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Harnessing sodic groundwater for sustainability in rice (*Oryza sativa*) – wheat (*Triticum aestivum*) cropping system

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ABSTRACT

High-input intensive agriculture and excessive use of flood irrigation has led to declining groundwater level and accumulation of sodium salts, leading to deteriorating water quality, soil organic matter and nutrient availability. Therefore, a three-year field experiment (2020–2023) was conducted to evaluate the judicious use of sodic groundwater through drip irrigation, gypsum, and mulch in a rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system at Budhmor village, Patiala district, Punjab. The study followed a split-split plot design with three irrigation regimes (through drip, and conventional flood), three gypsum levels (0, 25, and 50% gypsum), and two mulch treatments (with and without crop residue). Drip irrigation significantly reduced soil *p*H compared to flood irrigation due to enhanced leaching of soluble sodium. Gypsum application further lowered soil *p*H and improved organic carbon, nitrogen, phosphorus and potassium availability. The interaction between drip irrigation and gypsum (I_1G_3) produced the highest soil organic carbon, available nitrogen, phosphorus and potassium. Wheat yield increased from 29.94 q/ha under flood irrigation to 48.26 q/ha under I_1G_3 while direct-seeded rice yield was 30.80 q/ha under similar conditions. Gypsum significantly improved chlorophyll content in both crops, indicating enhanced physiological performance. Mulching had positive but non-significant effects on most parameters. Overall, the integrated use of drip irrigation at 80% ETc for wheat and 150% ETc for rice with 50% gypsum requirement was found most effective in mitigating sodicity, improving soil fertility, and sustaining crop productivity under sodic groundwater irrigation in the Indo-Gangetic plains.

Keywords: Direct seeded rice, Drip irrigation, Gypsum application, Poor-quality water

The rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system (RWCS) is the most dominant and productive cropping systems in South Asia, sustaining the food and livelihood security of over 400 million people (Bhatt *et al.* 2021). In Punjab and the adjoining Indo-Gangetic Plains (IGP), the RWCS has played a pivotal role in achieving India's Green Revolution targets through assured irrigation and high-input agriculture. However, decades of intensive cultivation, groundwater over-exploitation, and excessive use of surface flood irrigation have led to multiple environmental challenges, including declining groundwater tables, deteriorating water quality, and degradation of soil health (Bhatt *et al.* 2021). A major concern in this region is the use of sodic groundwater for irrigation, particularly in south-western and central Punjab. High residual sodium carbonate (RSC) in groundwater alters soil chemistry, disperses clay particles and impedes water infiltration, thereby deteriorating soil structure and reducing crop yields (Minhas *et al.* 2019). Under conventional flood irrigation, the accumulation of sodium salts in the rhizosphere accelerates secondary salinisation and leads to a decline in soil organic matter and nutrient availability (Singh *et al.* 2018).

To counter these challenges, improved irrigation and soil management practices are required. Drip irrigation has emerged as an efficient technology to optimise water use, minimise percolation losses, and maintain favourable soil-water-air relations (Mandal *et al.* 2007, Jat *et al.* 2024, Ramesh *et al.* 2024). Its use in conjunction with gypsum application, a proven chemical amendment for sodic soils, can provide a sustainable strategy to utilise poor-quality groundwater while maintaining soil health (Choudhary *et al.* 2004). Gypsum supplies soluble calcium that replaces exchangeable sodium, reduces soil *p*H, and improves aggregation. Moreover, the conjunctive use of canal and sodic groundwater allows partial dilution of salts and more balanced irrigation chemistry (Minhas *et al.* 2021). In addition to water and chemical amendments, mulching with crop residues is gaining importance as a complementary

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practice to conserve soil moisture, suppress evaporation, and enhance microbial activity (Minhas *et al.* 2019, Singh *et al.* 2020). Though mulching effects are well-documented in arid and semi-arid systems, its role under drip irrigation in sodic soils remains less explored (Nouri *et al.* 2019).

Therefore, an integrated approach involving drip irrigation method, gypsum-based sodicity management, and mulching could offer an effective solution for sustaining productivity and soil quality in regions constrained by sodic groundwater. Given this context, the present study was undertaken to assess the effects of different irrigation levels, gypsum application rates, and mulching on crop performance and chlorophyll content of wheat and direct-seeded rice (DSR); and to identify the most suitable combination of irrigation, amendment and residue management practices for sustainable crop production in sodic groundwater conditions under RWCS.

MATERIALS AND METHODS

A field experiment was conducted during 2020–2023 at a farmer's field in Budhmor village, Patiala district (30°19′ N, 76°23′ E; at an elevation of 251 m amsl), Punjab. The climate of the region is subtropical semi-arid, characterised by hot summers, cold winters, and an average annual rainfall of approximately 700 mm, about 75–80% of which occurs during the southwest monsoon season. The initial soil physico-chemical properties of the experimental site are presented in Table 1. The experimental soil was classified as silt loam, with alkaline reaction and high sodicity.

