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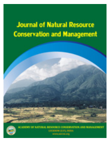

Efficacy of microbial bioformulations on soil properties and wheat yield under sodic water irrigation

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ABSTRACT

A field experiment was conducted at the Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana to assess the potential of microbial bio-formulations, either with or without gypsum, for reducing the sodicity stress caused by irrigation water on wheat crop. The experiment was laid out in a split plot design with irrigation water quality [canal water (CW) and sodic water (SW) and gypsum application (at the rate of 12.5%, 25% and 50% gypsum requirement (GR) under SW (RSC 12.5 meq L^{-1}) as the main treatment and microbial inoculums viz. (a) un-inoculated; (b) *Azo* (*Azotobacter*); (c) *Azo* + PSB (phosphorus solubilizing bacteria and (d) *Azo* + PSB + ZnSB (zinc solubilizing bacteria) as sub treatment with three replications. Results revealed that wheat grain yield in SW-irrigated plots decreased by 15% as compared to CW-irrigated plots. Similarly, irrigation with SW increased soil pH 'values by 9% compared with CW irrigation, whereas microbial biomass carbon (MBC) and dehydrogenase activity decreased by 19.0% and 36.6%, respectively. However, the SW-irrigated plots treated with microbial consortia (*Azo* + PSB + ZnSB) and gypsum application (12.5% or 25% of GR) had a higher wheat grain yields than the plots treated with gypsum (at 50% GR) alone. Similarly, soil pH and exchangeable sodium percentage decreased, whereas available nutrients (N, P, and K), MBC, and dehydrogenase activity increased with the combined application of gypsum and bioformulations. Therefore, it can be inferred that co-application of bio-formulations and gypsum can act as an effective strategy to manage soils irrigated with sodic water.

Keywords: Wheat yield, Irrigation water, Gypsum, Sodicity, Microbial consortia

INTRODUCTION

The accumulation of salt in soils is a serious threat to the sustainability of crop production in many arid and semiarid regions of the world. In such areas, annual precipitation is lower than evapotranspiration, leading to the accumulation of various salts in the soil (Zhao *et al.*, 2020). Large areas of irrigated land across arid and semi-arid regions are affected by groundwater-induced sodification, resulting in deterioration of soil structure and permeability. Sustained use of high RSC irrigation water accelerates exchangeable sodium accumulation and productivity decline (Minhas *et al.*, 2019). Limited availability of good-quality surface water supplies in these areas forces farmers to use poor-quality groundwater for supplemental irrigation. The increasing dependence on sodic groundwater for irrigation has intensified soil alkalinity and nutrient imbalance problems. Site-specific reclamation and water management strategies are therefore essential for sustaining crop yields (Choudhary and Mavi, 2023). Thus, the continuous irrigation with sodic water waters for irrigation results in the build-up of salts, causing lower crop yields (Meena *et al.*, 2025). Additionally, reduced biomass production under such degraded lands restricts the soil carbon inputs, leading to a decline in the soil's physical, chemical, and biological characteristics (Feng *et al.*, 2017; Zhao *et al.*, 2020). The issue is especially severe in northwestern India, where 41-84 % of the groundwater is of poor quality (Choudhary and Mavi, 2023).

The Indo-Gangetic basin in India faces a significant challenge due to inherent sodicity and the alkalization effects of irrigation on approximately 1.37 million hectares (Minhas *et al.*, 2019). Degradation of soil and water resources in intensively cultivated regions threatens long-term agricultural sustainability. Integrated soil reclamation and biological interventions are being promoted to restore productivity (Bhardwaj *et al.*, 2020). Furthermore, increasing competition for water resources resulting from rapid urbanization and industrial growth poses a major barrier to providing sufficient freshwater for irrigated agriculture. Declining freshwater availability has necessitated the conjunctive use of marginal-quality waters in agriculture. Efficient conservation and reuse strategies are critical to bridge irrigation demand gaps (Upadhyaya, 2020). This situation is leading farmers to rely on marginal-quality underground water, which is often saline or alkaline, to irrigate their fields, driven by the dual pressures of freshwater scarcity and the need to support a growing population. Climate variability and anthropogenic pressures are accelerating groundwater quality deterioration in many regions. This has direct implications for irrigation sustainability and soil health (Jalgaonkar *et al.*, 2020). With proper management tailored to specific sites, however, sodic groundwater can become an important irrigation resource, augmenting freshwater supplies and helping to boost crop productivity (Choudhary *et al.*, 2019; Doomra *et al.*, 2023). When effectively managed, these lower-quality waters can indeed play a crucial role in sustaining agricultural production (Singh *et al.*, 2022).

The Punjab region stands out as one of India's most heavily cultivated and irrigated areas, primarily relying on canals and groundwater for its irrigation needs. Long-term irrigation with waters of varying salinity levels alters soil carbon dynamics and biological activity. Such changes significantly influence soil resilience and crop performance (Singh *et al.*, 2022). While canal water is generally of good quality, groundwater can present challenges, often tainted by salinity or sodicity issues. When irrigation occurs with sodic water, it can lead to a buildup of exchangeable sodium within the clay particles. This process causes soil aggregates to disperse, which results in silt particles blocking soil pores and forming a hardened crust when the surface dries out. Irrigation-induced secondary salinization leads to clay dispersion, reduced infiltration, and surface crusting. These physicochemical constraints severely limit plant growth and nutrient uptake (Ashwin *et al.*, 2019). Additionally, soils affected by salt suffer from reduced productivity due to nutrient imbalances stemming from excessive salt and sodium levels. This imbalance can hinder nutrient availability and water absorption by plant roots, thereby impacting growth (Choudhary and Mavi, 2019).

