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Alleviation of sodic water irrigation induced sodicity through microbial bioformulations

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ABSTRACT

A field experiment was conducted during rainy (*kharif*) season of 2019, 2020 and 2021 at Punjab Agricultural University, Ludhiana, Punjab to evaluate the potential of microbial bio-formulations with or without gypsum for ameliorating irrigation water-induced sodicity stress. The experiment was laid out in a split plot design (SPD) with irrigation water quality and gypsum application as the main treatment and microbial bio-formulation inoculation as the sub treatment with three replications. The soil was irrigated with canal water (CW) and sodic water (SW) (RSC 12.5 meq/L) while gypsum was applied at three rates, viz. 12.5%, 25% and 50% of gypsum requirement (GR) under SW. Cotton seeds were inoculated just before sowing with microbial consortia, viz. (a) un-inoculated; (b) Azo (*Azotobacter*); (c) Azo + PSB (phosphorous solubilizing bacteria) and (d) Azo + PSB + ZnSB (Zinc solubilizing bacteria). Results revealed that compared with CW irrigated plots, seed-cotton yield decreased by 27.4% in SW irrigated plots. Likewise, soil *p*H values increased by 8.0% while microbial biomass carbon (MBC) decreased by 19.0% under SW compared with CW irrigation. Among different bioformulations, the pooled mean value of seed cotton yield (SCY) was the maximum (45.9 q/ha) for plots inoculated with consortia of Azo + PSB + ZnSB relative to the un-inoculated treatment (41.8 q/ha). Application of microbial consortia Azo + PSB + ZnSB with gypsum (12.5% or 25% of GR) to SW-irrigated plots showed seed-cotton yield greater than those plots amended with gypsum at 50% GR. Similarly, soil *p*H and exchangeable sodium percentage decreased, whereas MBC and dehydrogenase-activity increased with combined application of gypsum and bioformulations. Therefore, it can be concluded that the farmers facing scarcity of good quality gypsum can use these bio-formulation to substitute some part of the gypsum requirement for ameliorating soils irrigated with SW.

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

Limited availability of good quality surface water supplies in arid and semi-arid regions forces farmers to use the poor-quality ground water for supplemental irrigation. Consequently, persistent and continuous use of poor-quality waters for irrigation however results in build-up of salts causing lower crop yields. Moreover, decrease in biomass production under such degraded lands limits the soil carbon inputs, thus deteriorating soil health. The problem is particularly acute in northwestern India, where 41–84% of the ground waters are of poor quality (Choudhary and Mavi 2023). When properly managed, poor quality waters can become a valuable resource for irrigation and sustaining crop production (Singh *et al*. 2022).

The state of Punjab is one of the most intensively cultivated and irrigated areas of India where the main sources of irrigation are canal and ground water. Canal water is of good quality, while ground water is not always suitable for irrigation due to the problem of salinity, sodicity or both. Sodic water irrigation results in build-up of exchangeable sodium on clay complex, dispersion of aggregates and silt particles clog the soil pores hence forming a surface crust upon drying. Moreover, soil productivity is reduced in salt-affected soils because of nutrient imbalance through reduction in nutrient availability or water uptake by roots of growing plants (Choudhary and Mavi 2019).

In the past, many technologies have been developed to reclaim the sodic water irrigated soils. Among all the chemical amendments, gypsum is the most commonly used to ameliorate sodic soils. However, limited and unassured availability, and deterioration in quality of gypsum due to variety of reasons is forcing farmers to look for some alternative methods for reclaiming sodic soils. In this context, use of microbial bio-formulations for ameliorating salt-affected environments is an emerging technology. Several reports indicated that salt tolerant bacteria isolated from soil or plant tissues having plant growth promoting

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traits can help to alleviate salt stress by promoting seedling growth and increasing biomass of crop plants grown under salinity stress (Sahay and Patra 2014, Hidri *et al.* 2022). Even though earlier published work indicated beneficial role of bio-formulations in remediating saline soils, information is still scarce on the impact of microbial bio-formulations when applied to soils due to sodic water irrigation. Therefore, the present study was planned with an objective to evaluate the potential of microbial bio-formulations in ameliorating irrigation water induced sodicity stress under cotton.

