly over other amendments. At RSC 7.5 and 10, YG, GG and rice straw compost remained at par with each other in increasing MBC values over the respective controls.

Table 4.11 Effect of application of chemical and organic amendments on MBC (mg kg⁻¹ soil) in loamy sand and sandy clay loam soil after wheat harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	121.2	94.9	67.1	34.3	79.4	158.1	120.6	75.2	61.6	103.9
FYM	239.7	163.1	93.1	74.8	142.7	269.2	178.1	100.8	81.7	157.4
RSC	278.3	184.3	100.1	80.4	160.8	281.7	203.2	118.9	85.0	172.2
RS	247.3	161.6	97.3	78.6	146.2	275.5	158.1	100.7	82.1	154.1
BC	179.6	154.7	88.1	70.7	123.3	191.6	146.9	94.2	79.5	128.0
GG	194.7	157.3	102.9	83.3	134.5	220.1	175.4	122.6	90.3	152.1
YG	196.9	155.6	104.5	85.3	135.6	227.9	183.3	130.4	92.4	158.5
Mean	208.24	153.07	93.31	72.48		232.02	166.49	106.11	81.79	
LSD (5%)	RSC level = 2.92, amendment = 3.87, interaction = 7.74					RSC level = 3.09, amendment = 4.09, interaction = 8.18				

4.1.2 Rice crop

4.1.2.1 Biomass yield

The effect of sodic-water irrigation and application of various amendments on aboveground biomass of rice in ls and scl soils is presented in Figure 4.8. It is evident that biomass yield, irrespective of amendments, decreased significantly with increasing RSC levels of sodic-water irrigation by 17.2, 30.3 and 45.1% and 23.7, 36.6 and 48.7% at RSC 5, RSC 7.5 and RSC 10 in ls and scl compared with RSC 0, respectively. Sodium accumulation has been known to impact plant growth via osmotic stress, specific ion toxicity and nutritional imbalances caused due to high pH and ESP in sodic water irrigated soils. In contrast, application of chemical amendments increased biomass yield significantly over the control in both the soils at all levels of RSC due to their recurring application. Increase in biomass yield was observed due to better improvement in soil conditions under gypsum treated soils i.e. decrease in pH, SAR and ESP relative to other amendments. Saqib *et al* (2021) reported maximum decrease in biomass and crop yield during two years of experiment in rice crop

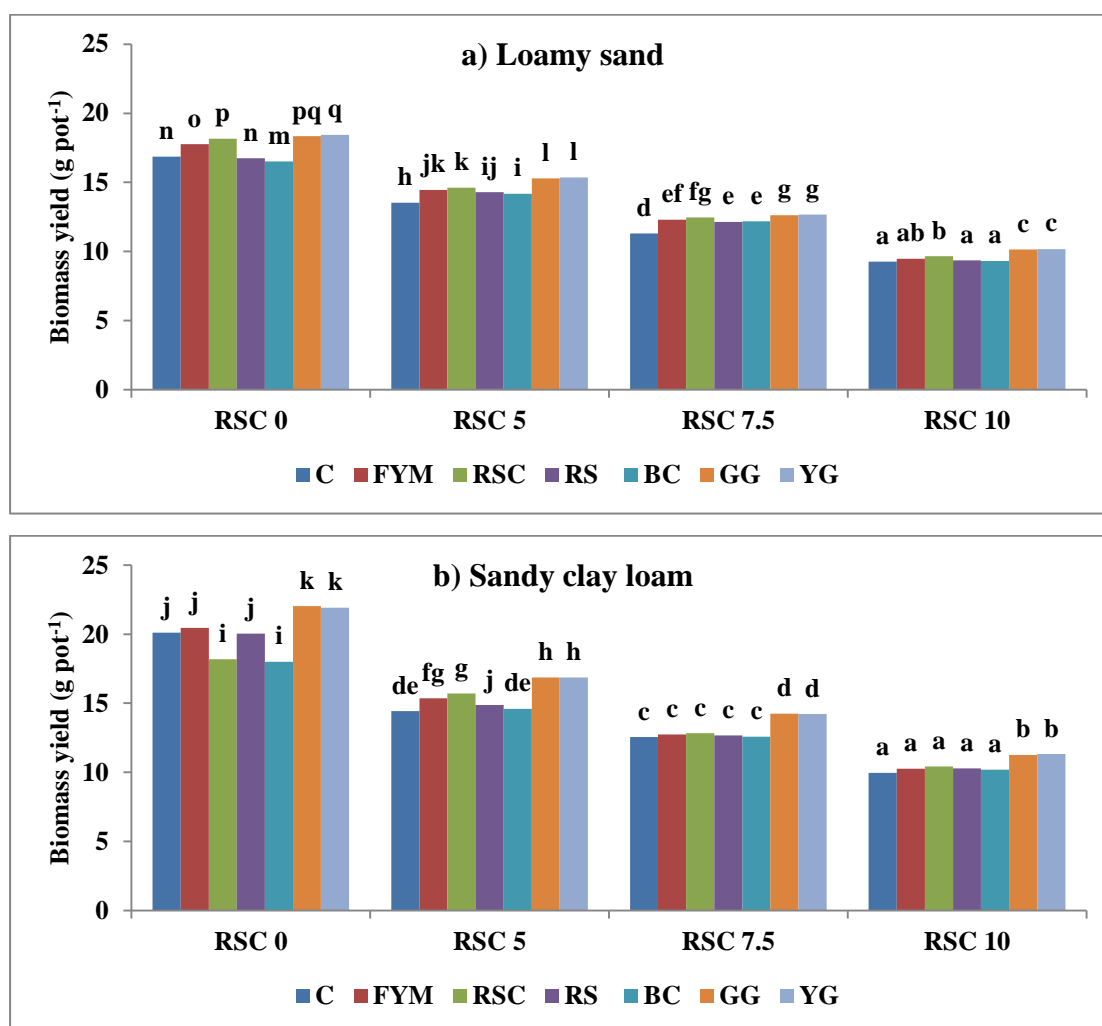


Fig 4.8 Effect of application of chemical and organic amendments on biomass yield of rice crop (g pot^{-1}) in a) loamy sand and b) sandy clay loam soil

where brackish water was solely used for irrigation. Among the organic amendments, rice straw compost and FYM improved biomass yield significantly at all RSC levels over the control in ls and only at RSC 5 level of sodic water irrigation in scl while no such significant effect was observed in RSC 7.5 and 10 level of sodic water irrigation in the latter. Improvement in soil physico-chemical properties through application of organic matter enhanced physiological functions in plants and ultimately growth and yield of plants (Murtaza *et al* 2015). Addition of organic matter improved soil biological activity which benefitted plants with nutrient uptake and thus the increased the biomass yield (Huang *et al* 2019).

4.1.2.2 Plant height

Plant height of rice crop decreased significantly by 6.2, 17.7 and 30.2% and 20.5, 29.3 and 40.0% at RSC 5, RSC 7.5 and RSC 10 compared with RSC 0 in ls and scl, respectively. Favourable effect of recurring application of gypsum was evident as increase in plant height was noted at all levels of RSC in both the soils. Improved availability of Ca²⁺ and other nutrients with reduction in SAR and ESP led to good growth of plants and thus

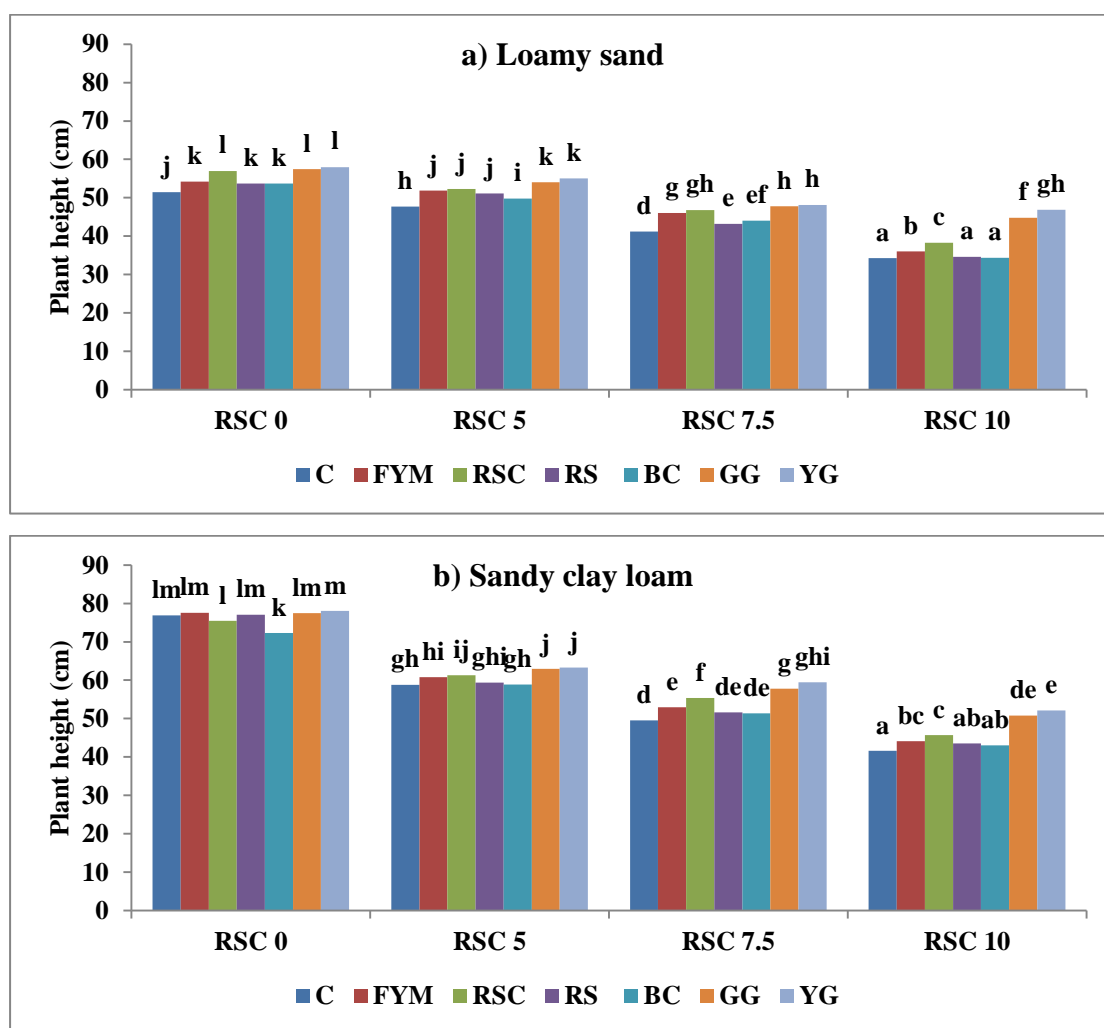


Fig 4.9 Effect of application of chemical and organic amendments on plant height (cm) of rice crop in a) loamy sand and b) sandy clay loam soil

increased plant height in gypsum-treated sodic-water irrigated pots. In ls, rice straw compost was statistically at par with FYM and RS at RSC 5 and with FYM alone at RSC 7.5 level in increasing plant height over the control. Application of FYM before wheat had significant residual effect than other organic amendments in rice crop in soils receiving RSC 10 water. In scl, rice straw compost application was at par with FYM and RS in RSC 5 irrigated soils whereas FYM application was found to be superior over other organic amendments at RSC 7.5 and 10 levels over RSC 0 treatment. Similar results have been obtained by Niamat *et al* (2019) with the application of Ca-fortified compost. Organic amendments increase the availability of nutrients and improve soil physico-chemical properties of soil which ultimately improve growth parameters and yield of plants (Choudhary *et al* 2011a; Murtaza *et al* 2015).