In the past, many technologies have been developed to reclaim the sodic and sodic-water irrigated soils. Among these, gypsum is the most common effective and successful method (Minhas *et al.*, 2019; Choudhary and Mavi, 2023). However, farmers are being forced to look for alternative sources for recovering sodic soils due to the uncertain availability and decline in the quality of mined gypsum for several reasons.

In this context, using microbial bio-formulations to improve salt-affected environments is an evolving and an environment friendly technology (Arora *et al.*, 2016). Several reports have indicated that salt-tolerant bacteria isolated from soil or plant tissues, which possess plant growth-promoting traits, can help mitigate salt stress by promoting seedling growth and enhancing the biomass of crop plants grown under salinity stress (Sahay and Patra, 2014; Hidri *et al.*, 2022). Although previous research has shown that bio-formulations can help remediate salty soils, information on the effects of microbial bio-formulations when applied to sodic water irrigated soil is still lacking. Therefore, the present study was designed to evaluate the potential of microbial bio-formulations in mitigating the sodicity stress caused by irrigation water in wheat.

MATERIALS AND METHODS

Experimental details

A field experiment was carried out the *rabi* seasons of 2020-21, 2021-22 and 2022-23 at the Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana. The local climate is classified as semi-arid and sub-tropical, characterized by hot and dry summers from April to June, a hot and humid period from July to September, and cold winters from November to January. Monthly temperatures range from an average of 12 °C in January to 34 °C in June, with the region receiving approximately 780 ± 282 mm of rainfall annually, over 80% of which occurs during the monsoon season (June to September). The soil in the experimental area is sandy loam. At the start of the field experiment, key soil properties measured included a pH of 8.2, electrical conductivity (EC) of 0.23 dS/m, soil organic carbon (SOC) content of 0.54%, $CaCO_3$ content of 4.35%, cation exchange capacity (CEC) of 8.8 cmol(p^+)/kg, and an exchangeable sodium percentage (ESP) of 8.0.

The experiment was designed as a split plot layout measuring 2.0 x 1.5 m, where irrigation water quality and gypsum application served as the main treatments, while the microbial bio-formulation acted as a sub-treatment, all with three replications. For this experiment, the soils were irrigated using either good-quality canal water (CW) or poor-quality sodic water (SW) with a residual sodium carbonate (RSC) of 12.5 meq L^{-1}. To create the poor-quality water for each plot, a specific amount of $NaHCO_3$ (190 g per plot per irrigation) was dissolved in canal water in large steel drums prior to each irrigation (Table 1).

Gypsum was calculated on basis of residual sodium carbonate (RSC) of irrigation water and was implemented at the rates of 0, 12.5%, 25% and 50% of the total gypsum requirement (GR) under sodic water irrigation. Prior to sowing, wheat seeds were coated with various microbial bio-formulations, including: (a) Un-inoculated; (b) *Azotobacter* (*Halo-Azo*); (c) Halo-*Azo* + Phosphorus-solubilizing bacteria (*Halo*-PSB); and (d) Halo-*Azo* + *Halo*-PSB + Zinc-solubilizing bacteria (*Halo*-ZnSB). These treatments were tested across different plots, some utilizing sodic water and others canal water. The specific bacterial strains used for seed coating included: *Halo-Azo*, featuring *Azotobacter beijerinckii* (KY007069); *Halo*-PSB, consisting of *Enterobacter cloacae* (KX681480); and Halo-Zn, incorporating *Bacillus subtilis* (KY007064). In total, there were twenty different combinations of irrigation water quality and microbial inoculation treatments applied.

Table 1. Composition of irrigation waters at Research Farm of PAU, Ludhiana

Characteristic	Canal water	Sodic water
Electrical conductivity (dS m^{-1})	0.29	1.40
Ca^{2+} (me L^{-1})	1.50	0.70
Mg^{2+} (me L^{-1})	0.90	0.80
Na^+ (me L^{-1})	0.40	15.5
CO_3^{2-}+ HCO_3^- (me L^{-1})	1.80	14.0
Cl^- (me L^{-1})	0.90	1.60
Residual sodium carbonate (RSC)	-	12.5

Right after preparing the field, we manually sowed wheat (*Triticum aestivum* var. PBW 725) at a depth of 4 cm, maintaining a spacing of 20 cm between rows, usually during the first or second week of November each year. For sodic water-irrigated soils, the recommended dose of fertilizer application for wheat included 125 kg N, 62 kg P_2O_5, and 30 kg K_2O ha^{-1}. These nutrients were provided using urea, diammonium phosphate, and muriate of potash. At the time of sowing, full doses of P and K, along with half of the N requirement were applied as a basal dose. The remaining N was applied around 25 to 30 days after sowing to support optimal growth. Both microbial bio-formulations and gypsum were used only once before sowing in the 2020-21, 2021-22, and 2022-23 seasons, with their observed after harvest of the crop. For irrigation, 75 mm of water was applied based on the irrigation water/pan evaporation (IW/Pan-E) ratio. Depending on the amount and distribution of rainfall in different years, four irrigations were given to wheat each year. At the time of harvesting, the grain yield of the wheat crop was computed by applying standard protocols.