MATERIALS AND METHODS

Experimental details: A field experiment was conducted during rainy (*kharif*) season of 2019, 2020 and 2021 at Punjab Agricultural University, Ludhiana, Punjab. The climatic condition of the experimental area falls under semi-arid climate and sub-tropical zone which is characterized by hot and dry summer from April to June followed by a hot and humid period during July to September and cold winters from November to January. The average monthly temperature of the region ranges between 13°C in January and 33°C in June with an annual rainfall of 779 ± 285 mm of which more than 80% is received during the monsoon season (June–September). At the initiation of the field experiment, the *p*H, EC, soil organic carbon (SOC), $CaCO_3$ content, cation exchange capacity (CEC) and exchangeable sodium percentage (ESP) of the soil were 8.2, 0.23 dS/m, 0.54%, 4.35%, 8.8 cmol (p^+)/kg and 8, respectively.

The experiment was laid out (2.0 × 1.5 m) in a split plot design with irrigation water quality and gypsum application as the main treatment and microbial bio-formulation inoculation as the sub treatment with three replications. Experimental soils were either irrigated with good-quality canal water (CW) or poor-quality sodic water (SW; RSC 12.5 meq/L) synthesized for each plot separately by dissolving a known quantity (190 g/plot per irrigation) of $NaHCO_3$, in canal water in large steel drums before each irrigation (Supplementary Table 1). Gypsum was calculated on the residual sodium carbonate (RSC) basis of irrigation water and applied at the rate of 0, 12.5%, 25% and 50% of the gypsum requirement (GR) under sodic water irrigation. The following microbial bio-formulations were used to coat the seedling of cotton before sowing: (a) Un-inoculated; (b) *Azotobacter* (Halo-Azo); (c) Azo + Phosphorus solubilizing bacteria (Halo-PSB); and (d) Azo + PSB + Zinc solubilizing bacteria (Halo-ZnSB) in different plots irrigated with sodic or canal water. Following bacteria and strains of bioformulation were used to coat the seedling of cotton: Halo-Azo: *Azotobacter beijerinckii* (KY007069), Halo-PSB: *Enterobacter cloacae* (KX681480) and Halo-Zn: *Bacillus subtilis* (KY007064). Total 20 combinations of irrigation water quality and microbial inoculation were tested.

Cotton (*Gossypium hirsutum* hybrid var. RCH 773) was sown manually at 5 cm soil depth with a 67.5 cm row to row spacing and 75 cm plant to plant spacing during first or second week of May each year. Cotton was fertilized with 105 kg N/ha, 30 kg P_2O_5/ha, and 30 kg K_2O/ha from urea, single superphosphate and muriate of potash, respectively. Full dose of P and K and half dose of N were applied as basal application at the time of sowing and remaining dose of N fertilizer were applied at 25–30 days after sowing. In addition to soil application of fertilizers, four sprays of potassium nitrate (2%) were supplemented at weekly intervals starting from 50% flowering. Microbial bio-formulations were applied as seed treatment. Gypsum was applied only once during 2019, 2020 and 2021 before sowing of cotton. For every irrigation, 60 mm water was applied on the basis of irrigation water/pan evaporation (IW/Pan-E) ratio of 0.6 for cotton. Depending upon the amount and distribution of rainfall in different years, 3 irrigations each year were given to cotton. At the time of harvesting, seed cotton yield was computed by implying standard protocols.

Soil analysis: Soil samples (0–15 cm) were collected after harvest of crop and dried in shade, grounded, passed through a 2 mm sieve and stored in polythene bags to determine soil properties. The soil *p*H and EC were measured in 1:2 soil:water suspension as given by Jackson (1973). The soil organic carbon (SOC) was determined by Walkley-Black's rapid titration method (Walkley and Black 1934) while calcium (Ca^{2+}) and magnesium (Mg^{2+}) in soil solution was determined by Versenate method. Exchangeable sodium percentage (ESP) was calculated as:

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

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

Statistical analysis: Data from field experiment was statistically analyzed under split plot design using CPCS-I package developed by Punjab Agricultural University. The data was also subjected to linear correlations analysis to establish the relationship between soil *p*H, ESP, seed cotton yield, SOC, MBC and dehydrogenase activity.