The treatments were based on a split-split plot design of three levels of irrigation (I), three levels of gypsum application rates (GR), and two levels of mulch management (M) in split-split plot design and each treatment was replicated thrice. The irrigation regimes in mian plot were I_1, Drip irrigation at 80% of crop evapotranspiration (ETc) for wheat and 150% ETc for rice; I_2, Drip irrigation at 100% ETc for wheat and 175% ETc for rice; I_3, Surface flood irrigation (conventional method) with gypsum in sub-plots i.e. G_1, 0% GR; G_2, 25% GR; G_3, 50% GR. M_1, Crop residue mulch applied after sowing/transplanting and M_2, No mulch in sub-plot. Each plot measured 5 m × 4 m with a 1 m buffer zone to prevent lateral water movement from one to another. The experiment followed direct seeded rice (DSR)–wheat rotation for three years. The sowing of the DSR was done during the month of June using a seed rate of 25 kg/ha. While, wheat was sown in the month of November at a row spacing of 20 cm using 100 kg/ha of seed. Fertilisers were applied @120:60:40 kg $N:P_2O_5:K_2O$/ha for wheat and 150:60:40 kg $N:P_2O_5:K_2O$/ha for rice, respectively. Nitrogen was applied in three splits with half as basal, and the remaining in two equal top dressings. All agronomic practices such as weed control, fertiliser management, and pest control were adopted as per Punjab Agricultural University (PAU) recommendations. Crop residues were chopped and uniformly spread over the soil surface for mulch treatments (M_1).

Table 1 Initial soil physicochemical properties of the experimental site and water quality parameters of the groundwater used for irrigation

Parameters	Initial value
Soil quality parameter	
*p*H	9.33
Electrical conductivity (EC_e) (dS/m)	0.57
Organic carbon (%)	0.56
Available nitrogen (kg/ha)	154.8
Available phosphorus (kg/ha)	23.3
Available potassium (kg/ha)	200.4
Available sulfur (S) (mg/kg)	25.3
Exchangeable sodium percentage (ESP) (%)	30.2
DTPA-extractable iron (Fe) (mg/kg)	5.56
DTPA-extractable manganese (Mn) (mg/kg)	2.49
DTPA-extractable zinc (Zn) (mg/kg)	1.33
DTPA-extractable copper (Cu) (mg/kg)	0.35
Calcium carbonate ($CaCO_3$) (%)	1.02
Water quality parameter	
*p*H	8.86
Electrical conductivity (EC) (dS/m)	0.71
Calcium (Ca^{2+}) (meq/L)	0.20
Calcium + Magnesium (Ca^{2+} + Mg^{2+}) (meq/L)	1.51
Sodium (Na^+) (meq/L)	6.11
Potassium (K^+) (meq/L)	0.11
Chloride (Cl^-) (meq/L)	0.15
Carbonate + Bicarbonate (CO_3^{2-} + HCO_3^-) (meq/L)	6.01
Sodium adsorption ratio (SAR)	5.21
Residual sodium carbonate (RSC) (meq/L)	4.52

Crop water requirement (ETc) was computed based on reference evapotranspiration (ETo) using the FAO Penman-Monteith equation (Allen *et al.* 1998), multiplied by appropriate crop coefficients (Kc) for each growth stage. For drip treatments, irrigation was applied through pressure-compensating emitters at 1.5 L/h discharge rate. The irrigation frequency varied between 2–3 days depending on crop stage and weather conditions. For surface irrigation, water was applied at the farmer's usual frequency (10–12 cm depth/irrigation). In conjunctive use treatments, the sodic groundwater was partially neutralised with gypsum beds, while canal water (when available) was alternated to maintain ionic balance.

Soil samples were collected from the 0–15 cm soil depth after harvest of wheat crop and analysed for key soil chemical properties. The soil *p*H and EC were measured in a 1:2.5 soil-water suspension using a *p*H meter and conductivity bridge (Jackson 1973). Soil organic carbon content was estimated using wet oxidation method (Walkley and Black 1934). Soil available nitrogen (N), phosphorus (P) and potassium (K) were determined by Subbiah and Asija (1956), Olsen *et al.* (1954) and neutral 1 N ammonium acetate (Jackson 1973), respectively. The available sulphur was analysed as per Chesnin and Yien (1951) and available micronutrients were analysed using Lindsay and Norvell (1978) method. Exchangeable sodium percentage (ESP) and calcium carbonate content were analysed following standard procedures (Richards 1954).