4.1.2.3 Uptake of cations (Na, K, Ca, Mg)

The uptake of sodium, potassium, calcium and magnesium by plants due to sodic water irrigation and application of various amendments for both soils is presented in Figures 4.9 and 4.10. The Na uptake increased after harvest of rice as compared with that after wheat due to greater biomass yield obtained and relatively more number of irrigations with RSC waters for rice crop. It was evident that Na uptake increased and the increase was significant over the control by 1.39, 1.86 and 2.06 times and 1.84, 1.96 and 2.19 times at RSC 5, 7.5 and 10 levels in ls and scl, respectively. The increase in Na uptake commensurating with increase in sodium concentration in soil solution under saline irrigated conditions is well documented by Gao *et al* (2008) and Niamat *et al* (2019). Among all amendments, maximum and significant decrease in Na uptake over the respective unamended controls was observed in BC treatment in both the soils. This treatment was at par with both gypsum treatments at RSC 7.5 in ls. Biochar stimulated Na immobilization from the soil solution onto the negatively charged surface thus protecting plant tissues from ion toxicity. Also, gypsum supplied with subsequent irrigations reduced the solution Na⁺ concentration by releasing Ca²⁺ ions into the soil solution thus counteracting the detrimental effect of consistent sodic-water application. K uptake decreased with increase in sodicity of irrigation water significantly over the control by 34.3, 58.5 and 76.7% in ls and, 33.1, 63.9 and 77.2% in scl, respectively at RSC 5, 7.5 and 10 level of sodic-water irrigation.

Upon amelioration, significant increase in K uptake by plants in FYM application closely followed by rice straw compost treatment was observed over the control in both the soils at all RSC levels. Increase in K uptake under FYM and rice straw compost amended pots can be attributed to the enhanced availability of soluble K in soil upon decomposition due to higher concentration of K in these organic amendments relative to other organic amendments.

The decrease in Ca uptake was significant over the control by 53.1, 76.0 and 83.5% in ls and, by 61.7, 80.2 and 86.6% in scl, respectively at RSC 5, RSC 7.5 and RSC 10 levels.

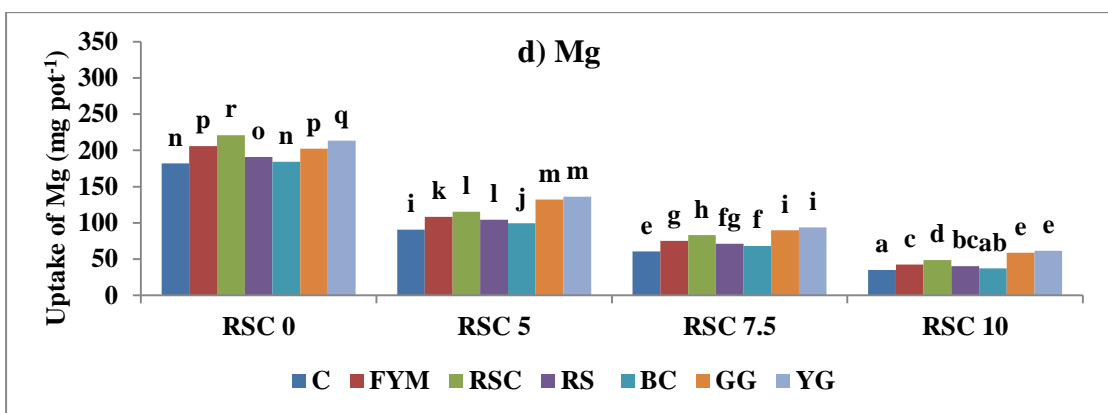
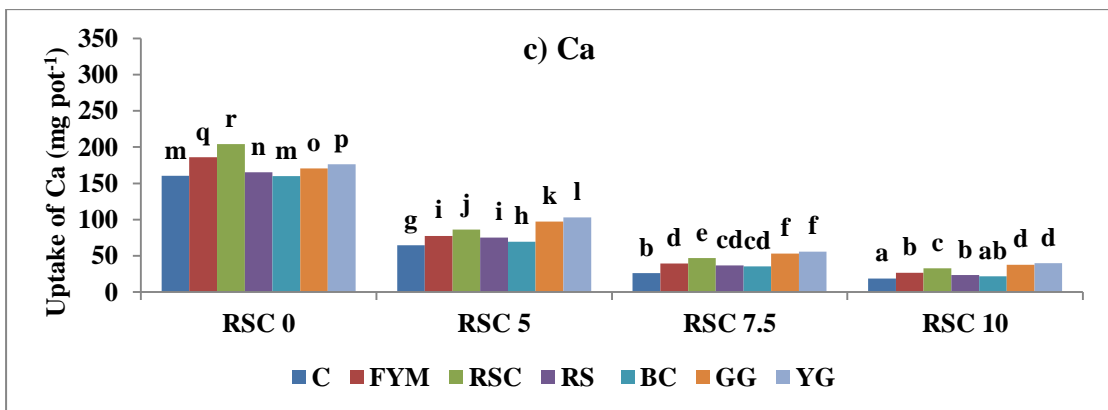
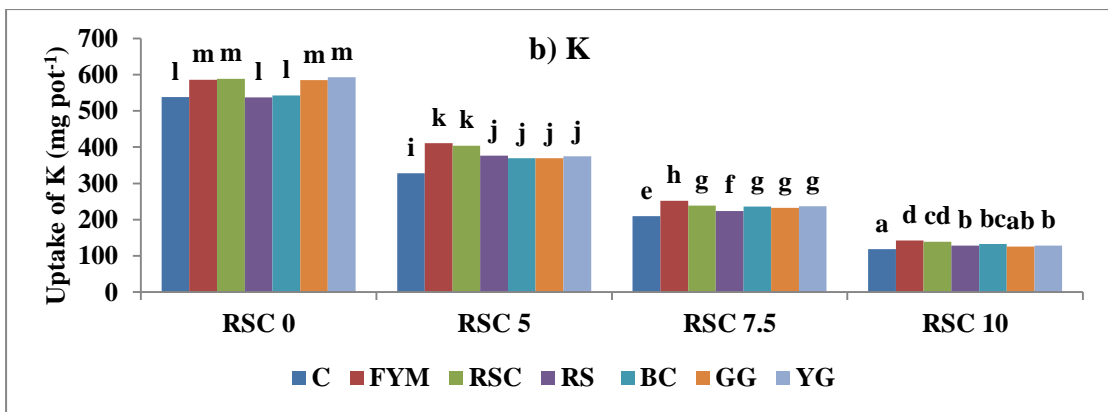
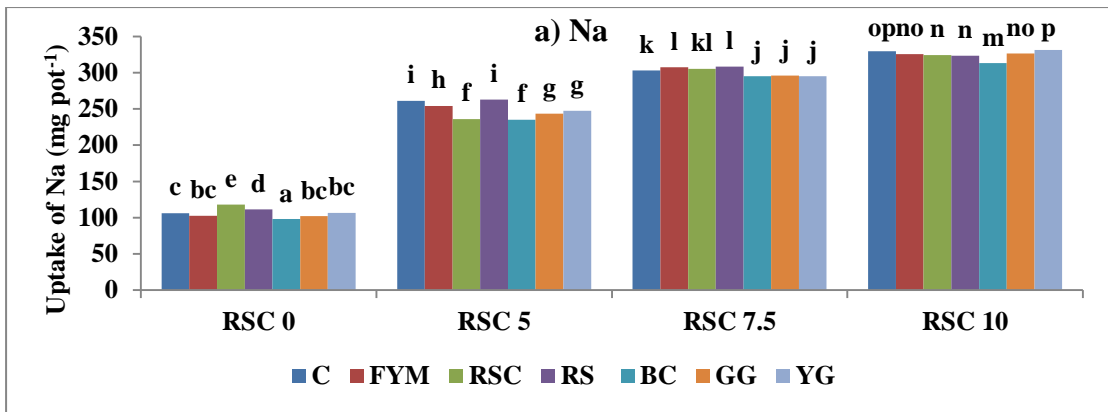


Fig. 4.10 Effect of application of chemical and organic amendments on uptake (mg pot^{-1}) of a) sodium b) potassium c) calcium d) magnesium by rice plants in loamy sand soil

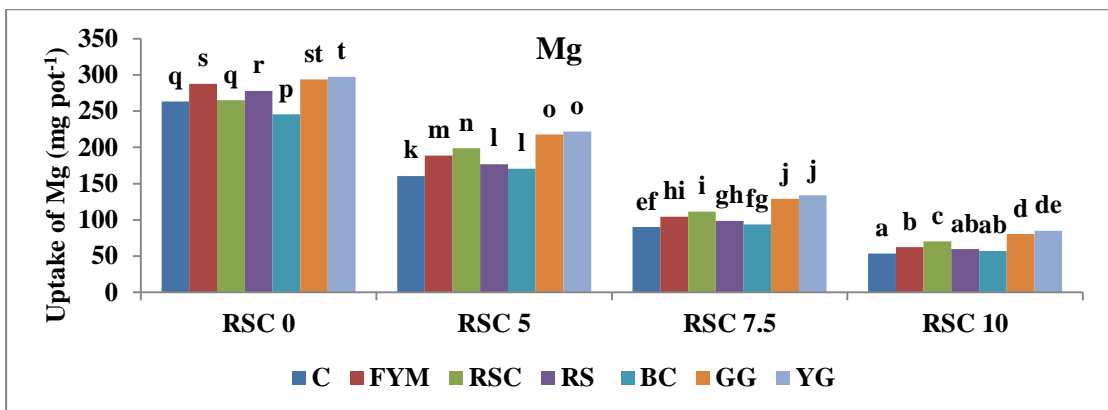
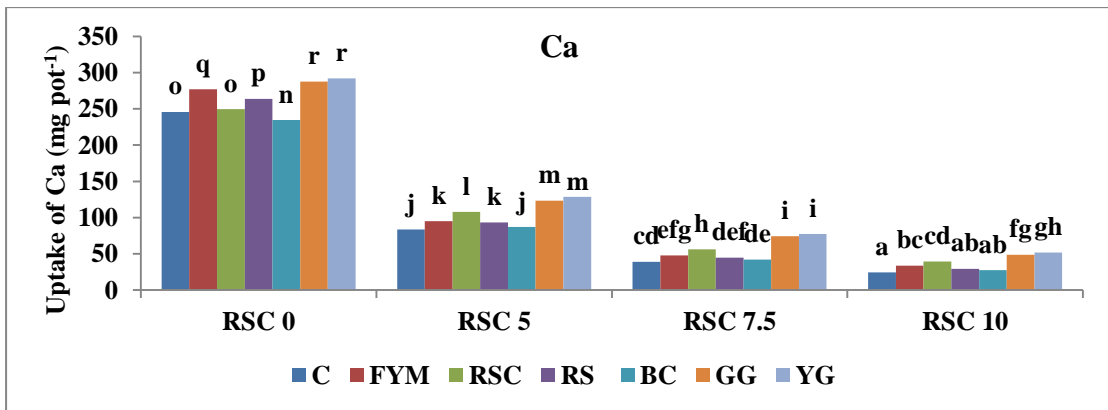
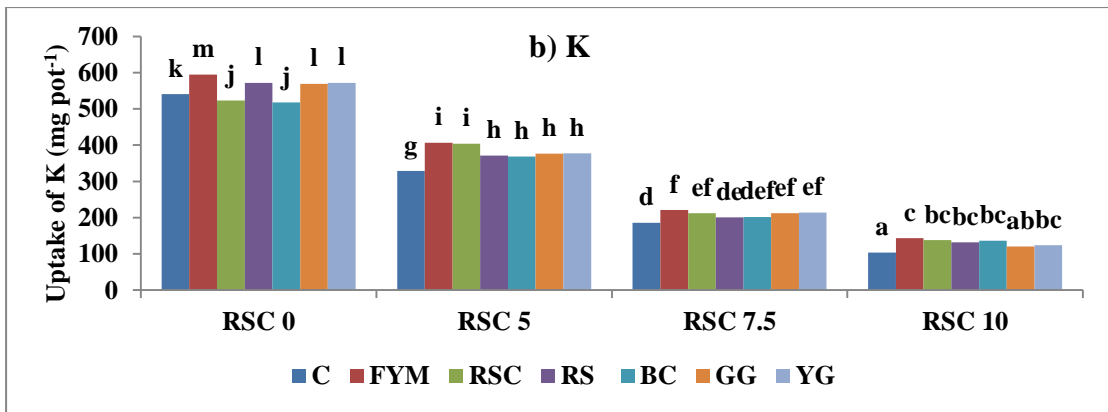
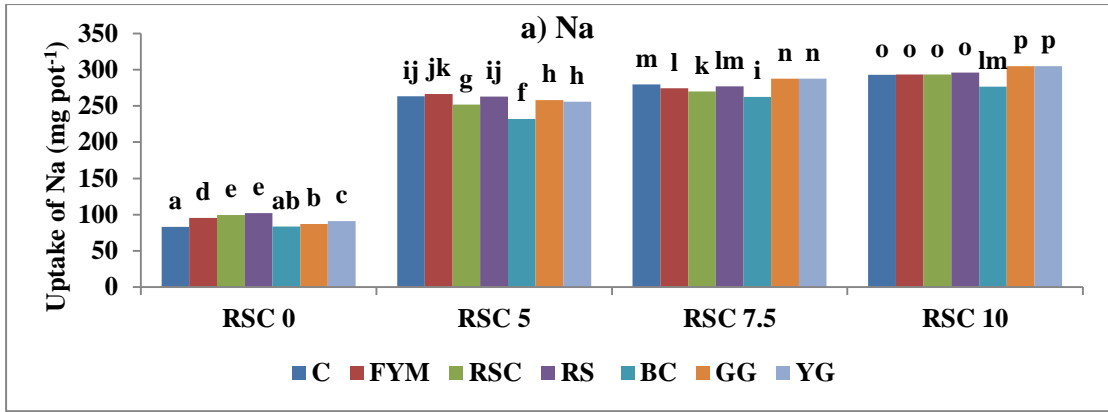