Soil analysis

Soil samples at the depth of 0-15 cm were collected after harvest of the wheat crop and dried in shade, ground, passed through a 2 mm sieve, and stored in polythene bags. The processed soil samples were used to determine the soil properties like soil pH, EC, soil organic carbon (SOC), exchangeable sodium percentage (ESP), dehydrogenase activity, and soil microbial biomass carbon (SMBC). The soil pH and EC were measured in 1:2 soil: water suspension as given by Jackson (1973), while SOC was determined by Walkley-Black's rapid titration method using diphenylamine indicator (Walkley and Black, 1934). The available nitrogen (N) was determined by the alkaline permanganate method given by Subbiah and Asija (1956), available phosphorus (P) by using 0.5 M $NaHCO_3$ (pH 8.5)

(Olsen *et al.*, 1954), and available potassium (K) was determined by using neutral normal ammonium acetate solution (pH 7.0) by flame photometer (Merwin and Peech, 1950). Exchangeable sodium percentage (ESP) was calculated as:

$$\text{ESP (\%)} = \frac{Na^+}{CEC} \times 100, \text{ all ions in meq } l^{-1}$$

Dehydrogenase activity was determined with the help of a colorimeter at 485 nm (Casida *et al.*, 1982). Microbial biomass carbon (MBC) was determined by the method given by Vance *et al.*, (1987).

Statistical analysis

Data from the field experiment were analyzed using a split-plot design with the CPCS I package developed at Punjab Agricultural University. Additionally, linear correlation analysis was performed to examine the relationships among soil pH, EC, ESP, SOC, wheat grain yield, MBC, and dehydrogenase activity.

RESULTS AND DISCUSSION

Effect of gypsum and bio-formulations on soil properties

Soil pH

It was evident from the data (Fig. 1) that the soil pH value increased by 9% under SW-irrigated plots compared with CW-irrigated plots. Gypsum application at the rate of 12.5%, 25%, and 50% GR significantly decreased soil pH over SW-irrigated plots. Zhang *et al.* (2020) reported that soil pH significantly decreased with the application of gypsum over the control treatment. In this study, found that soil pH values decreased when treatments included both gypsum and bioformulations. Specifically, the addition of bioformulations, along with 25% and 50% GR, effectively reduced the soil pH below the critical level of 8.8 (soil:water ratio of 1:2), which differentiates non-sodic from sodic soil. The combination of gypsum and microbial inoculations applied to sodic-water irrigated soil contributed to this decline in pH. This likely occurs because the Na^+ ions in the exchange complex are replaced by Ca^{2+} ions from gypsum, causing sodium to leach out in the form of sodium sulfate, ultimately reducing its concentration below the root zone. Furthermore, microbial inoculations produce weak organic acids through their metabolic activities, which also help lower soil pH. Supporting this, Gupta *et al.* (2015) documented a pH reduction when gypsum was applied at a rate of 25% GR, alongside pressmud (10 t ha^{-1}) and bioinoculants. Thus, it is more advantageous to use gypsum at a rate of 25% GR combined with bioformulation inoculums, rather than relying solely on 50% GR of gypsum.

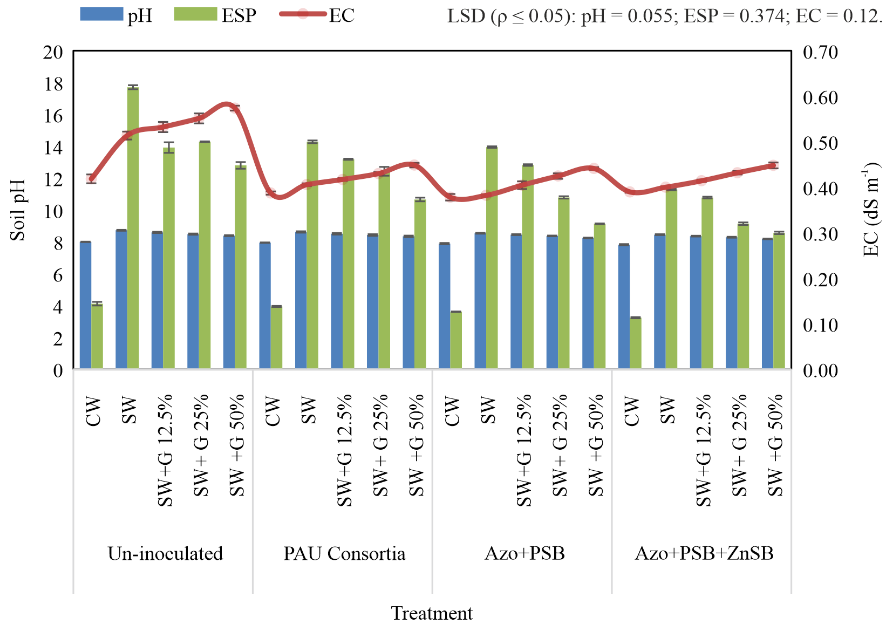


Fig. 1. Effect of gypsum and bio-formulations on pH, EC and ESP of soil
(Note: CW = Canal water; SW (Sodic-water) = RSC 12.5 meq L-1; G = Gypsum; *Azo* = *Azotobacter*; PSB = P solubilizing bacteria; ZnSB = Zn solubilizing bacteria)