The total chlorophyll content in the flag leaves was determined using Arnon (1949). Grain yield was determined from a 5 m² net plot area and expressed at 12% moisture content. All collected data were analysed using Analysis of Variance (ANOVA) appropriate for split-split plot design (Gomez and Gomez 1984). The significance of treatment effects was tested at the 5% probability level ($p \leq 0.05$). When significant, treatment means were separated using critical difference (CD) values. Statistical computations were performed using SPSS 25.0 and MS Excel software packages.

RESULTS AND DISCUSSION

Soil chemical properties: The soil *p*H was significantly influenced by the main effects of irrigation and gypsum application while the effects of mulch and their interactions (I × G and I × M) were found to be statistically non-significant (Table 2). Drip irrigation at 100% ETc for wheat and 175% ETc for rice (I_2) recorded a significantly lower mean soil *p*H (8.66) compared to flood irrigation (I_3: 9.19). The lower *p*H under drip irrigation treatments might be attributed to better leaching of soluble sodium salts through frequent but smaller irrigation volumes, which helped in reducing alkalinity buildup in the root zone. In contrast, the relatively higher *p*H under flood irrigation can be ascribed to poor drainage and intermittent drying-wetting cycles that limit sodium leaching and promote the reformation of exchangeable sodium carbonate. Gypsum application markedly reduced soil *p*H from 9.19 under G_1 to 8.51 under G_3.

These findings confirmed the well-established mechanism of gypsum as an effective amendment in sodic soils. Soluble calcium from gypsum replaces exchangeable sodium, forming leachable sodium sulfate, thereby reducing soil *p*H and sodicity (Qadir and Oster 2004). The synergistic effect of drip irrigation and gypsum in lowering soil alkalinity (I_2G_3: 8.24) highlights the concurrent operation of physical (leaching), chemical (cation exchange), and biological (microbial activity) amelioration mechanisms (Sharma *et al.* 2016).

The soil organic carbon (SOC) content was significantly affected by irrigation and gypsum, as well as by their interaction (I × G), while mulch effects were non-significant (Table 2). The highest mean SOC (0.59%) occurred under I_1 which was significantly higher than I_3 (0.52%). The higher SOC under drip irrigation might be due to optimal soil moisture and aeration conditions, which reduce oxidation losses and enhance microbial stabilisation of organic matter (Wang *et al.* 2015). Gypsum application also increased SOC from 0.53% (G_1) to 0.58% (G_3), likely due to improved soil aggregation and formation of calcium-organic matter complexes that protect carbon from microbial decomposition (Rengasamy 2010).

The interaction between irrigation and gypsum revealed the highest SOC (0.65%) under 80% ETc in wheat and 150% ETc in rice with 50% GR gypsum (I_1G_3), demonstrating that integrated physical and chemical amelioration effectively enhances carbon sequestration in sodic soils.

Table 2 Effect of irrigation, gypsum and mulch on soil *p*H and organic carbon content (three years pooled data)

Levels of irrigation	Levels of gypsum application				Level of mulch		
	G_1	G_2	G_3	Mean	M_1	M_2	Mean
Soil *p*H							
I_1	9.17	8.89	8.32	8.79	8.83	8.76	8.79
I_2	9.01	8.74	8.24	8.66	8.71	8.61	8.66
I_3	9.39	9.23	8.96	9.19	9.23	9.16	9.19
Mean	9.19	8.95	8.51	8.88	8.92	8.84	8.88
CD (p = 0.05)	I = 0.19	G = 0.36	I × G = NS		I = 0.19	M = NS	I × M = NS
Soil organic carbon content (%)							
I_1	0.55	0.57	0.65	0.59	0.59	0.59	0.59
I_2	0.53	0.55	0.57	0.55	0.55	0.55	0.55
I_3	0.51	0.53	0.53	0.52	0.53	0.52	0.52
Mean	0.53	0.55	0.58	0.55	0.55	0.55	0.55
CD (p = 0.05)	I = 0.03	G = 0.02	I × G = 0.03		I = 0.03	I = 0.04	I × M = NS

I, Irrigation; G, Gypsum; M, Mulching; NS, Non-significant. Treatment details are given under Materials and Methods.

The available nitrogen (N) content in soil was significantly influenced by both irrigation and gypsum application, whereas mulch effects were non-significant (Table 3). The highest mean available N (158.91 kg/ha) was recorded under I_1 followed by I_2 and I_3. Improved N availability under drip irrigation can be attributed to reduced leaching and denitrification losses, better aeration, and enhanced microbial mineralisation under optimum moisture conditions (Singh *et al.* 2020). Gypsum also significantly improved available N from 152.9 kg/ha (G_1) to 157.9 kg/ha (G_3), reflecting enhanced microbial activity and nitrification as soil sodicity declined (Sharma *et al.* 2016). The I × G interaction was significant, indicating that the benefit of gypsum was more pronounced under drip irrigation. The combined treatment (I_1G_3) recorded the highest N content (165.07 kg/ha), supporting the importance of concurrent physical and chemical reclamation processes. The slight but non-significant improvement under mulching can be attributed to improved soil moisture and reduced volatilisation (Zhang *et al.* 2019).