Fig. 4.11 Effect of application of chemical and organic amendments on uptake (mg pot^{-1}) of a) sodium b) potassium c) calcium d) magnesium by rice plants in sandy clay loam soil

The decline in Ca uptake due to increasing sodicity of irrigation water can be attributed to increase in external Na concentration which displaces Ca from the binding sites on the outer surface of plasma lemma of root cell or from intercellular membrane which decreased the Ca uptake by plants (Lynch and Lauchli 1985). Application of YG, GG and rice straw compost increased the Ca uptake significantly over the respective control at all levels of RSC in both the soils. This could be attributed to increased availability of Ca^{2+} ions upon gypsum dissolution and higher concentration of calcium in rice straw compost.

The Mg uptake by rice plants followed similar trend as observed in case of Ca i.e. with increase in levels of RSC of sodic water; Mg uptake decreased significantly by 43.8, 61.3 and 76.7% in ls and 31.7, 61.8 and 76.5% in scl at RSC 5, 7.5 and 10 level of sodic water irrigation, respectively. Calcium competes with magnesium for binding sites on the root plasma lemma and magnesium being hydrated is less favoured over calcium in sodic soil condition thus reducing its uptake as compared to uptake of calcium. Therefore, high levels of Na result in decreased availability of Ca and Mg (Hansen and Munns 1988). In the present study, application of YG, GG and rice straw compost was effective in increasing Mg uptake of significantly over the unamended control.

4.1.2.4 Photosynthetic rate

The data pertaining to the effect sodic water irrigation and application of various amendments on photosynthetic rate (Pn) of rice plants is presented in Figure 4.11 for both soils. The data revealed that irrigation with the increasing RSC levels of irrigation water decreased the Pn in plants significantly over the control by 22.0, 46.9 and 59.3% and 20.3, 35.4 and 52.7% in ls and scl, respectively. In previous studies it has been observed that poor soil conditions such as increased pH, SAR and ESP under sodic water irrigation leads to reduced photosynthetic efficiency and plant adaptation as a whole (Zhu 2001). This increase in sodicity leads to increase in stress injury and disturbs ionic concentration in plant tissues which ultimately affects crop yields (Munns 2002; Hajiboland *et al* 2014). Application of chemical amendments (YG and GG) increased the Pn increased over the respective controls in both the soils at all levels of RSC of irrigation water. Application of rice straw compost proved most effective organic amendment at each RSC level in both the soils.

Availability of desired Ca in the soil solution which replaced Na from the clay lattice and supplementation of S and better uptake of K upon gypsum application led to improved SAR and ESP of soils which ultimately improved plant adaptation and thus bringing about better photosynthetic efficiency under sodic water irrigated conditions (Porra 2002; Soni *et al* 2016; Venkata Rao *et al* 2014). Application of rice straw compost also led to significant reduction in SAR and ESP values in both the soils thus, leading to improvement in plant physiological adaptation and improvement in Pn.

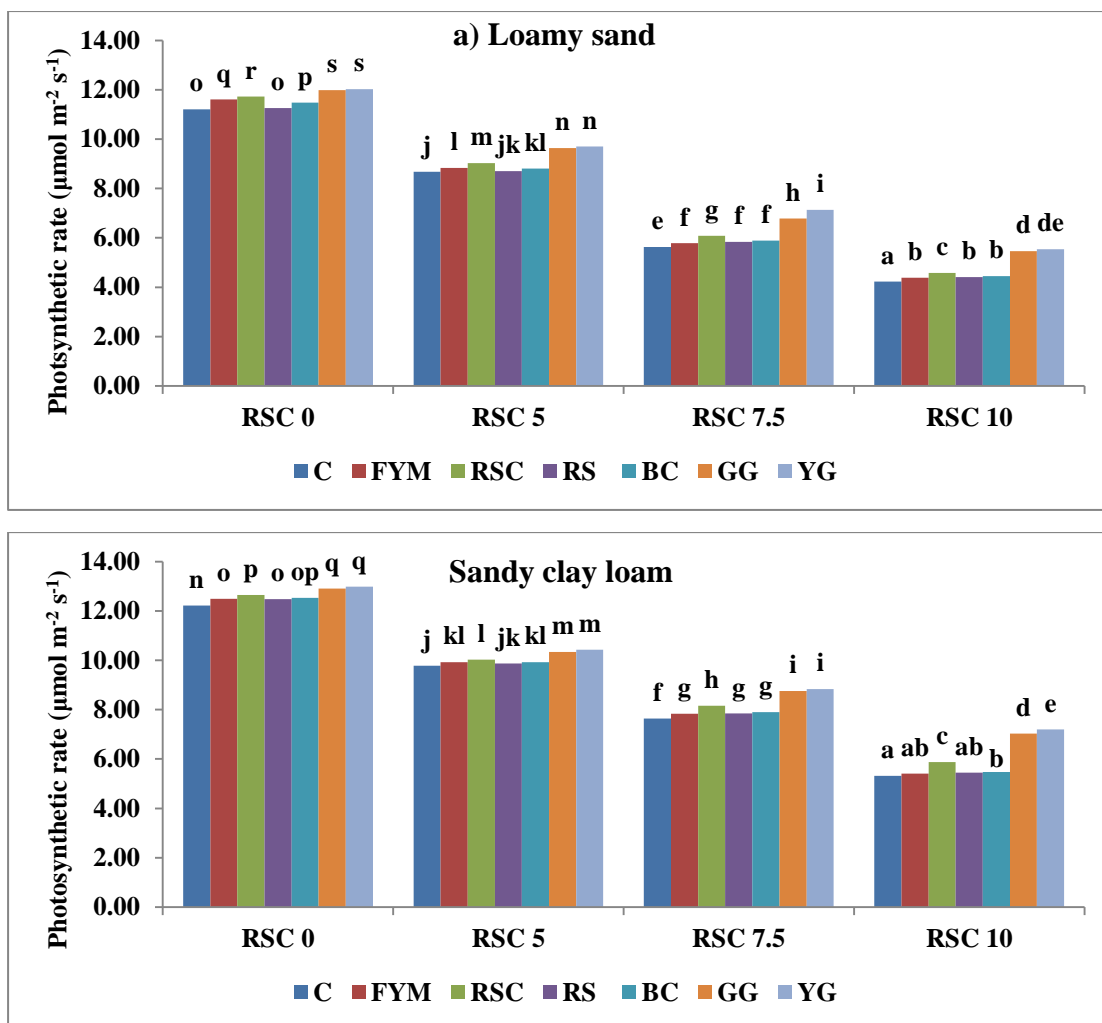


Fig. 4.12 Effect of application of chemical and organic amendments on photosynthetic activity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) of rice plants in a) loamy sand and b) sandy clay loam soil

4.1.2.5 Stomatal conductance (gS)

The results presented in Figure 4.12 pertaining to the effect of application of various amendments in sodic water irrigated soils on stomatal conductance (gS) by plants revealed that stomatal exchange was negatively impacted with the increase in RSC levels of irrigation water in both the soils. The decrease was significant over the control by 22.2, 38.3 and 47.2% in ls and, 11.9, 33.7 and 43.6% in scl over RSC 0 at RSC 5, 7.5 and 10, respectively. Stomatal conductance decreased with sodic water irrigation due to increase in sodicity stress in plants (Sheoran *et al* 2021) as evident from higher uptake and accumulation of Na in plant tissues and associated reduced K availability which is responsible for stomatal opening. However, significant increases in mean gS over the respective control was observed with the application of YG (13.8-16.1% in ls and 9.0-15.3% in scl) followed by GG (11.6-13.6% in ls and 7.3-13.2% in scl). Rice straw compost application increased the stomatal conductance significantly over other organic amendments and the unamended control in both the soils. It

was in fact at par with GG at RSC 10 treatment in ls. Gypsum and rice straw compost application led to increase in stomatal conductance due to decrease in pH, SAR and ESP and, improved soil physico-chemical properties and nutrition to plants from gypsum dissolution and decomposition of rice straw compost and other organic amendments.