RESULTS AND DISCUSSION

Effect of gypsum and bioformulations on seed cotton yield (SCY): The results of the study revealed that compared with canal water (CW) irrigated plots, pooled mean value of seed cotton yield decreased by 27.4% in sodic water (SW) irrigated plots (Table 1). Greater uptake of Na^+ ions and deterioration of soil physical properties due to continuous use of SW negatively impacted plant growth. This was also confirmed by significant enhancement in soil *p*H and ESP values in the plots irrigated with SW compared with CW (Table 2) and also by a negative relationship between SCY and soil *p*H, ESP in the present study. Meanwhile, application of gypsum along with sodic water significantly increased the pooled mean value of seed cotton yield by 13.5%, 16.5% and 20% with 12.5%, 25% and 50% of GR, respectively, compared with plots irrigated with only sodic water of RSC 12.5 meq/L. Among different bio-formulations,

Table 1 Effect of irrigation water quality, gypsum and microbial bio-formulations on seed cotton yield (q/ha)

Year	Microbial inoculation)	Irrigation water					
		CW	SW	SW + $G_{12.5\%}$	SW + $G_{25\%}$	SW + $G_{50\%}$	Mean
2019	Un-inoculated	44.8	32.5	38.0	39.1	39.6	38.8
	Azo	46.3	34.8	38.0	40.5	41.5	40.2
	Azo + PSB	47.5	35.6	40.5	41.0	42.8	41.5
	Azo + PSB + ZnSB	49.2	36.5	41.7	41.8	43.4	42.5
	Mean	47.0	34.9	39.6	40.6	41.8	
	LSD (0.05): IW = 1.84, MI = 1.22, IW × MI = NS						
2020	Un-inoculated	48.0	34.8	40.7	41.9	42.4	41.6
	Azo	49.6	37.3	40.7	43.4	44.5	43.1
	Azo + PSB	51.0	38.2	42.5	43.5	46.0	44.2
	Azo + PSB + ZnSB	52.9	39.2b	44.8	44.9	46.7	45.7
	Mean	50.4	37.4	42.2	43.4	44.9	
	LSD (0.05): IW = 0.23, MI = 0.09, IW × MI = 0.21						
2021	Un-inoculated	51.9	37.6	44.0	45.3	45.9	44.9
	Azo	53.8	40.4	44.1	47.0	48.2	46.7
	Azo + PSB	55.3	41.4	46.0	47.7	49.8	48.1
	Azo + PSB + ZnSB	57.4	42.6	48.6	48.8	50.7	
	Mean	54.6	40.5	45.7	47.2	48.6	
	LSD (0.05): IW = 0.197, MI = 0.08, IW × MI = 0.20						
Pooled data	Un-inoculated	48.2	35.0	40.9	42.1	42.6	41.8
	Azo	49.9	37.5	41.0	43.6	44.7	43.3
	Azo + PSB	51.3	38.4	43.0	44.1	46.2	44.6
	Azo + PSB + ZnSB	53.2	39.4	45.1	45.2	46.9	45.9
	Mean	50.6	37.6	42.5	43.7	45.1	
	LSD (0.05): IW = 0.72, MI = 0.18, IW × MI = 0.45						

SW, Sodic water, CW, Canal water; RSC, Residual sodium carbonate (12.5 meq/L); IW, Irrigation water; G, Gypsum; Azo, *Azotobacter*; PSB, P solubilizing bacteria; ZnSB, Zinc solubilizing bacteria; LSD, Least significant difference; NS, Non-significant.

the maximum pooled mean SCY (45.9 q/ha) increased in soil inoculated with Azo + PSB + ZnSB treatment relative to the un-inoculated treatment (41.8 q/ha). While combined application of gypsum (12.5% or 25% of GR) and bio-formulation (Azo + PSB + ZnSB) to plots irrigated with sodic water showed seed cotton yield similar to gypsum only (50% of GR) plots.

The reduction in *p*H and ESP in plots irrigated with SW but amended with bioformulations individually or in combination with gypsum was also in agreement with positive impact of amendments on SCY. Bailly and Weisskopf (2012) reported that crop yield increased in bio-formulation treated soil possibly due to production of secondary metabolites and volatile organic compounds in the rhizosphere by micro-organisms that stimulated plant growth. Besides, Ullah and Bano (2019) also recorded higher potato yield due to greater potential of halophilic microbes in converting tryptophane to indole-acetic acid thereby, increasing area of the leaf for photo-assimilation. In the present study, irrespective of the water quality, the MBC and dehydrogenase activity in the inoculated plots with or without gypsum application was significantly greater than the un-inoculated soil thereby, highlighting the beneficial role of bioformulations in enhancing seed cotton yield. This was also evident from a positive correlation between SCY and MBC in the study (Fig. 1e).