Electrical conductivity (EC)

The information presented in Fig. 1 shows a notable increase in EC values for the SW-irrigated plots when compared to those under CW irrigation. Interestingly, when gypsum was applied, the EC values rose from 0.43 dS m^{-1} in the SW plots to 0.48 dS m^{-1} in the 50% GR plots. This rise in EC following gypsum application can be linked to the dissolution of gypsum, which leads to the release of certain salts into the soil solution (Amrhein and Suarez, 1987). However, application of bioformulations along with gypsum (25% and 50% of GR) in SW-irrigated plots significantly decreased the EC values relative to the uninoculated SW-irrigated plots. Stanford *et al.* (2003) also reported that microbial inoculants and organic amendments decrease the soil EC to a significant level.

Exchangeable sodium percentage (ESP)

The results showed a notable increase in the ESP value, rising from 4.1% in the CW plots to 17.7% in the soil that was irrigated with SW, as illustrated in Fig. 1. This increase was likely influenced by the calcareous composition of the experimental soil, which contained approximately 4% $CaCO_3$. This characteristic likely helped to limit the accumulation of sodium within the exchange complex (Choudhary *et al.*, 2011) during SW irrigation, resulting in a more balanced ESP level throughout the study. In comparison to the ESP in SW-irrigated plots, the addition of gypsum whether at 25% or 50% GR along with microbial inoculants successfully reduced the ESP levels. The application of gypsum enhances calcium content in the soil solution while lowering sodium levels, which ultimately leads to a decrease in ESP values. Furthermore, the combined use of *Azo*, PSB, and ZnSB inoculants alongside gypsum at 25% GR proved to be more effective in reducing the ESP of SW-irrigated soil than using gypsum at 50% GR alone, as seen in Fig. 1. It appears that these microbial formulations may aid in the dissolution of native $CaCO_3$ and gypsum through the production of organic acids, siderophores, and extracellular polysaccharides, thereby effectively lowering soil ESP values.

Soil organic carbon (SOC)

A perusal of data in Fig. 2 revealed that SOC significantly decreased by 28.8% under SW-irrigated soils as compared to CW-irrigated soils, while application of gypsum at the rate of 50% GR significantly increased the SOC by 35.7% relative to SW-irrigated soils. The decline of soil organic carbon

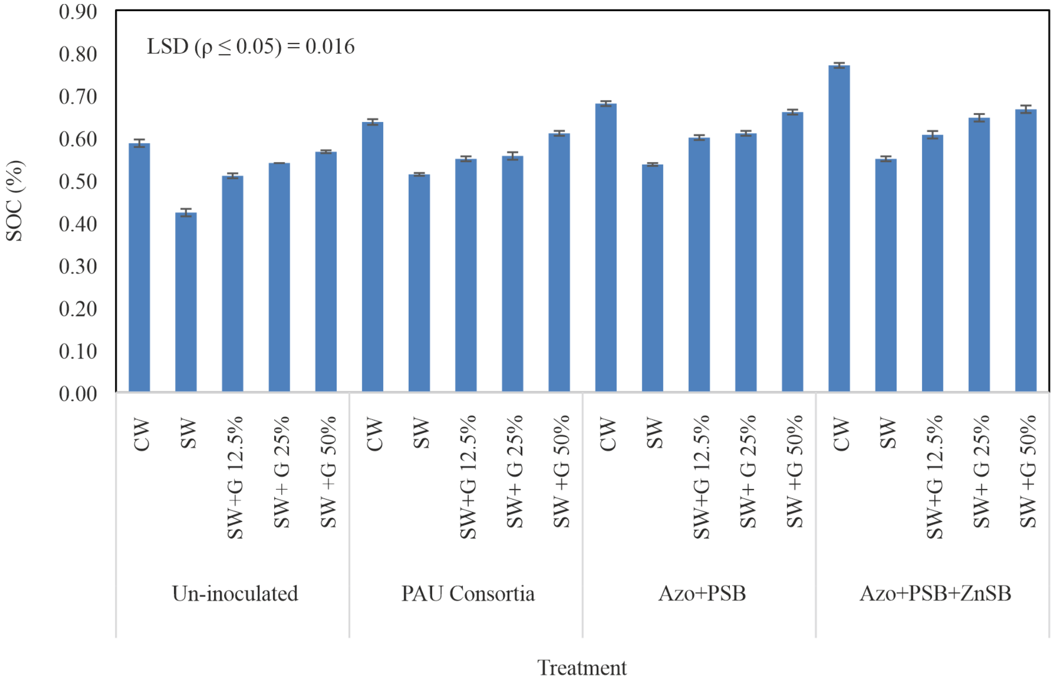


Fig. 2. Effect of gypsum and bio-formulations on soil organic carbon
(Note: CW = Canal water; SW (Sodic-water) = RSC 12.5 meq L^{-1}; G = Gypsum; *Azo* = *Azotobacter*; PSB = P solubilizing bacteria; ZnSB = Zn solubilizing bacteria)