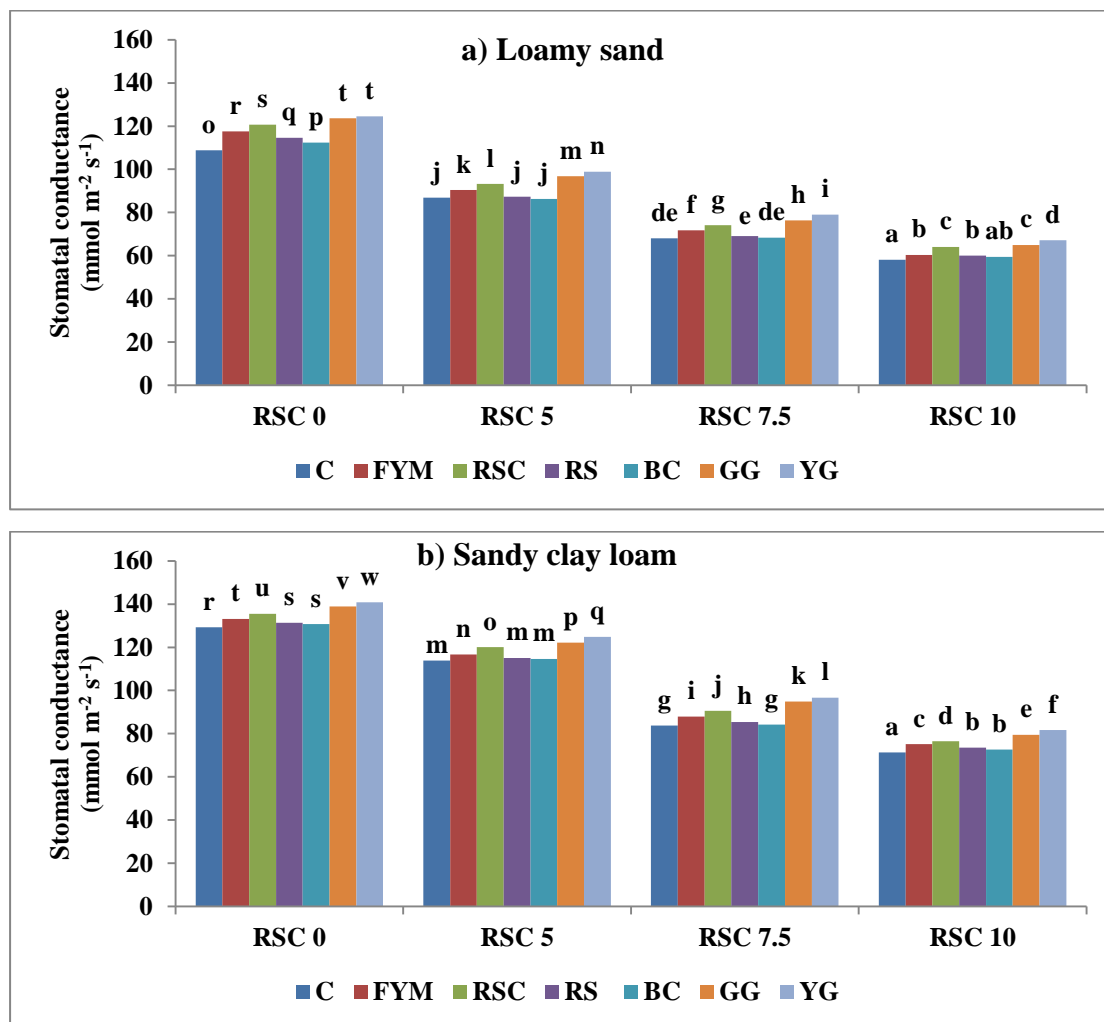


Fig. 4.13 Effect of application of chemical and organic amendments on stomatal conductance ($\text{mmol m}^{-2} \text{s}^{-1}$) of rice plants in a) loamy sand and b) sandy clay loam soil

4.1.2.6 Proline

Figure 4.13 depicts the effect of sodic water irrigation and application of amendments in soils on proline content in plants. The data revealed that proline content increased significantly from 1.42 to 1.78 mg g^{-1} in ls and from 1.18 to 1.55 mg g^{-1} in scl as RSC increased from 0 to 10 meq L^{-1} . Proline accumulation in leaves is linked to the expression of genes encoding key enzymes of proline synthesis pyrroline-5-carboxylate (P5C) and low activity of oxidising enzymes (proline dehydrogenase) which are controlled by osmotic and salt stress (Uma *et al* 1995). However, upon amelioration, significant decreases in mean proline content over the control was observed with the application of YG (12.4% in ls and

13.8% in scl) followed by GG (10.6% in ls and 11.0% in scl). The organic amendments also reduced the sodicity stress and followed order of decrease in proline content as: rice straw compost > FYM > RS > BC in both the soils. It has been observed that both rice and wheat cope with salt stress by regulating ion movement in leaves and shoots (Dadshani *et al* 2019), maintaining lower Na^+/K^+ ratio (El-Hendawy *et al* 2017) and by accumulating osmoprotectants to safeguard from reactive oxygen species (ROS) (Chunthaburee *et al* 2016). Further, gypsum and rice straw compost application reduced proline content in plant tissues indicating better soil conditions for plant growth and thus, providing resistance against sodicity stress caused due to consistent sodic water irrigation.

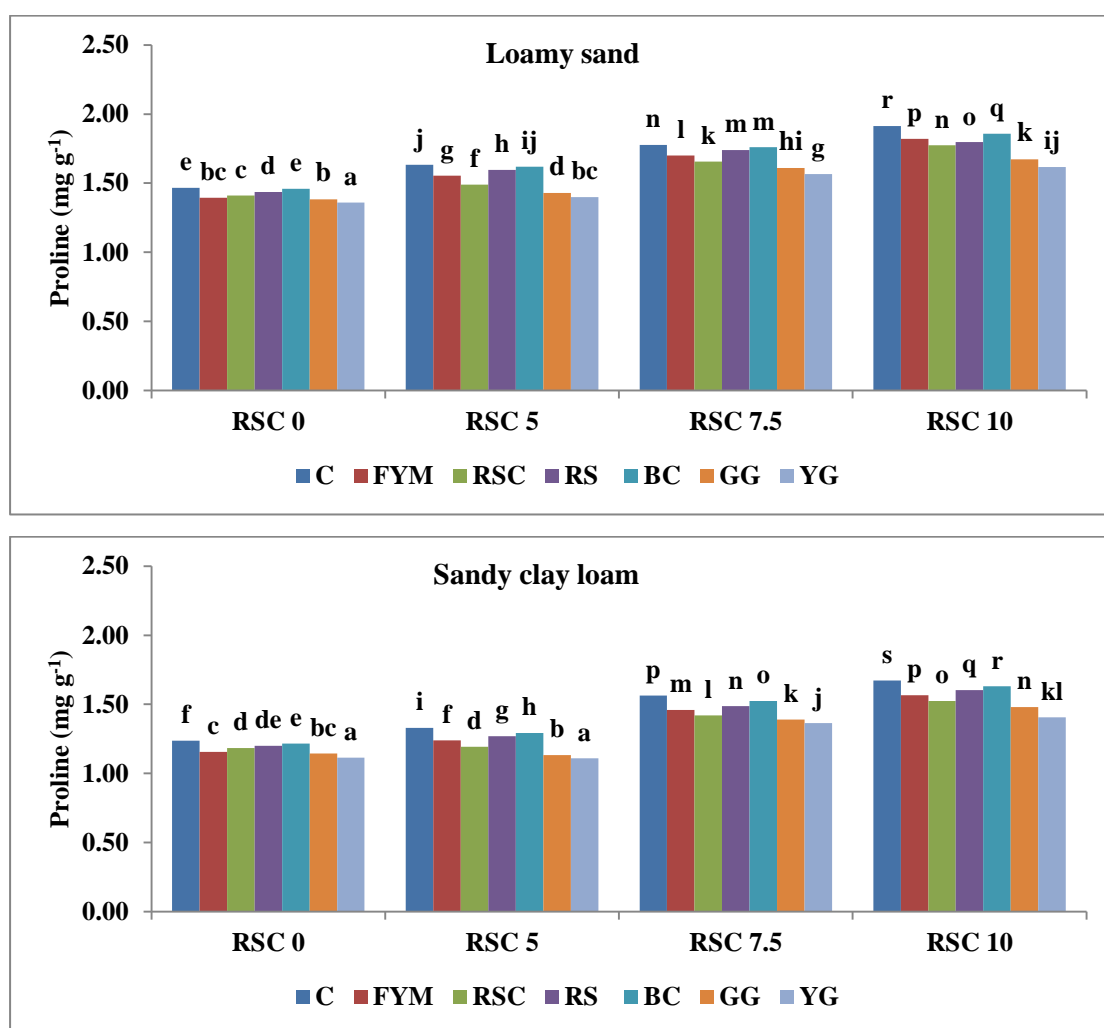


Fig. 4.14 Effect of application of chemical and organic amendments on proline content (mg g^{-1}) in leaves of rice crop in a) loamy sand and b) sandy clay loam soil

4.1.2.7 Soil pH and EC

The data regarding the effect of sodic water irrigation and application of inorganic and organic amendments on pH of both the soils is presented in Table 4.12. The mean pH values were relatively lower after rice harvest compared with that of post-harvest wheat soil primarily due to increase in pCO_2 upon submergence in rice crop which depressed production

of OH⁻ ions in the soil solution on hydrolysis of sodium bicarbonate. Nevertheless, increase in sodicity of irrigation water increased the mean pH values significantly by 10.9, 21.3 and 24.4% in ls and, 6.2, 10.8 and 17.3% in scl at RSC 5, RSC 7.5 and RSC 10 levels of sodic water irrigation over RSC 0 treatment, respectively. On the other hand, recurring effect of gypsum application and residual effect of organic amendment application decreased the mean pH values significantly with the maximum decrease observed with the application of YG (3.0% in ls and 5.2% in scl) followed by GG (2.2% in ls and 4.7% in scl) relative to the unamended control at all RSC levels. Gypsum releases calcium ions upon dissolution which react with bicarbonate ions to precipitate calcite (CaCO₃) and releases H⁺ in soil solution

Table 4.12: Effect of application of chemical and organic amendments on pH and EC in loamy sand and sandy clay loam soil after rice harvest

pH										
Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	7.45	8.79	9.52	9.75	8.88	7.79	8.41	8.89	9.49	8.65
FYM	7.77	8.67	9.41	9.65	8.88	7.94	8.39	8.76	9.47	8.64
RSC	7.78	8.55	9.36	9.65	8.83	7.86	8.38	8.79	9.53	8.64
RS	7.78	8.81	9.42	9.77	8.94	7.87	8.44	8.81	9.53	8.66
BC	7.84	8.79	9.63	9.77	9.01	7.81	8.43	8.91	9.45	8.65
GG	7.85	8.21	9.20	9.50	8.69	7.87	8.18	8.37	8.53	8.24
YG	7.68	8.26	9.22	9.30	8.61	7.82	8.17	8.33	8.48	8.20
Mean	7.74	8.58	9.39	9.63		7.85	8.34	8.70	9.21	
LSD (5%)	RSC level = 0.02, amendment = 0.03, interaction = 0.06					RSC level = 0.01, amendment = 0.02, interaction = 0.04				
EC (dS m⁻¹)										
	ls					scl				
C	0.79	1.23	1.33	1.41	1.19	0.75	0.89	1.28	1.97	1.22
FYM	1.00	1.35	1.41	1.06	1.20	0.75	1.19	1.36	1.75	1.26
RSC	1.09	1.28	1.32	1.39	1.27	1.01	0.88	1.31	1.63	1.21
RS	0.74	1.18	1.30	1.51	1.18	0.91	1.10	1.33	1.63	1.24
BC	0.91	1.39	1.40	1.58	1.32	0.88	0.92	1.29	1.60	1.18
GG	0.68	1.28	1.30	1.44	1.18	0.78	1.44	1.59	3.11	1.73
YG	0.89	1.22	1.33	1.42	1.22	0.78	1.50	1.63	2.56	1.62
Mean	0.87	1.28	1.34	1.40		0.84	1.13	1.40	2.04	
LSD (5%)	RSC level = 0.022, amendment = 0.029, interaction = 0.057					RSC level = 0.027, amendment = 0.037, interaction = 0.074				

which neutralize hydroxide ions (OH^-) and decreases soil pH. The decrease in exchangeable sodium due to application of gypsum also prevents hydrolysis of clays which can produce OH^- ions (Ahmed *et al* 2006). Among the organic amendments, rice straw compost decreased the mean pH values in ls soil while no residual effect was observed in scl. Organic amendments release organic acids which are responsible for dissolution of native lime in soil and release of Ca^{2+} ions into the soil solution (Robbins 1986, Choudhary *et al* 2011a, Prapagar *et al* 2012) leading to reduction in soil alkalinity and improved soil properties. The interaction among RSC levels of irrigation water and applied amendments was significant for pH in both the soils. The pH values were significantly lower with YG and GG at all levels of RSC except at RSC 10 where YG performed better. Rice straw compost at RSC 5 in ls and BC at RSC 10 in scl decreased pH significantly over the control. In scl, application of gypsum was effective in reducing the effect of irrigation with RSC 10 by keeping pH values close to those observed under the unamended RSC 5 treatment.