Effect of gypsum and bio-formulations on soil parameters

Soil pH: In the study, mean soil *p*H values increased by 8% in the SW compared with CW irrigation (Table 2). With the application of gypsum, soil *p*H significantly decreased with application of 12.5%, 25% and 50% of GR, respectively. Similarly, soil *p*H values were also lower in treatments with combined application of gypsum and bio-formulations. It was observed that application of bio-formulations along with gypsum 25% or 50% of GR proved effective in further lowering the *p*H below the threshold level of 8.8 (soil:water ratio, 1:2) that distinguishes non-

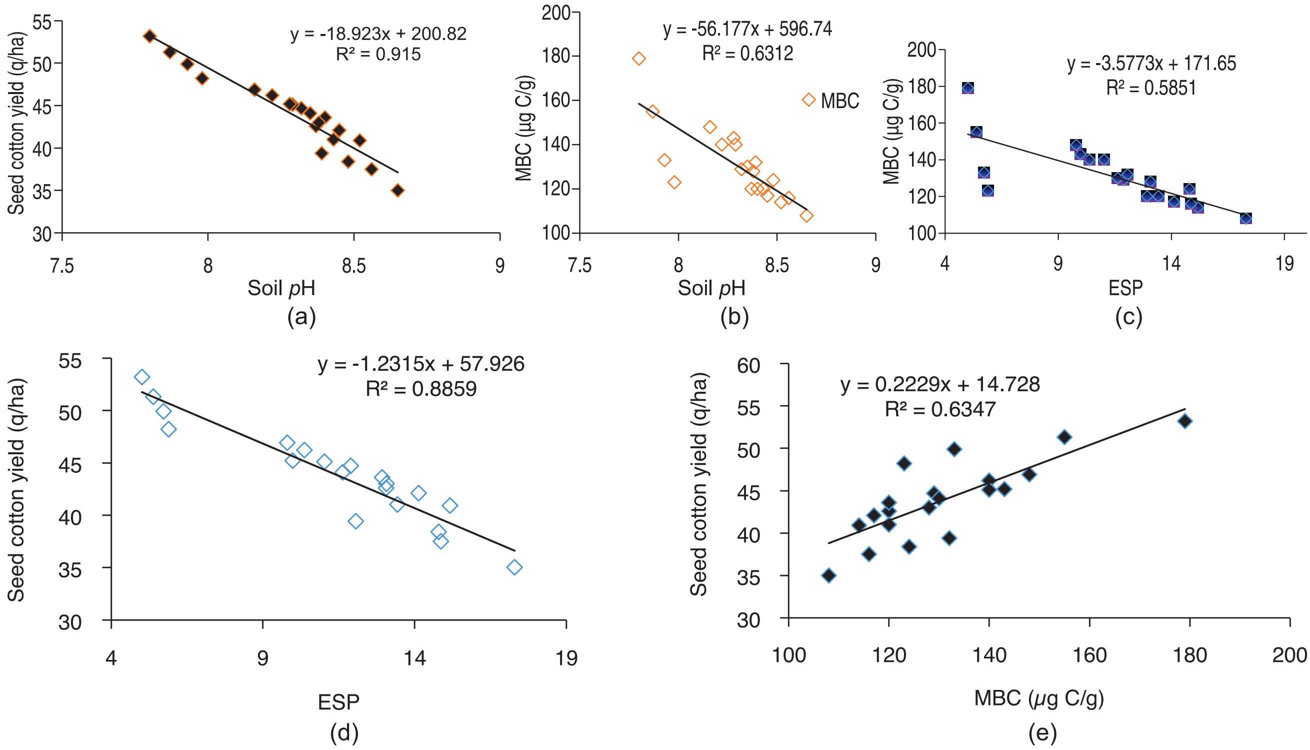

Fig. 1 Relationship (a) between soil *p*H and seed cotton yield (b) soil *p*H and MBC (c) ESP and MBC (d) ESP and seed cotton yield (e) MBC and seed cotton yield.
MBC, Microbial biomass carbon; ESP, Exchangeable sodium percentage.