(SOC) in soil irrigated with sodic water can be attributed to the alkaline hydrolysis of organic matter. On the other hand, the observed increase in SOC within the study appears to result from two main factors: (i) a direct improvement of soil properties, including pH and exchangeable sodium percentage (ESP), and (ii) an indirect boost in biomass production. Additionally, the presence of calcium ions (Ca^{2+}) from gypsum helps mitigate this loss by (i) creating a cation bridge between Ca^{2+} and organic carbon and (ii) facilitating the formation of soil aggregates, which in turn increases carbon associated with those aggregates. Basak *et al.* (2021) also noted a significant rise in total organic carbon in alkaline soils treated with gypsum. Notably, plots that were inoculated with a mix of *Azo*, PSB, and ZnSB, along with gypsum at 25% of the gypsum requirement (GR), showed a 14% greater SOC than those treated with gypsum alone at 50% GR. Meena *et al.* (2025) also reported that the SOC increased up to 20% when soils were co-inoculated with *Halo Azo* + *Halo* PSB in sodic soils.

Soil available nutrients (N, P and K)

The data shown in Fig. 3 indicated that value of soil available N, P and K significantly decreased by 33.4, 36.2 and 36.7%, respectively in SW-irrigated plots as compared to the CW-irrigated plots. Application of gypsum (12.5%, 25% and 50% GR) and microbial inoculums progressively increased soil available N, P and K. However, significantly greater values of available N, P, and K were obtained in plots inoculated with *Azo* + PSB + ZnSB and gypsum application (25% GR) as compared to gypsum alone plots (50% GR) in SW-irrigated soils. Using salt-tolerant microbes can help support nutrient cycling in saline-sodic soils. These microbes achieve this by producing essential enzymes such as glucosidase, phosphatase, protease, amylase, and urease, in addition to various compatible solutes and other metabolites (Dendooven *et al.*, 2010). For example, phosphobacteria from the microbial inoculation causes production of organic acids that converts the insoluble form of P to soluble form and thus results in effective solublization of soil P (Sirinivasa and

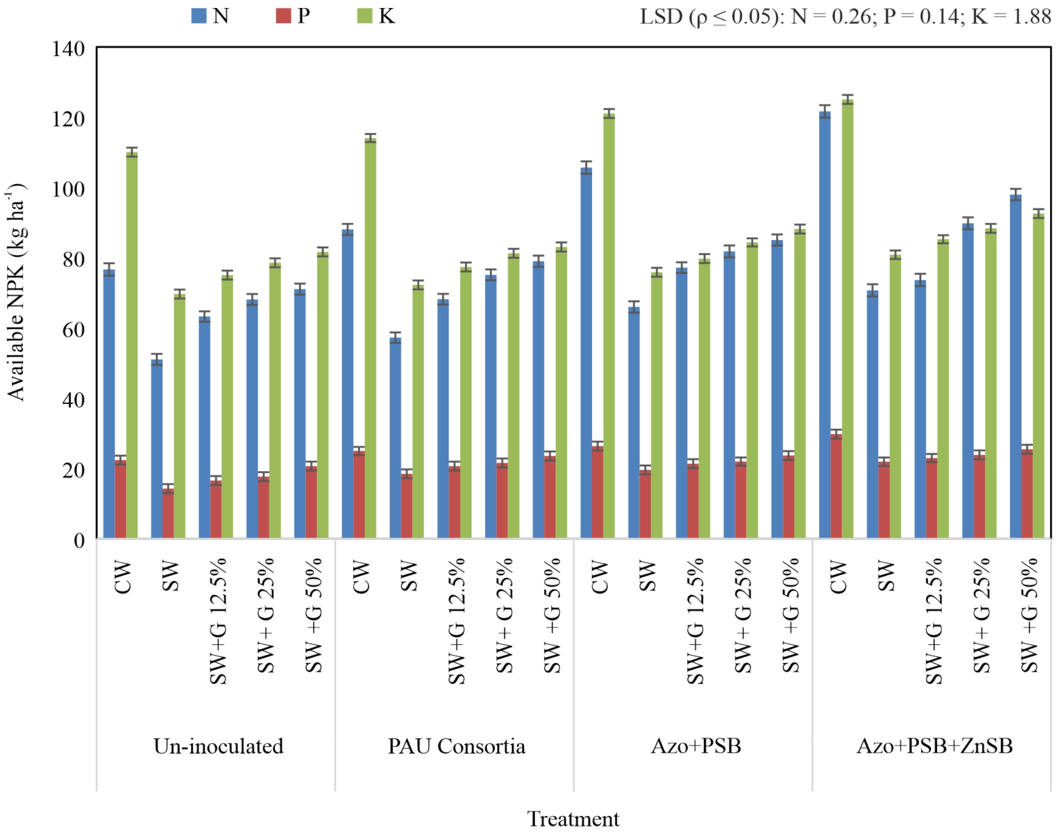


Fig. 3. Effect of gypsum and bio-formulations on soil available N, P and K
(Note: CW = Canal water; SW (Sodic-water) = RSC 12.5 meq L^{-1}; G = Gypsum; *Azo* = *Azotobacter*; PSB = P solubilizing bacteria; ZnSB = Zn solubilizing bacteria)