The mean soil EC values also decreased post-harvest rice as compared to post-harvest wheat crop which could be due to relatively higher uptake of cations by rice crop due to higher biomass yield. However, significant increases in mean values of EC were observed with the increase in RSC of irrigation water in both soils. It could be due to continuous addition of Na in irrigation water and Ca released from soil-exchange complex increasing electrolyte concentration over the control. Addition of chemical amendments led to significant increase over control in the mean EC values in both the soils suggesting release of ions such as calcium and sulphates into the soil solution upon gypsum dissolution. Residual effect of organic amendment application was not observed in reducing EC values.

4.1.2.8 Organic carbon

The mean soil organic carbon (OC) values showed decrease post-harvest rice compared with post-harvest of wheat crop which could be due to more downward movement of labile C beyond 15 cm depth of pot as sampling was carried out in upper 15 cm soil depth only. Further, mean OC values decreased with increase in sodicity of irrigation water in both the soils which was significant by 10.8, 14.5 in ls and 21.9% and, by 3.5, 20.0 and 25.6% in scl at RSC 5, RSC 7.5 and RSC 10 levels compared with RSC 0, respectively. The increase in sodicity of irrigation water and high ESP of soils leads to mineralization of organic matter which causes C mineralization and leads to dispersion of soil organic matter as observed by Dendooven *et al* (2010). Similar decrease in SOC was observed by Basak *et al* (2021) with continued irrigation of RSC_{iw} in the unamended soil for prolonged time. In contrast, residual effect of FYM application was observed as maximum mean increase in OC was noted with this treatment and it was significant over the unamended control. The addition of organic manures is associated with incorporation of organic material and increase in number and activity of microorganisms as reported by Kumar *et al* (2007) and Thind *et al* (2007). The

interactive effect of sodic water irrigation and amendment application had a significant effect on OC in both soils. Application of FYM increased the OC significantly over the respective controls and other applied amendments at all levels of RSC in both the soils except at RSC 10 in scl where it was at par with BC.

Table 4.13 Effect of application of chemical and organic amendments on soil organic carbon (OC %) in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.25	0.23	0.21	0.19	0.22	0.53	0.49	0.44	0.39	0.46
FYM	0.33	0.28	0.27	0.26	0.28	0.61	0.58	0.49	0.48	0.54
RSC	0.28	0.25	0.25	0.21	0.25	0.57	0.56	0.42	0.41	0.49
RS	0.24	0.23	0.21	0.22	0.22	0.57	0.51	0.41	0.39	0.47
BC	0.28	0.24	0.24	0.25	0.25	0.55	0.54	0.45	0.48	0.50
GG	0.25	0.22	0.21	0.17	0.21	0.49	0.50	0.42	0.36	0.44
YG	0.26	0.23	0.22	0.18	0.22	0.50	0.51	0.43	0.34	0.45
Mean	0.27	0.24	0.23	0.21		0.55	0.53	0.44	0.41	
LSD (5%)	RSC level = 0.004, amendment = 0.006, interaction = 0.01					RSC level = 0.009, amendment = 0.013, interaction = 0.026				

4.1.2.9 Soluble cations (Na, K, Ca, Mg)

The mean values soluble Na were higher in post-harvest rice season soil compared with the soil of post-harvest wheat season which is the direct consequence of higher number of sodic water irrigations and more accumulation of sodium ions in soil solution due to lack of drainage during rice season. Additionally, increase in soluble Na was progressive and significant by 3.7, 6.7 and 12.2 times in ls and 5.5, 6.2 and 10.5 times in scl at RSC 5, 7.5 and 10 over the control, respectively. The increase in soluble Na resulted due to its addition from sodium bicarbonate rich irrigation waters. However, positive effect of recurring gypsum application was observed as the soluble sodium content decreased significantly over RSC 0 by 12.5-12.8% in ls and 22.2-23.3% in scl, respectively at different RSC levels. Among the organic amendments, rice straw compost in both the soils resulted in the maximum and significant decrease in soluble sodium content over the unamended control. The significant interaction between RSC levels and applied amendments implied that YG followed by GG significantly decreased soluble Na at all levels of RSC compared with other amendments and control in ls soil. Decrease in soluble Na was significant for YG at RSC 5 being at par with rice straw compost at RSC 7.5 and significantly decreased for BC at RSC 10 in scl soil.

Table 4.14 Effect of application of chemical and organic amendments on soluble cations (meq L⁻¹) in loamy sand soil after rice harvest

Amendments	Soluble Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	3.77	14.32	33.78	46.45	24.58
FYM	4.45	14.73	28.99	41.85	22.51
RSC	3.92	15.41	27.53	50.36	24.30
RS	2.56	15.14	27.72	51.00	24.11
BC	3.16	21.68	27.06	52.56	26.12
GG	2.28	15.49	19.53	36.74	18.51
YG	3.32	12.78	14.78	30.98	15.47
Mean	3.35	15.65	25.63	44.28	
LSD (5%)	RSC level = 0.50, amendment = 0.65, interaction = 1.31				
	Soluble Ca+Mg				
C	2.47	1.77	1.57	1.33	1.78
FYM	2.67	1.87	1.85	1.53	1.98
RSC	3.80	2.15	1.93	1.75	2.41
RS	3.20	1.97	1.75	1.45	2.09
BC	3.40	2.33	1.57	1.43	2.18
GG	3.97	2.67	2.20	2.00	2.71
YG	4.13	3.33	2.47	2.20	3.03
Mean	3.38	2.30	1.90	1.67	
LSD (5%)	RSC level = 0.07, amendment = 0.09, interaction = 0.19				
	Soluble K				
C	0.62	0.54	0.49	0.42	0.52
FYM	1.50	1.21	1.38	1.17	1.32
RSC	0.95	0.78	0.68	0.56	0.74
RS	0.94	0.88	0.80	0.68	0.82
BC	0.95	1.22	1.16	1.07	1.10
GG	0.74	0.68	0.59	0.53	0.63
YG	0.70	0.65	0.56	0.50	0.60
Mean	0.91	0.85	0.81	0.70	
LSD (5%)	RSC level = 0.017, amendment = 0.023, interaction = 0.05				

Table 4.15 Effect of application of chemical and organic amendments on soluble cations (meq L⁻¹) in sandy clay loam soil after rice harvest

Amendments	Soluble Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	3.59	27.54	38.21	52.37	30.43
FYM	4.01	26.71	28.59	47.33	26.66
RSC	5.02	26.48	26.83	45.21	25.89
RS	5.28	27.88	29.60	47.03	27.45
BC	3.80	29.37	29.51	42.17	26.21
GG	3.78	26.32	28.11	49.90	27.03
YG	3.53	25.17	27.34	48.85	26.22
Mean	4.14	27.06	29.74	47.55	
LSD (5%)	RSC level = 0.39, amendment = 0.51, interaction = 1.02				
	Soluble Ca+Mg				
C	3.33	1.73	1.63	1.42	2.03
FYM	3.53	1.80	1.71	1.67	2.18
RSC	4.80	1.96	1.59	1.75	2.52
RS	3.07	1.56	1.43	1.60	1.92
BC	3.47	1.62	1.65	1.60	2.09
GG	4.95	2.52	2.12	1.76	2.83
YG	5.02	2.63	2.21	1.79	2.92
Mean	4.02	1.98	1.76	1.65	
LSD (5%)	RSC level = 0.08, amendment = 0.11, interaction = 0.22				
	Soluble K				
C	2.20	1.63	0.55	0.23	1.15
FYM	2.10	1.61	0.68	0.62	1.25
RSC	2.61	1.42	0.45	0.42	1.23
RS	1.91	1.32	0.57	0.47	1.07
BC	2.14	1.43	0.53	0.48	1.15
GG	2.34	1.35	0.65	0.35	1.17
YG	2.31	1.32	0.62	0.32	1.14
Mean	2.23	1.44	0.58	0.41	
LSD (5%)	RSC level = 0.035, amendment = 0.047, interaction = 0.093				

With increase in the sodicity of irrigation water, soluble calcium and magnesium (Ca+Mg) content declined significantly by 32.0, 43.8 and 50.6% in ls and, 50.7, 56.2 and 59.0% at RSC 5, RSC 7.5 and RSC 10 in scl, respectively over RSC 0. Decrease in Ca+Mg in sodic water irrigated soil is subject to antagonism by continuously added Na and precipitation with anions such as carbonates and bicarbonates in the soil and thus it progressively decreases with increase in sodicity of irrigation water. On the other hand, significant increase in soluble Ca+Mg was observed with the application of YG and GG over control at all RSC levels. Gypsum is the supplier of calcium in soil solution upon dissolution due to its inorganic nature which increased the soluble Ca+Mg significantly over the applied organic amendments. Further, application of rice straw compost resulted in maximum increase in soluble Ca+Mg compared to other organic amendments in ls (35.4%) and scl (24.1%). Rice straw compost (compared with other organic amendments) contains higher calcium and magnesium content which was released upon decomposition and thus, it increased soluble Ca+Mg significantly over other organic amendments. The interaction among RSC levels and applied amendments for soluble Ca+Mg in both the soils demonstrated that significant increases in soluble Ca+Mg were observed with YG followed by GG at all RSC levels in ls while in scl, YG and GG were at par with each other at RSC 5 and 7.5 and were at par with rice straw compost at RSC 10 in increasing soluble Ca+Mg. The increase in soluble Ca+Mg with YG was significant over the control for RSC 5 inferring timely supply of Ca ions into the soil solution. Rice straw compost was effective in increasing soluble Ca+Mg at RSC 10 in ls significantly over other organic amendments.

Likewise, reduction in soluble K content was significant by 6.7, 10.1 and 22.5% in ls and, by 35.4, 66.8 and 80.7% in scl over RSC 0, respectively at RSC 5, RSC 7.5 and RSC 10 levels. However, increase in soluble K over control was observed in FYM application alone in both the soils. Soluble K^+ was observed to be increased in organic amended soil compared with unamended control as observed by Mahmoud *et al* (2019). The interactive effect of sodicity levels and application of amendments had a significant impact on soluble K in both the soils. FYM increased the soluble K significantly at all levels of RSC while being at par with BC at RSC 5 in ls. While in scl, FYM significantly increased soluble K at RSC 7.5 and 10 while barely keeping with control for RSC 5 implying faster recovery of potassium at higher levels of RSC due to application of amendments.