sodic from the sodic soil. Application of gypsum along with microbial inoculations under SW irrigation decreased the soil *p*H possibly due to replacement of the sodium ion with calcium in gypsum from the exchange complex and thereby, leaching of the sodium in the form of sodium sulphate below the root zone soil. On the other hand, microbial inoculations release weak organic acids into the soil solution in the form of secretion through metabolic activities responsible for lowering the soil *p*H. Likewise, Gupta *et al.* (2015) reported reduction in soil *p*H amended with gypsum 25% of GR along with press-mud (10 t/ha) and bio-inoculants. Therefore, it will be beneficial if gypsum is applied at the rate of 25% of GR in combination with bio-formulation inoculums rather than the gypsum 50% of GR alone.

Electrical conductivity (EC): Mean EC values significantly increased in SW irrigated plots compared with CW irrigated plots (Table 2). Application of gypsum, however, increased the mean EC values from 0.44 dS/m in SW to 0.47 dS/m for 50% GR. This increase in the EC with the addition of gypsum could be ascribed to the fact that gypsum dissolution caused release of some salts into the soil solution (Amrhein and Suarez 1987). In case of microbial inoculations, the mean EC value significantly decreased in Azo (0.44 dS/m), Azo + PSB (0.40 dS/m) and Azo + PSB + ZnSB (0.45 dS/m) inoculums, respectively relative to the un-inoculated SW irrigate plots (0.50 dS/m). However, irrespective of the treatment combinations, the values obtained for EC were well below the hazardous level of salinity in soils i.e. 0.8 dS/m (soil:water ratio, 1:2) equivalent to EC value of 4 dS/m (Ayers and Westcot 1985). Stanford *et al.* (2003) reported that decrease in the EC of soil with the application of gypsum in sodic soil. However, they also concluded that microbial inoculants and organic amendments also decreased the EC value of soil to a significant level.

Exchangeable sodium percentage (ESP): Mean ESP value significantly increased from 5.50 under CW irrigated plots to 14.80 in SW irrigated plots (Table 2). It is very likely that the calcareous nature of the experimental soil (about 4% $CaCO_3$) encouraged less build-up of sodium on the exchange complex under SW irrigation that kept ESP at relatively lower levels in the study. Compared to plots irrigated with SW (17.30), application of gypsum at 25% and 50% of GR decreased ESP value to 14.13 and 13.06, respectively, while Azo, Azo + PSB and Azo + PSB + ZnSB inoculums decreased mean ESP value to 14.87, 14.80 and 12.06, respectively. Gypsum application in SW irrigated plots significantly decreased mean ESP value by 10.8%, 17.6% and 23.6% at 12.5%, 25% and 50% of GR, respectively compared with SW irrigated plots. Application of gypsum increases calcium content in the soil solution by decreasing the sodium content hence resulting in lowering of ESP. Besides, combined application of Azo + PSB + ZnSB inoculums and gypsum (25% GR) proved more beneficial in reducing ESP of SW irrigated soil when compared with application of gypsum (50% GR) alone (Table 2). Possibly, microbial bio-formulations helped in the dissolution of native $CaCO_3$ and applied gypsum due to production of organic acids, siderophore and extracellular polysaccharides thereby, lowering the ESP values. Meena and Prakasha (2024) also reported significant decrease in the ESP in sodic soils amended with gypsum. Choudhary *et al*. (2019) reported that irrigation with SW alone resulted in higher soil *p*H (>9) and ESP as compared with CW irrigation.

Soil organic carbon (SOC): Mean SOC significantly decreased by 25.8% in SW irrigated soils relative to CW irrigated soils (Table 3). Gypsum application significantly increased the SOC by 26.5% @50% GR treatment. Loss of soil organic carbon in sodic soil takes place because of the alkaline hydrolysis of organic matter. Whereas, the increase in SOC in the study may be related to (a) direct improvement in soil properties like *p*H and ESP and (b) indirectly through enhanced biomass production. Moreover, the Ca^{2+} from the gypsum prevents this loss by (a) forming a cation bridge of Ca^{2+} with organic carbon and (b) improving the soil aggregate formation and increasing aggregate-associated carbon. Basak *et al.* (2021) also reported significant increase in the total organic carbon in alkaline soils amended with gypsum. Significantly greater SOC value (14.3%) was obtained for soils inoculated with Azotobacter + PSB + ZnSB combined with gypsum dose @25% GR than the gypsum alone @50% GR.