Sundari, 2004). Similarly, Etesami *et al*. (2017) reported that microorganisms solubilize the insoluble K to soluble form through various mechanisms such as production of inorganic and organic acids, acidolysis, polysaccharides, complexolysis, chelation and exchange mechanisms.

Dehydrogenase activity (DHA)

The mean value of dehydrogenase activity showed a noteworthy decline of 36.6% in the SW-irrigated plots when compared to those that were CW-irrigated (Fig. 4). Alharbi *et al*. (2023) reported that fresh water irrigated soil revealed higher dehydrogenase activity than the saline water irrigated. Meanwhile, dehydrogenase activity increased by 20.1%, 36.5% and 46.5% in SW-irrigated plots when gypsum was applied at the rate 12.5%, 25% and 50% GR, respectively. Additionally, in SW-irrigated plots treated with *Azo*, *Azo* + PSB and *Azo* + PSB + ZnSB solubilizing bacteria, dehydrogenase activity increased by 28%, 44%, and 61% compared to the un-inoculated control. The highest dehydrogenase activity was observed with the application of gypsum at 25% of the GR in combination with microbial inoculation, yielding values between 20.5 to 26.4 µg TPF g^{-1} soil hr^{-1}. In contrast, the plots that received only gypsum at 50% of the GR resulted in a lower dehydrogenase activity of just 18.2 µg TPF g^{-1} soil hr^{-1}. This indicated that using gypsum at lower rate (25% GR) in combination with inoculum proved to be more effective than applying only gypsum at 50% of GR. This is likely due to the enhanced build-up of soil organic carbon (SOC) in the inoculated soil. A study by Hidri *et al.* (2022) also found that soils treated with microbial inoculants (saline + *Glutamicibacter* sp. and saline + *Pseudomonas* sp.) showed a significant increase in dehydrogenase activity in the rhizosphere compared to non-inoculated soils.

Microbial biomass carbon (MBC)

Soil microbial biomass carbon (MBC) was found to be 19% lower in plots irrigated with SW compared to those receiving CW (Fig. 4). However, the application of gypsum and microbial bio-formulations either alone or in combination led to an increase in the MBC. Notably, the microbial bio-formulations had a more significant positive impact on MBC than gypsum alone. When examining the different bio-formulations, it was observed that MBC significantly increased by 16.1% and 27.1% in plots that inoculated either with *Azo* + PSB or *Azo* + PSB+ ZnSB in the SW-irrigated plots compared to the un-inoculated control. The combination of

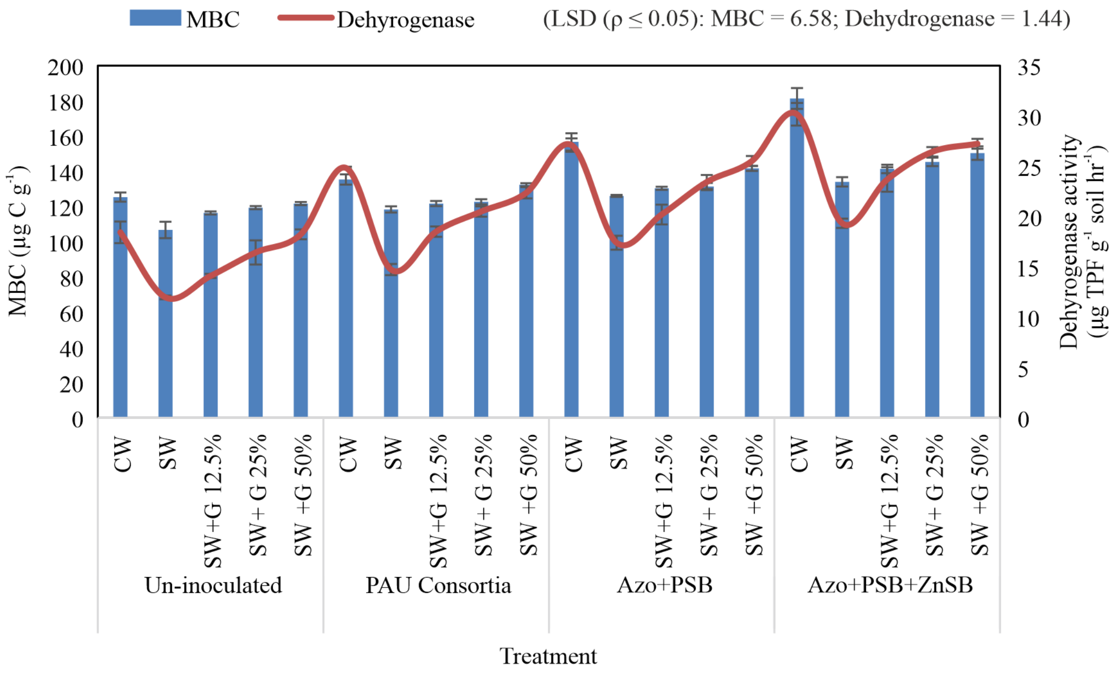


Fig. 4. Effect of gypsum and bio-formulations on soil microbial biomass carbon and dehydrogenase activity (Note: CW = Canal water; SW (Sodic-water) = RSC 12.5 meq L^{-1}; G = Gypsum; *Azo* = *Azotobacter*; PSB = P solubilizing bacteria; ZnSB = Zn solubilizing bacteria)