4.1.2.10 Sodium adsorption ratio

The mean SAR values increased post-harvest in rice season soil compared with soil after wheat season mainly on account of significantly higher soluble sodium recorded after rice crop. Mean SAR values increased significantly over the control by 4.63, 9.20 and 17.78 times in ls and by 8.31, 9.75 and 16.60 times in scl at RSC 5, RSC 7.5 and RSC 10 levels, respectively. Mean SAR values were higher for scl than ls due to higher clay content and

CEC. Consistent sodic water irrigation raised sodium levels in soil solution and subsequent decrease in calcium and magnesium content, thereby increasing SAR values significantly over the control. However, recurring application of gypsum decreased SAR values significantly over the control for YG (51.6% in ls and 25.7% in scl) and GG (38.1% in ls and 22.2% in scl) treatments. Decrease in SAR was observed as a direct consequence of “valence dilution” as described by Reeve and Bower (1960). The addition of Ca²⁺ through gypsum dissolution caused the reduction in SAR values and thus soil gets flocculated. The interactive effect of increasing level of sodic water irrigation and application of amendments on SAR was significant. The decrease in SAR was significant for YG followed by GG at all RSC levels in ls. Next to gypsum, FYM proved efficient in decreasing SAR at RSC 10 while slight and insignificant decrease was observed for other amendments in ls. While in scl, YG and GG were equally effective in reducing SAR values over other amendments at RSC 5 and 7.5 while at RSC 10, RSC and BC proved significantly better over gypsum and over other amendments in reducing SAR values inferring their beneficial residual effects in rice crop.

Table 4.16 Effect of application of chemical and organic amendments on SAR in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	3.39	15.23	38.23	56.91	28.44	2.79	29.61	42.28	62.19	34.22
FYM	3.86	15.26	30.17	47.81	24.28	3.02	28.22	30.92	51.92	28.52
RSC	2.84	14.86	28.00	53.86	24.89	3.24	26.80	30.12	48.44	27.15
RS	2.03	15.28	29.64	59.91	26.72	4.27	31.58	35.05	52.58	30.87
BC	2.42	20.13	30.59	62.11	28.81	2.89	32.65	32.49	47.14	28.79
GG	1.62	13.40	18.66	36.74	17.60	2.41	23.46	27.35	53.24	26.61
YG	2.31	9.91	13.32	29.54	13.77	2.23	21.93	26.02	51.59	25.44
Mean	2.64	14.87	26.94	49.56		2.98	27.75	32.03	52.44	
LSD (5%)	RSC level = 0.69, amendment = 0.91, interaction = 1.83					RSC level = 0.59, amendment = 0.78, interaction = 1.56				

4.1.2.11 Soluble anions

The data pertaining to effect of sodic water irrigation and application of various amendments on carbonate, bicarbonate, chloride and sulphate in ls and scl soils is presented in Tables 4.17 and 4.18, respectively. The soluble carbonate content significantly increased over RSC 0 by 0.45, 1.62 and 2.43 times in ls and 1.43, 3.04 and 4.20 times in scl at RSC 5, 7.5 and 10 levels, respectively. Upon amelioration, maximum reduction in soluble carbonate

content was observed with gypsum application (both types) compared with the control. Also, significant decrease was observed with the application of rice straw compost and BC among the organic amendments. The corresponding and significant increase in bicarbonate content was observed to be 0.88, 1.91 and 3.96 times in ls and 0.84, 1.53 and 3.51 times in scl over the control at RSC 5, 7.5 and 10 levels, respectively. However, gypsum applications were effective in significantly decreasing the mean values of soluble bicarbonate. Among the organic amendments, rice straw compost significantly decreased the mean values of soluble bicarbonate by 3.4% in ls and only 1.9% in scl compared with the unamended control. The interaction among RSC levels and applied amendments was significant for carbonate and bicarbonate content in both the soils. Significant decrease in carbonate content was observed with YG and GG followed by rice straw compost at all levels of RSC in ls. While, rice straw compost was at par with YG at RSC 10 in scl in decreasing carbonate content. Maximum and significant decrease in bicarbonate content was observed with GG at RSC 5 and 10 while decrease was insignificant for YG and GG at RSC 7.5 in ls. On the other hand, YG in scl significantly decreased bicarbonate content over GG at RSC 7.5 and 10 and at par with GG at RSC 5.

The mean chloride content also increased from 3.28 to 5.85 meq L⁻¹ in ls and from 4.30 to 8.28 meq L⁻¹ in scl as RSC varied from 0 to 10 meq L⁻¹. This might have been a consequence of decrease in chloride uptake due to poor plant growth because of increase in sodicity of irrigation water i.e. more of the added muriate of potash at the start of the experiment remained unused in the soil. Application of both types of gypsums was more effective in significantly reducing the mean soluble chlorides over control in both the soils. Among the organic amendments, rice straw compost was the most effective. The interaction among RSC levels and applied amendments was significant for chloride content. Application of YG followed by GG decreased chloride content significantly over the respective controls and other amendments at all levels of RSC in both the soils. The organic amendments remained at par with each other in decreasing chloride content (except FYM) at all levels of RSC in both the soils.

With the increase in sodicity of irrigation water, the sulphate content of soils increased significantly over the control. The soluble sulphate increased from 0.81 to 1.07 meq L⁻¹ in ls and from 1.04 to 1.66 meq L⁻¹ in scl as RSC of irrigation water increased from 0 to 10 meq L⁻¹. Increase in sulphate content in soil solution with increase in sodicity of irrigation water can be attributed to decrease in sulphate uptake due to poor plant growth i.e. more of the added SSP remained unused in the soil solution. Maximum decrease in sulphate content was observed with the application of GG (12.0% in ls and 10.2% in scl) followed by YG (10.2% in ls and 8.8% in scl). This decrease can be attributed to the formation of sodium sulphate from sulphate ions supplied through gypsum and sodium ions present in the soil

Table 4.17 Effect of application of chemical and organic amendments on soluble anions (meq L⁻¹) in loamy sand soil after rice harvest

Amendments	CO ₃ ²⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	1.48	2.33	4.21	5.43	3.37
FYM	1.80	2.52	4.37	6.68	3.84
RSC	1.54	2.22	4.01	5.05	3.21
RS	1.66	2.31	4.14	5.19	3.33
BC	1.61	2.23	4.10	5.24	3.29
GG	1.41	2.13	3.92	4.92	3.10
YG	1.45	2.17	3.96	4.98	3.14
Mean	1.56	2.27	4.10	5.36	
LSD (5%)	RSC level = 0.019, amendment = 0.025, interaction= 0.05				
Amendments	HCO ₃ ⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	2.87	6.00	8.73	15.00	8.15
FYM	3.13	6.53	9.07	16.37	8.78
RSC	2.93	5.73	8.57	14.23	7.87
RS	3.27	5.80	8.63	14.53	8.06
BC	3.20	5.87	8.70	14.77	8.13
GG	2.67	4.60	8.27	13.70	7.31
YG	2.53	4.20	8.00	13.37	7.03
Mean	2.94	5.53	8.57	14.57	
LSD (5%)	RSC level = 0.11, amendment = 0.14, interaction = 0.28				
Amendments	Cl ⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	3.20	4.17	5.10	6.20	4.67
FYM	3.47	4.33	5.23	6.47	4.88
RSC	3.53	4.07	4.83	5.83	4.57
RS	3.57	4.17	4.90	6.00	4.66
BC	3.27	4.13	4.87	5.93	4.55
GG	3.03	3.87	4.50	5.33	4.18
YG	2.87	3.70	4.23	5.17	3.99
Mean	3.28	4.06	4.81	5.85	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.16				
Amendments	SO ₄ ²⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.77	0.92	1.13	1.51	1.08
FYM	0.82	1.00	1.23	1.59	1.16
RSC	0.86	0.82	1.02	1.38	1.02
RS	0.88	0.85	1.06	1.43	1.05
BC	0.84	0.88	1.11	1.46	1.07
GG	0.74	0.78	0.96	1.30	0.95
YG	0.76	0.80	0.99	1.33	0.97
Mean	0.81	0.87	1.07	1.43	
LSD (5%)	RSC level = 0.008, amendment = 0.01, interaction = 0.02				

Table 4.18 Effect of application of chemical and organic amendments on soluble anions (meq L⁻¹) in sandy clay loam soil after rice harvest

Amendments	CO ₃ ²⁻				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	1.59	4.07	6.77	8.88	5.33
FYM	1.75	4.28	7.02	9.32	5.59
RSC	1.62	3.81	6.36	7.88	4.92
RS	1.68	3.93	6.57	8.53	5.18
BC	1.64	3.87	6.42	8.46	5.10
GG	1.50	3.70	6.21	7.79	4.80
YG	1.53	3.76	6.26	7.84	4.85
Mean	1.61	3.92	6.52	8.38	
LSD (5%)	RSC level = 0.022, amendment = 0.03, interaction = 0.06				
	HCO ₃ ⁻				
C	3.47	6.83	9.13	16.37	8.95
FYM	3.73	7.13	9.27	16.53	9.17
RSC	3.60	6.63	8.83	16.07	8.78
RS	3.70	6.70	8.90	16.13	8.86
BC	3.67	6.73	8.97	16.33	8.93
GG	3.13	5.40	8.43	14.37	7.83
YG	3.07	5.27	8.20	14.13	7.67
Mean	3.48	6.39	8.82	15.70	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.18				
	Cl				
C	4.27	5.20	6.37	8.43	6.07
FYM	4.40	5.43	6.57	9.43	6.46
RSC	4.43	5.03	5.73	8.10	5.83
RS	4.50	5.13	5.83	8.27	5.93
BC	4.30	5.20	5.77	8.20	5.87
GG	4.10	5.00	5.27	7.87	5.56
YG	4.07	4.83	5.10	7.63	5.41
Mean	4.30	5.12	5.80	8.28	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.16				
	SO ₄ ²⁻				
C	0.98	1.22	1.58	1.72	1.37
FYM	1.06	1.32	1.67	1.82	1.47
RSC	1.11	1.05	1.46	1.61	1.31
RS	1.12	1.10	1.52	1.65	1.35
BC	1.09	1.15	1.55	1.67	1.37
GG	0.95	1.00	1.41	1.55	1.23
YG	0.97	1.03	1.43	1.56	1.25
Mean	1.04	1.12	1.52	1.66	
LSD (5%)	RSC level = 0.01, amendment = 0.01, interaction = 0.02				

solution which might have leached down below the sampling layer with irrigation water. Among the organic amendments, rice straw compost and RS significantly decreased the sulphate content over the unamended control. The interaction among RSC levels and applied amendments was significant for sulphate content. Maximum and significant decrease in sulphate content was observed with GG followed by YG and rice straw compost at all levels of RSC in ls and whereas in scl, YG and GG were at par with each other at RSC 10 in decreasing sulphate content.

4.1.2.12 Exchangeable cations

It is evident from Table 4.19 that the mean exchangeable Na in soils increased over control which was significantly greater for ls (5.11, 7.51 and 18.76 times) than scl (2.57, 4.70 and 12.84 times) soil at RSC 5, 7.5 and 10 levels, respectively. The sandy clay loam soils are highly buffered which delays the development of sodicity in these soils compared with less buffered loamy sand soils. Increase or decrease in concentration of exchangeable cation is dependent on exchange taking place between soil solution and exchange phase. These are affected by relative concentration of different cations in soil solution and on their equilibrium chemistry (Oster and Frenkel 1980). Thus, it can be concluded that increase in soluble Na with increase in sodicity of irrigation water led to more sodium going onto the exchange sites to maintain equilibrium. Similar results were also reported by Chaganti and Crohn (2015). Recurring gypsum application decreased the mean exchangeable Na content significantly over the control for YG (28.5% in ls and 19.8% in scl) and GG (25.1% in ls and 16.3% in scl). The decrease in exchangeable Na due to application of gypsum can be attributed to the ready supply of calcium ions upon gypsum dissolution that replaced sodium from the exchange sites. Among the organic amendments, FYM in ls and FYM at par with rice straw compost in scl decreased the mean exchangeable sodium content considerably below the the unamended control. Organic amendments may have held the sodium ions on the negatively charged sites rendering them unavailable to plants for uptake. Significant interaction among RSC levels and applied amendments revealed that YG and GG were at par with rice straw compost at RSC 5 and with FYM at RSC 7.5 in decreasing exchangeable sodium while YG at RSC 10 decreased exchangeable sodium significantly over GG in ls. In scl, gypsum proved better in decreasing exch. Na values followed by rice straw compost (except at RSC 7.5 where FYM was effective) at all levels of RSC.