Microbial biomass carbon (MBC): Mean value of MBC decreased by 18.9% in SW compared with CW irrigated plots (Table 3). Conversely, an increase in the MBC was recorded when gypsum and microbial bio-formulations were applied individually or in combination. In general, microbial bio-formulation application showed greater positive influence on MBC than gypsum application. Among different bio-formulations, mean value of MBC significantly increased by 6.9%, 16.4% and 27.6% in plots inoculated either with Azo, Azo + PSB and Azo + PSB + ZnSB inoculums, respectively under SW relative to the un-inoculated SW treatment. Application of gypsum @25% GR significantly increased the mean MBC by 6.7%, whereas, its application @50% GR increased the mean MBC content by 11.7% relative to the un-amended plots. Meena and Prakasha (2024) also reported that application of gypsum significantly increased the MBC in sodic soils. Combined application of gypsum (@25% GR or 50% GR) plus Azo + PSB or Azo + PSB + ZnSB to plots irrigated with sodic water significantly increased the MBC over the un-amended and un-inoculated soils under SW irrigation. Arora *et al.* (2016) also reported that MBC significantly increased in the soils co-inoculated with consortia of microbes and FYM. This was also evident from a negative correlation observed between soil MBC and ESP in the study (Fig. 1c).

Table 2 Effect of irrigation water quality, gypsum and microbial bio-formulations on soil *p*H, EC and ESP (3 years pooled data)

Treatment		Irrigation water					
		CW	SW	SW + $G_{12.5\%}$	SW + $G_{25\%}$	SW + $G_{50\%}$	Mean
			Soil *p*H				
Microbial inoculation	Un-inoculated	7.98	8.65	8.52	8.45	8.37	8.40
	Azo	7.93	8.56	8.43	8.40	8.32	8.33
	Azo + PSB	7.87	8.48	8.38	8.35	8.22	8.26
	Azo + PSB + ZnSB	7.80	8.39	8.29	8.28	8.16	8.18
	Mean	7.89	8.52	8.41	8.37	8.27	
LSD (0.05): IW = 0.126; MI = 0.03; IW × MI = NS							
			EC (dS/m)				
Microbial inoculation	Un-inoculated	0.42	0.50	0.45	0.57	0.53	0.50
	Azo	0.39	0.40	0.46	0.46	0.46	0.41
	Azo + PSB	0.38	0.37	0.40	0.41	0.44	0.40
	Azo + PSB + ZnSB	0.45	0.47	0.42	0.45	0.45	0.45
	Mean	0.41	0.44	0.43	0.47	0.47	
LSD (0.05): IW = 0.049; MI = 0.027; IW × MI = 0.048							
			ESP				
Microbial inoculation	Un-inoculated	5.89	17.30	15.17	14.13	13.06	13.11
	Azo consortia	5.72	14.87	13.43	12.93	11.9	11.77
	Azo + PSB	5.39	14.80	13.07	11.63	10.37	11.05
	Azo + PSB + ZnSB	5.01	12.06	11.03	9.98	9.80	9.58
	Mean	5.50	14.80	13.20	12.20	11.30	
LSD (0.05): IW = 0.292; MI = 0.261; IW × MI = 0.585							

SW, Sodic water, CW, Canal water; RSC, Residual sodium carbonate (12.5 meq/L); IW, Irrigation water; G, Gypsum; Azo, *Azotobacter*; PSB, P solubilizing bacteria; ZnSB, Zinc solubilizing bacteria; LSD, Least significant difference; NS, Non-significant.

Table 3 Effect of irrigation water quality, gypsum and microbial bio-formulations on SOC, MBC and dehydrogenase activity after 3 years of experimentation