gypsum (25% or 50% GR) with *Azo* + PSB or *Azo* + PSB + ZnSB significantly increased MBC in SW-irrigated plots compared to the un-amended and un-inoculated ones. This aligns with findings from Trivedi *et al.* (2017), which noted a notable rise in MBC in soils co-inoculated with a consortium of microbes along with farm yard manure.

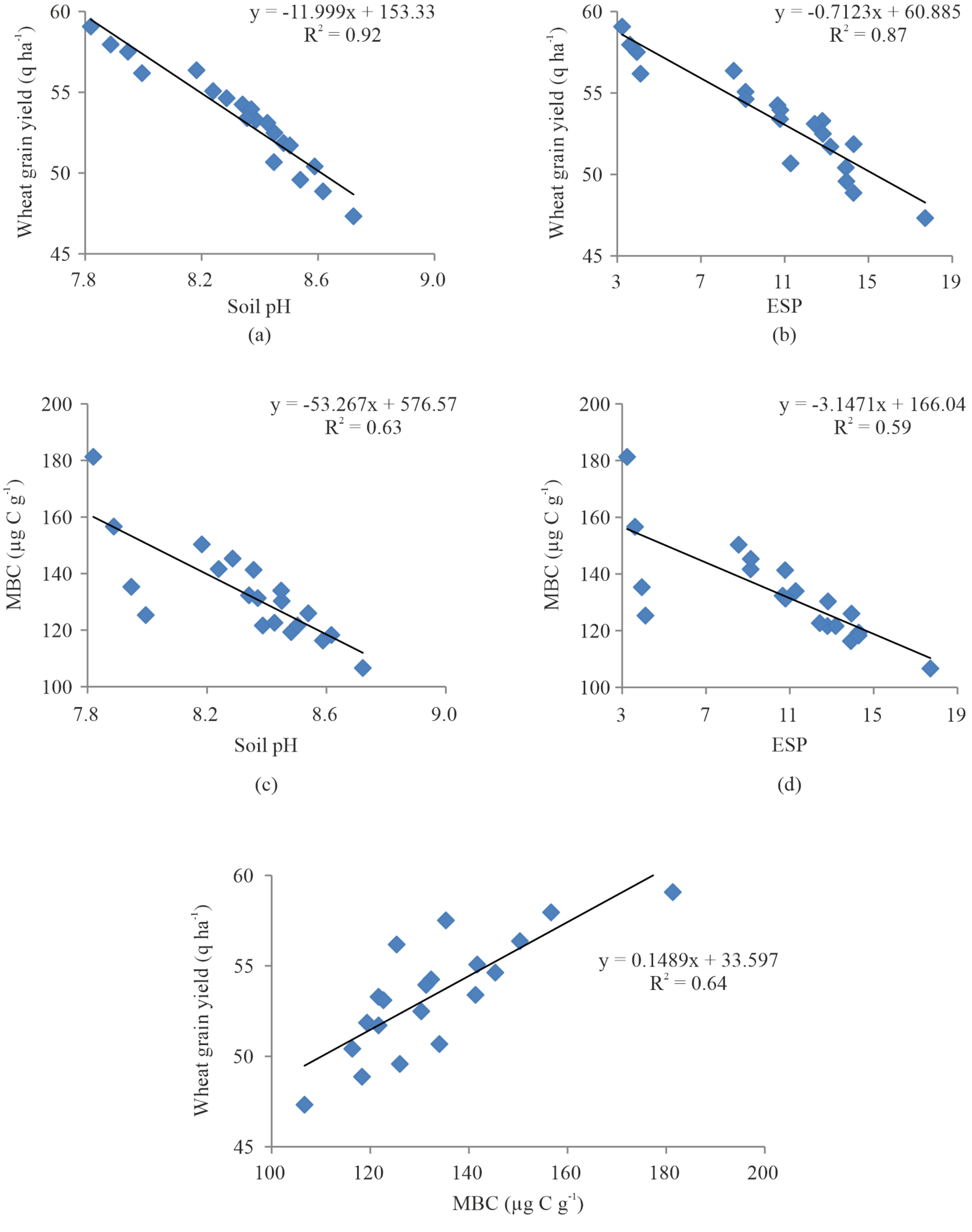
Wheat grain yield

The perusal of data shown in Table 2 revealed that wheat grain yield significantly declined by 15% under SW-irrigated plots compared to those irrigated with CW. This decline aligns with significant enhancement in soil pH and ESP values in the SW-irrigated plots, which ultimately deteriorated soil physical properties. The continuous use of SW negatively impacts plant growth (Fig. 1). Moreover, a negative relationship between wheat grain yield and soil pH or ESP in the present study also revealed adverse effect of SW irrigation on crop yield (Fig. 5a and 5b). However, application of gypsum (12.5%, 25% and 50% GR) and microbial inoculums significantly increased the wheat grain yield over plots irrigated with SW only. In various bio-formulations, the highest mean grain yield of wheat (54.8 q ha^{-1}) was observed in soil inoculated with *Azo* + PSB + ZnSB, compared to the un-inoculated treatment which yielded 51.8 q ha^{-1}. Furthermore, when gypsum was applied at 12.5% or 25% GR, in combination with *Azo* + PSB + ZnSB, the wheat grain yield was comparable to plots receiving gypsum alone at 50% of GR. The observed reduction in pH and ESP in plots irrigated with sodic water that were amended with bio-formulations, either alone or alongside gypsum, aligns well with the positive outcomes on wheat grain yield. Bailly and Weisskopf (2012) noted that the increase in crop yield from bio-formulation-treated soil can likely be attributed to the production of secondary metabolites and volatile organic compounds in the rhizosphere by microorganisms, which in turn promotes plant growth. Moreover, Ullah and Bano (2019) found that higher yields in potatoes due to the enhanced ability of halophilic microbes to convert tryptophan into indole-acetic acid, which results in a larger leaf

Table 2. Effect of irrigation water, gypsum and microbial bio-formulations on wheat grain yield (q ha^{-1})

Year	Microbial inoculation (MI)	Irrigation water (IW)					
		CW	SW	SW + G12.5%	SW + G25%	SW + G50%	Mean
2020-21	Un-inoculated	55.9	46.6	49.1	50.4	51.9	50.8