The mean values for exchangeable Ca+Mg decreased by 2.4, 5.8 and 8.6 % in ls and 0.75, 4.0 and 5.4% in scl at RSC 5, 7.5 and 10 levels with respect to RSC 0, respectively. Increase in Na concentration in solution phase induced from continuous sodic water irrigation led to displacement of Ca+Mg from the exchange sites on clay complex thus, reducing the content of exchangeable Ca+Mg. Upon amelioration, maximum increase in the mean values for exchangeable Ca+Mg over the control was observed with the application of

Table 4.19 Effect of application of chemical and organic amendments on exchangeable cations (meq 100 g⁻¹ soil) in loamy sand soil after rice harvest

Amendments	Exch Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.36	2.34	3.21	8.27	3.54
FYM	0.40	2.27	3.14	5.89	2.93
RSC	0.47	2.19	3.26	8.72	3.66
RS	0.34	2.30	3.18	9.15	3.74
BC	0.37	2.68	3.16	9.28	3.87
GG	0.33	2.03	3.09	5.15	2.65
YG	0.36	2.01	3.02	4.73	2.53
Mean	0.37	2.26	3.15	7.31	
LSD (5%)	RSC level = 0.031, amendment = 0.041, interaction = 0.081				
	Exch Ca+Mg				
C	4.23	4.80	4.63	4.33	4.50
FYM	5.60	5.33	4.90	4.80	5.16
RSC	4.63	5.40	5.20	5.17	5.10
RS	5.00	5.00	4.87	4.77	4.91
BC	5.57	5.27	4.87	5.10	5.20
GG	6.30	5.60	5.43	5.13	5.62
YG	6.40	5.77	5.53	5.27	5.74
Mean	5.39	5.31	5.06	4.94	
LSD (5%)	RSC level = 0.06, amendment = 0.08, interaction = 0.15				
	Exch K				
C	0.32	0.29	0.26	0.22	0.27
FYM	0.54	0.51	0.49	0.45	0.50
RSC	0.41	0.38	0.33	0.17	0.32
RS	0.60	0.57	0.36	0.29	0.46
BC	0.51	0.49	0.46	0.42	0.47
GG	0.29	0.27	0.27	0.26	0.27
YG	0.28	0.26	0.25	0.25	0.26
Mean	0.42	0.40	0.34	0.29	
LSD (5%)	RSC level = 0.009, amendment = 0.013, interaction = 0.026				

Table 4.20 Effect of application of chemical and organic amendments on exchangeable cations (meq 100 g⁻¹ soil) in sandy clay loam soil after rice harvest

Amendments	Exch Na				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.69	2.75	4.01	10.50	4.49
FYM	0.71	2.54	3.86	10.16	4.32
RSC	0.76	2.37	4.12	9.91	4.29
RS	0.76	2.66	4.15	10.47	4.51
BC	0.65	2.83	4.21	10.60	4.57
GG	0.67	2.19	3.81	8.36	3.76
YG	0.65	2.14	3.74	7.86	3.60
Mean	0.70	2.50	3.99	9.69	
LSD (5%)	RSC level = 0.065, amendment = 0.087, interaction = 0.174				
	Exch Ca+Mg				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	7.53	9.80	8.47	6.40	8.05
FYM	9.60	10.23	10.13	9.87	9.96
RSC	10.60	10.27	10.27	10.00	10.28
RS	11.00	10.13	10.03	9.73	10.23
BC	10.57	10.60	10.30	10.13	10.40
GG	12.50	11.37	11.10	12.13	11.78
YG	12.77	11.60	11.27	12.30	11.98
Mean	10.65	10.57	10.22	10.08	
LSD (5%)	RSC level = 0.07, amendment = 0.09, interaction = 0.17				
	Exch K				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.46	0.32	0.29	0.23	0.33
FYM	0.59	0.43	0.39	0.35	0.44
RSC	0.51	0.35	0.35	0.24	0.36
RS	0.55	0.36	0.34	0.22	0.37
BC	0.48	0.40	0.39	0.25	0.38
GG	0.49	0.32	0.28	0.22	0.33
YG	0.41	0.31	0.29	0.20	0.30
Mean	0.50	0.36	0.33	0.25	
LSD (5%)	RSC level = 0.008, amendment = 0.009, interaction = 0.019				

YG (27.3% in ls and 48.8% in scl) followed by GG (24.4% in ls and 46.3% in scl). In the process of dissolution, gypsum releases calcium ions into the soil solution, reducing the amount of exchangeable Na. Also, significant increase in mean exchangeable Ca+Mg over the control was observed with application of BC in scl; it was statistically at par with FYM and rice straw compost application in ls. The higher amount of Ca+Mg calcium present in these amendments, which were released following decomposition, can be attributed to the rise in exchangeable Ca+Mg. The interaction among RSC levels and applied amendments was significant for exchangeable Ca+Mg in both the soils. Application of YG increased exch. Ca+Mg significantly over GG at RSC 5 while being at par with it at RSC 7.5 in ls. While at RSC 10, YG was at par with rice straw compost and GG in increasing exchangeable calcium and magnesium. In scl, YG followed by GG increased exchangeable Ca+Mg at all levels of RSC. Amending the soil with BC significantly increased exchangeable Ca+Mg over other organic amendments at RSC 5 whereas it was at par with rice straw compost at RSC 7.5 and 10.

Exchangeable potassium significantly decreased by 4.76, 19.04 and 31.0% in ls and, by 28.0, 34.0 and 50.0% in scl at RSC 5, 7.5 10 levels, over RSC 0, respectively. Excess Na in soil solution due to high RSC waer irrigation caused an increase in proportion of Na going on exchange sites causing a reduction in exchangeable K. In contrast, mean values for exchangeable K significantly increased with the application of organic amendments; FYM, BC and RS showed promising results. The K on exchange sites of clay complexes under sodic water irrigation increased because of application of organic amendments releasing potassium during their decomposition. The interactive effect of increase in levels of sodic water and application of amendments on exchangeable K was significant. Rice straw followed by FYM which was at par with BC at RSC 5 in increasing exchangeable K in ls while FYM significantly differed from BC at RSC 7.5 and 10. In scl, FYM differed significantly from BC at RSC 5 and 10 while remaining at par at RSC 7.5 in increasing exchangeable K.

4.1.2.13 Exchangeable sodium percentage

The mean ESP values were lower in the post-harvest rice season soil compared with the soil after wheat harvest due to decrease in exchangeable sodium and increase in sodium ions in solution form. However, ESP of the soil increased by significant margin in ls (4.9, 6.9 and 15.4 times) compared with scl (2.4, 4.2 and 11.0 times) at RSC 5, 7.5 and 10 levels over RSC 0, respectively. It was mainly due to lower CEC values of ls soil. Increase in ESP in soils under sodic water irrigation may be ascribed to greater supply of sodium and proportionately higher exchange of Na⁺ ions from the soil solution with Ca²⁺ ions on the exchange complex. Favourable effect of both types of gypsum was noted as significant decrease in ESP values over the control was observed, followed by FYM and rice straw

Table 4.21 Effect of application of chemical and organic amendments on exchangeable sodium percentage in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	4.69	29.83	38.76	90.44	40.93	6.13	22.88	31.86	79.61	35.12
FYM	5.04	28.48	37.51	62.99	33.50	6.15	20.67	30.38	75.80	33.25
RSC	5.88	26.63	38.43	92.14	40.77	6.54	19.14	32.11	73.61	32.85
RS	4.43	29.16	38.24	99.24	42.77	6.64	21.93	32.88	79.23	35.17
BC	4.69	33.58	37.91	99.71	43.98	5.64	23.25	33.24	79.77	35.47
GG	4.26	25.42	37.16	55.71	30.64	5.80	18.13	30.19	63.03	29.29
YG	4.62	25.04	36.23	51.12	29.25	5.64	17.65	29.59	59.27	28.04
Mean	4.80	28.31	37.75	78.77		6.08	20.52	31.46	72.91	
LSD (5%)	RSC = 0.35, amendment = 0.46, interaction = 0.93					RSC = 0.52, amendment = 0.69, interaction = 1.37				

compost application in both the soils. Gypsum application provided with calcium ions upon dissolution which accelerated $\text{Na}^+ - \text{Ca}^{2+}$ exchange on clay complex. Moreover, FYM and rice straw compost increased pCO_2 and released Ca^{2+} ions into the soil solution upon decomposition which lowered the ESP values in soils receiving these amendments. Similar results were observed by Sheoran *et al* (2021) in sodic water irrigated soils amended with gypsum and pressmud. The interactive effects of RSC levels and amendment application were significant for ESP in both the soils. In ls soil, significant decrease in ESP with YG followed by GG was recorded over the respective controls at RSC 7.5 and 10. In scl, YG and GG were at par at RSC 5 and 7.5 but significantly differing from each other at RSC 10 in decreasing ESP. Compared with gypsums, organic amendments (except FYM at RSC 10 in ls) were not that efficient in reducing ESP in both soils. Nevertheless, Rice straw compost decreased ESP significantly at lower RSC level (RSC 5) over the respective unamended treatments in both soils.

4.1.2.14 Microbial biomass carbon

The microbial activity decreased post-harvest rice crop in soil compared with soil after wheat harvest season primarily due to build-up of anaerobic conditions due to submergence and dilution of sodicity caused due to more rains under rice crop. However, irrigation with sodic water significantly decreased MBC as presented in Table 4.22. The mean values of MBC decreased by 15.3, 31.1 and 41.5% in ls and, by 14.3, 24.7 and 60.2% in scl at RSC 5, 7.5 and 10, respectively over RSC 0. The reduction in MBC may have been caused

Table 4.22 Effect of application of chemical and organic amendments on MBC (mg kg⁻¹ soil) in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	117.77	107.61	86.54	78.37	97.57	158.99	139.45	121.58	102.11	130.53
FYM	124.40	120.76	97.99	82.85	106.50	166.78	145.94	130.52	113.61	139.21
RSC	156.72	126.14	101.16	85.36	117.35	177.74	152.55	135.13	116.97	145.60
RS	144.77	116.79	95.19	79.13	108.97	171.49	141.13	126.12	106.01	136.19
BC	155.98	123.92	99.76	84.19	115.96	175.96	148.02	128.54	108.63	140.29
GG	135.57	113.97	94.37	79.22	105.78	162.12	140.21	121.66	103.95	131.99
YG	137.84	115.49	95.85	80.64	107.46	164.36	142.38	123.13	105.02	133.72
Mean	139.01	117.81	95.84	81.39		168.21	144.24	126.67	108.04	
LSD (5%)	RSC level = 1.04, amendment = 1.38, interaction = 2.77					RSC level = 0.97, amendment = 1.29, interaction = 2.59				

due to the deterioration of soil physical and chemical properties which impacts microbes and their activity in soil. Batra *et al* (1997) also noted that increase in ESP and high pH along with deteriorated physical conditions of soil decreased MBC in sodic environment. However, residual effect of organic amendments after rice season was evident in improving microbial activity over inorganic amendments. Maximum increase in MBC was observed with the application of rice straw compost followed by BC in both the soils and at all levels of sodic water irrigation. The interactive effect of RSC levels and applied amendments was significant. Increase in MBC upon application of rice straw compost which was at par in ls soil with BC at all RSC levels. In scl, rice straw compost was significantly superior over the other amendments in increasing MBC at all levels of RSC.