Treatments		Irrigation water					
		CW	SW	SW + $G_{12.5\%}$	SW + $G_{25\%}$	SW + $G_{50\%}$	Mean
		Soil organic carbon (%)					
Microbial inoculations	Un-inoculated	0.58	0.40	0.50	0.53	0.56	0.51
	Azo	0.63	0.49	0.54	0.55	0.60	0.56
	Azo + PSB	0.67	0.53	0.59	0.60	0.65	0.61
	Azo + PSB + ZnSB	0.76	0.54	0.60	0.64	0.66	0.64
	Mean	0.66	0.49	0.56	0.58	0.62	
LSD (0.05): IW = 0.005; MI = 0.005; IW × MI = 0.010							
		Microbial biomass carbon (µg C/g)					
Microbial inoculations	Un-inoculated	123	108	114	117	120	116
	Azo	133	116	120	120	129	124
	Azo + PSB	155	124	128	130	140	135
	Azo + PSB + ZnSB	179	132	140	143	148	148
	Mean	148	120	126	128	134	
LSD (0.05): IW = 4.12; MI = 7.04; IW × MI = 7.87							
		Dehydrogenase activity (µg TPF/g soil/hr)					
Microbial inoculations	Un-inoculated	22.8	15.8	17.8	19.8	21.2	19.5
	Azo	26.8	18.5	21.1	21.8	23.2	22.3
	Azo + PSB	29.0	21.2	27.0	26.1	27.5	26.2
	Azo + PSB + ZnSB	32.6	24.0	28.0	28.1	29.2	28.4
	Mean	27.8	19.9	23.5	24.0	25.3	
LSD (0.05): IW = 1.55; MI = 1.06; IW × MI = NS							

SW, Sodic water, CW, Canal water; RSC, Residual sodium carbonate (12.5 meq/L); IW, Irrigation water; G, Gypsum; Azo, *Azotobacter*; PSB, P solubilizing bacteria; ZnSB, Zinc solubilizing bacteria; LSD, Least significant difference; NS, Non-significant.

Dehydrogenase activity (DHA): The mean value of dehydrogenase activity significantly decreased by 28.4% in SW compared with CW irrigated soil (Table 3). Upon gypsum application @12.5, 25 and 50% of GR dose, mean value of dehydrogenase activity increased by 18.1%, 20.6% and 27.1% in SW irrigated soils, respectively. Meena and Prakasha (2024) also reported that application of gypsum significantly increased the dehydrogenase activity in sodic soils. Likewise, mean value of dehydrogenase activity increased by 14.4%, 34.4% and 45.6%, respectively in soils irrigated with SW but amended with either *Azotobacter* or Azo + PSB or Azo + PSB + ZnSB solubilizing bacteria inoculums, respectively compared with un-inoculated treatment. Application of gypsum @25% GR along with microbial inoculation under SW irrigation plots showed the DHA value ranging between 21.8 to 28.1 µg TPF/g soil/hr relative to only 21.2 µg TPF/g soil/hr obtained in soil receiving only gypsum @50% GR. This indicated that using gypsum at lower rate (@25% GR) along with inoculum was more effective than applying only gypsum @50% GR in increasing DHA in the soil most likely due to greater SOC in the inoculum amended soil. Hidri *et al.* (2022) reported that microbial inoculated soils (saline + *Glutamicibacter* sp. and saline + *Pseudomonas* sp.) significantly increased dehydrogenase activity in the rhizosphere compared to the non-inoculated soil.

Economics (Gypsum vs. Gypsum + Bioformulation): Normally, the cost of each bottle (110 ml) of bioformulation (Azo, PSB and ZnSB) was ₹100 to inoculate seed for 1 acre of land. Thus, the total cost of bioformulation treatment (Azo, PSB and ZnSB) was ₹750 to inoculate a hectare of land. On the other hand, gypsum for 1 ha of land was costlier (₹3600 for @50% GR) (Supplementary Table 2). Whereas, the cost of bioformulation and gypsum @25% GR was ₹2550 for a hectare of land. Therefore, farmers can partially switch to use of microbial bio-formulations along with lesser dose of gypsum (@25% of GR) for ameliorating soils irrigated with SW to harvest more yield as well as economic benefits (saving ₹1050 /ha) especially where the availability of quality gypsum is not assured.

It can be concluded from the above study that gypsum and microbial bio-formulations either used independently or in conjunction with each other would be able to substantially reduce the sodicity stress under SW irrigation. The results of the study also indicate that application of liquid bioformulations along with reduced gypsum dose (25% of GR) will be a cost-effective strategy in reducing the adverse effects of sodic water irrigation on cotton productivity especially where availability of quality gypsum is not assured. Apart from reducing overall cost of production under sodic environments, application of the microbial formulations along with reduced dose of gypsum (@25% GR) will bring in associated benefits by progressively improving microbial activity, biomass to sustain soil health and productivity in the long-term.

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