	Azo	56.9	47.6	50.7	51.8	52.6	51.9
	Azo + PSB	57.0	48.3	51.1	52.6	53.4	52.5
	Azo + PSB + ZnSB)	57.4	49.8	52.1	53.4	54.9	53.5
	Mean	56.8	48.1	50.8	52.1	53.2	
	LSD (0.05): IW = 1.07, MI = 1.19, IW × MI = 2.14						
2021-22	Un-inoculated	55.7	47.1	51.0	52.1	53.8	51.9
	Azo	56.8	49.9	51.7	53.4	54.9	53.3
	Azo + PSB	57.2	50.3	52.8	54.0	55.5	53.9
	Azo + PSB + ZnSB	57.5	50.8	53.5	54.2	56.3	54.8
	Mean	56.8	49.5	52.3	53.4	55.5	
	LSD (0.05): IW = 0.67, MI = 0.44, IW × MI = 1.33						
2022-23	Un-inoculated	58.0	48.2	51.1	53.0	54.2	52.9
	Azo	58.9	49.1	52.8	54.1	55.3	54.1
	Azo + PSB	59.7	50.1	53.6	55.3	56.4	55.0
	Azo + PSB + ZnSB	60.8	51.1	54.6	56.2	57.9	56.1
	Mean	59.3	49.7	53.0	54.7	55.9	
	LSD (0.05): IW = 0.62, MI = 1.46, IW × MI = 1.24						
Pooled mean	Un-inoculated	56.2	47.3	50.4	51.9	53.3	51.8
	Azo	57.5	48.9	51.7	53.1	54.2	53.1
	Azo + PSB	58.0	49.6	52.5	54.0	55.1	53.8
	Azo + PSB + ZnSB	59.1	50.7	53.4	54.6	56.4	54.8
	Mean	57.7	49.1	52.0	53.4	54.8	
	LSD (0.05): IW = 0.36, MI = 0.73, IW × MI = 0.71						

(Note: CW = Canal water; SW (Sodic-water) = RSC 12.5 meq L^{-1}; G = Gypsum; *Azo* = *Azotobacter*; PSB = P solubilizing bacteria; ZnSB = Zn solubilizing bacteria)



(e)

Fig. 5. Relationship between (a) soil pH and wheat grain yield (b) ESP and wheat grain yield (c) soil pH and MBC (d) ESP and MBC (e) MBC and wheat grain yield

area for effective photosynthesis. Arora *et al*. (2016) reported that increase in grain yield was 8.5%, 12.5% and 18.0% due to inoculation with bio-formulations, *viz*. *Halo-Azo*, *Halo*-PSB and *Halo-Azo* + *Halo*-PSB, respectively over the un-inoculated treatment.

CONCLUSIONS

The study clearly demonstrates that both gypsum and microbial bio-formulations, whether used separately or together, can significantly alleviate sodicity stress in soils under sodic water irrigation.

Additionally, the findings suggest that applying liquid bio-formulations with a reduced gypsum dose (just 25% of the gypsum requirement) could be a cost-effective approach to mitigate the negative impacts of sodic water irrigation on wheat yield, particularly in regions where high-quality gypsum is scarce. Furthermore, combining microbial formulations with this reduced gypsum application (at 25% GR) not only helps in addressing immediate challenges but also enhances microbial activity and biomass over time, promoting long-term soil health and productivity.

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