4.1.2.15 Bulk density (BD)

The data pertaining to the effect of different levels of sodic water irrigation and application of various amendments on BD in ls and scl soils is presented in Table 4.23. Soil bulk density increased from 1.49 to 1.64 g cc⁻¹ in ls and 1.43 to 1.57 g cc⁻¹ in scl as RSC levels increased from 0 to 10 meq L⁻¹. Increase in BD was ascribed to breaking of aggregates and downward movement of clay particles clogging pores that induces compaction of sub-soil (Minhas *et al* 2021). Application of GG (5.7% in ls and 7.2% in scl) followed by YG (4.9% in ls and 6.5% in scl) led to the maximum decrease in the mean BD. Rice straw compost and RS decreased the mean BD values significantly below the unamended control while remaining at par in both the soils. Ibrahim *et al* (2020) found a decrease in bulk density on application of

Table 4.23 Effect of application of chemical and organic amendments on bulk density (g cc⁻¹) in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	1.517	1.570	1.633	1.693	1.603	1.457	1.507	1.593	1.643	1.550
FYM	1.510	1.527	1.610	1.650	1.574	1.443	1.473	1.570	1.600	1.522
RSC	1.490	1.523	1.583	1.630	1.557	1.420	1.437	1.537	1.580	1.494
RS	1.513	1.513	1.613	1.620	1.565	1.450	1.427	1.530	1.580	1.497
BC	1.487	1.547	1.583	1.660	1.569	1.432	1.457	1.550	1.580	1.505
GG	1.460	1.473	1.527	1.590	1.512	1.403	1.400	1.457	1.490	1.438
YG	1.467	1.487	1.537	1.607	1.524	1.417	1.407	1.470	1.507	1.450
Mean	1.492	1.520	1.584	1.636		1.432	1.444	1.530	1.569	
LSD (5%)	RSC level = 0.009, amendment = 0.012, interaction = 0.024					RSC level = 0.003, amendment = 0.004, interaction = 0.008				

rice straw compost in a saline-sodic soil. Similar findings were reported by Smith *et al* (2000) with compost application. This may be attributed to improvement in soil structure through addition of organic material from organic amendments which links mineral particles together and forms macro-aggregates (Oades 1993). It improves soil aggregate stability and, increases porosity and water holding capacity. The interactive effect of application of various amendments in soils irrigated with different levels of RSC of sodic water irrigation on soil BD was significant. Application of YG and GG in ls soil decreased BD significantly over other amendments and respective controls at all levels of RSC. In scl, YG and GG treatments differed significantly (GG>YG) at RSC 7.5 and 10 while remaining at par at RSC 5 in decreasing BD. Rice straw compost decreased BD significantly over other organic amendments at RSC 5 while all organic amendments were equally effective at other two RSC levels in both the soils.

4.1.2.16 Mean weight diameter

The increase in sodicity of irrigation water resulted in decreasing the mean weight diameter (MWD) values (Table 4.24). The decrease was significant by 18.2, 27.2 and 33.3% in ls and 5.8, 15.7 and 19.6% in scl soil at RSC 5, 7.5 and 10 level of sodic water irrigation over the control, respectively. The maximum increase in MWD on the other hand was observed with the application of YG and GG in both the soils. Minhas *et al* (2021) also observed increase in MWD of soils under sodic water irrigation with the application of gypsum. This increase can be attributed to the instant supply of calcium ions to soils which

help in flocculation and aggregate formation thus, helping stabilize the structure of sodic soils. The interactive effect of RSC levels and applied amendments on MWD was significant. Increase in MWD with YG followed by GG was noted at all levels of RSC in both the soils. Among the organic amendments, rice straw was more effective than other organic amendments in increasing MWD at all levels of RSC. Similar results were obtained by Somerville *et al* (2020) who found that the aggregate stability improved as a result of amending soils with organic treatments. Decomposition of compost releases polysaccharides and other polymeric substances which act as aggregating substances and increase micropores in the soil (Masciandro *et al* 2002). Organic matter bridges cations and clay particles to form macro-aggregates which improve micro-aggregate stability (Bronick and Lal 2005). Studies done by Li *et al* (2011) and Ouyang *et al* (2013) demonstrated a close relationship between soil organic matter content and soil aggregate stability.

Table 4.24 Effect of application of chemical and organic amendments on mean weight diameter (cm) in loamy sand and sandy clay loam soil after rice harvest

Amendments	ls					scl				
	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean	RSC 0	RSC 5	RSC 7.5	RSC 10	Mean
C	0.27	0.22	0.19	0.17	0.21	0.44	0.41	0.37	0.34	0.39
FYM	0.32	0.25	0.22	0.19	0.25	0.50	0.45	0.40	0.37	0.43
RSC	0.35	0.27	0.24	0.21	0.27	0.53	0.48	0.43	0.41	0.46
RS	0.32	0.28	0.26	0.25	0.28	0.48	0.50	0.45	0.43	0.47
BC	0.30	0.24	0.21	0.19	0.24	0.50	0.44	0.39	0.38	0.43
GG	0.37	0.29	0.27	0.26	0.30	0.56	0.51	0.48	0.46	0.50
YG	0.38	0.31	0.30	0.29	0.32	0.58	0.53	0.50	0.48	0.52
Mean	0.33	0.27	0.24	0.22		0.51	0.48	0.43	0.41	
LSD (5%)	RSC level = 0.004, amendment = 0.005, interaction = 0.009					RSC level = 0.003, amendment = 0.004, interaction = 0.007				

CHAPTER V

SUMMARY

Water is one of the most valuable yet a finite resource which needs to be judiciously assigned to different sectors. The ever-growing competition for water use due to rapid industrialization and urbanization along with depleting water quality has forced the farmers to irrigate their fields with poor quality water more often than before. Irrigation with sodic water has led to degradation of soils posing a major threat to irrigated agriculture in some arid and semi-arid areas. Areas under continuous irrigation with sodic water have seen a rise in soil salinity and sodicity as a consequence of which, physical properties of soils are severely impacted. Sodic soils become physically challenged due to presence of excess sodium (15% or more) on the exchange sites of the clay complex. The soils remain in dispersed condition due to slaking of aggregates caused by excess sodium, clogging soil pores forming surface crust upon drying. These soils, therefore, face infiltration problems, low permeability of water and air disturbing soil air water relationship hampering seed germination. Soil productivity is reduced in salt-affected soil because of nutrient imbalance, reduction in nutrient availability or water uptake by roots of growing plant and resultant reduction in yield and quality of crops (Ayers and Westcot 1985). The amelioration of soils irrigated with sodic water is achieved by various methods among which application of chemical and organic amendments. Gypsum is the most common amendment applied to sodic soils due to its ability to furnish calcium ions which replace sodium from the exchange complex thus improving the soil structure. But the availability of good quality gypsum in these days is limited which leave the room for exploration of other resources for reclamation. In this regard, organic amendments have been studied extensively in different regions. Application of organic manures to sodic soils adds organic matter and nutrients as an advantage besides facilitating sodium leaching, decreasing ESP and EC, and enhances water-holding capacity and infiltration rate (El-Shakweer *et al* 1998; Naeni and Cook 2000). The native CaCO_3 is dissolved by evolution of H^+ on decomposition of organic matter which facilitates the reclamation of sodic soils (Ghafoor *et al* 2008). However, the rate of reclamation is slow upon the addition of organic manures. Various organic amendments can be used for restoration of physical, chemical and biological parameters in sodic soils. Some of these include composts, farm yard manure, biochar and crop residues (rice/ wheat straw). Present study was engaged to collate the ameliorative effects of chemical and organic amendments applied in sodic water irrigated soils under rice-wheat system.

A pot study was conducted in rice-wheat cropping system under sodic water irrigation with wheat as the first crop to study the restorative effect of chemical and organic amendments on soil properties and biomass yield. The pots were arranged in completely

randomized order with different levels of sodic water irrigation on the basis of RSC levels and application of various inorganic (yellow and grey gypsum, YG and GG) and organic amendments like farm yard manure (FYM), rice straw compost, rice straw (RS) and biochar (BC) in two different textured soils i.e. loamy sand (ls) and sandy clay loam (scl). Gypsum was applied at soil test basis as well as to neutralize the sodicity of irrigation water with subsequent irrigations given to the crop throughout the duration of the experiment. Various plant parameters such as biomass yield, plant height, uptake of cations (Na, K, Ca and Mg), photosynthetic rate, stomatal conductance and proline content were recorded. Soil pH, EC, OC, soluble and exchangeable cations (Ca, Mg, Na and K) and MBC were recorded after harvest of wheat and rice whereas bulk density (BD) and mean weight diameter (MWD) were taken at the end of the experiment.

In the nutshell, the present study showed that irrigation with sodic water significantly increased pH, EC, SAR, ESP, proline content of leaves and uptake of sodium whereas it decreased biomass yield, photosynthetic activity, stomatal conductance, microbial biomass carbon and uptake of Ca, Mg and K compared with RSC 0 irrigated with non-sodic good quality water but no amendments. It was observed in wheat and rice crop that with increase in sodicity of irrigation water, the rise in ESP over the control was higher for ls (14.4-30 times in wheat and 4.9-15.4 times in rice) than scl (3.2-11.5 times in wheat and 2.4-11.0 times in rice) soil at all RSC levels, respectively which could be attributed to lower CEC of loamy sand soil. The SAR values showed greater increase in scl (10.7-21.1 times in wheat and 8.31-16.60 times in rice) than ls (6.0-18.8 times in wheat and 4.63-17.78 times in rice) soil with increase in sodicity of irrigation. However, application of gypsum (both types) decreased the ESP in wheat (25.9-27.7% in ls and 17.8-21.0% in scl) and rice crop (25.1-28.5% in ls and 16.6-20.2% in scl). Similarly, SAR values also decreased upon gypsum application (both types) whereby in ls soil after wheat crop harvest, the values dropped below the critical limit for sodicity i.e. 13 while in scl soil the decrease in SAR (38.6-42.7% in scl) was significant yet it remained above the critical limit. Biomass yield increased over the control by 4.4-6.1% in ls and 3.3-4.4% in scl with the application of rice straw compost and FYM in wheat crop. However, in succeeding rice crop biomass yield was found highest under gypsum (GG and YG) treated pots by 10.7-11.1% in ls and 12.6-12.8% in scl. Uptake of sodium increased with increase in sodicity of irrigation water the values of which decreased with BC application in both the soils and both the crops due to transient binding effect of biochar on sodium ions in soil. The pH values soared higher with increase in level of sodic water irrigation however, gypsum application effectively lowered pH values by significant margin in both the soils after harvest of both the crops. Gypsum application performed better in reducing soil pH in scl than ls at RSC 10 level of sodic water irrigation. Organic amendments increased organic carbon (OC) of the soil in the order: FYM > BC~rice straw compost > RS in both the soils under

wheat crop. However, residual effect of amendment application was only observed in case of FYM application in the succeeding rice crop. Microbial biomass carbon (MBC) improved under the rice straw compost followed by FYM and RS in both the soils under wheat as well as rice crop. Addition of gypsum improved the soil structure by decreasing the bulk density (BD) and improving aggregation as was evident from increased mean weight diameter (MWD) in gypsum treated soils. Hence, it can be concluded that application of gypsum (YG and GG@ 50% GR) with subsequent irrigations of sodic water reduced sodicity stress in wheat and following rice. Among the organic amendments, rice straw compost and FYM proved beneficial in restoring soil properties of sodic soils and sustaining yields of wheat and rice. However, long term field trials need to be conducted to study the restorative and ameliorative potential of yellow gypsum vis-à-vis normal gypsum and its combined application with organic amendments in soils receiving sodic water irrigation.

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