Soil available phosphorus (P) was also significantly influenced by irrigation and gypsum application (Table 3). The highest mean P content (24.30 kg/ha) was obtained under I_1, significantly higher than I_3. Enhanced P availability under drip systems results from better moisture control and reduced P fixation due to moderated *p*H (Minhas *et al.* 2021). Gypsum application further improved P availability, increasing from 22.05 kg/ha (G_1) to 23.36 kg/ha (G_3). The additional soluble Ca^{2+} from gypsum might reduced exchangeable Na^+, thereby promoting P desorption and enhancing microbial P mineralisation (Meena *et al.* 2025). The I × G interaction was significant, and the I_1G_3 combination yielded the highest P content (25.70 kg/ha).

Available potassium (K) content was significantly affected by irrigation, gypsum, and mulch (Table 3). The highest K availability (215 kg/ha) was observed under I_1, significantly higher than I_3 (202 kg/ha). Gypsum improved K availability from 205 kg/ha (G_1) to 214 kg/ha (G_3) through cation exchange, where Ca^{2+} replaces Na^+ on soil colloids, releasing K^+ into solution (Kumar *et al.* 2023). Mulching slightly reduced K availability, possibly due to restricted vertical movement under lower evaporation, but the difference was minor. Collectively, these results indicated that combining drip irrigation and gypsum application effectively enhances soil N, P, and K availability by improving physical structure, reducing sodicity, and supporting biological nutrient cycling in sodic soils (Sharma *et al.* 2016).

Wheat grain yield and chlorophyll content: Irrigation, gypsum, and mulch treatments markedly influenced wheat grain yield (Table 4). The highest mean yield (41.81 q/ha) was recorded under I_1, significantly superior to I_3 and

Table 3 Effect of irrigation, gypsum and mulch on available nitrogen, phosphorus and potassium content (three years pooled data)

Levels of irrigation	Levels of gypsum application				Level of mulch		
	G_1	G_2	G_3	Mean	M_1	M_2	Mean
Available nitrogen (kg/ha)							
I_1	154.70	156.96	165.07	158.91	159.24	158.58	158.91
I_2	152.96	154.76	156.75	154.82	155.14	154.51	154.82
I_3	151.05	151.75	151.93	151.58	151.40	151.76	151.58
Mean	152.90	154.49	157.92	155.10	155.26	154.95	155.10
CD (p = 0.05)	I = 2.10	G = 1.69	I × G = 2.92		I = 2.10	M = NS	I × M = NS
Available phosphorus (kg/ha)							
I_1	23.04	24.17	25.70	24.30	24.17	24.43	24.30
I_2	22.93	24.53	24.81	24.09	23.96	24.21	24.09
I_3	20.19	21.15	19.58	20.31	20.19	20.43	20.31
Mean	22.05	23.28	23.36	22.90	22.77	23.02	22.90
CD (p = 0.05)	I = 1.42	G = 0.77	I × G = 1.34		I = 1.42	M = NS	I × M = NS
Available potassium (kg/ha)							
I_1	209	215	221	215	213	217	215
I_2	207	211	215	211	210	212	211
I_3	200	203	205	202	201	204	202
Mean	205	209	214	210	208	211	210
CD (p = 0.05)	I = 3.94	G = 3.22	I × G = NS		I = 3.94	M = 2.79	I × M = NS

I, Irrigation; G, Gypsum; M, Mulching; NS, Non-significant. Treatment details are given under Materials and Methods.

Table 4 Effect of irrigation, gypsum and mulch on the wheat grain yield and chlorophyll content (three years pooled data)

Levels of Irrigation	Levels of gypsum application				Level of mulch		
	G_1	G_2	G_3	Mean	M_1	M_2	Mean
Wheat grain yield (q/ha)							
I_1	36.99	40.18	48.26	41.81	42.62	41	41.81
I_2	37.34	39.66	42.21	39.74	40.44	39.03	39.74
I_3	28.80	29.59	31.44	29.94	30.06	29.82	29.94
Mean	34.38	36.47	40.64	37.16	37.71	36.62	37.16
CD (p = 0.05)	I = 2.07	G = 1.85	I × G = 3.21		I = 2.07	M = NS	I × M = NS
Wheat chlorophyll content (mg/g)							
I_1	2.25	2.52	2.89	2.55	2.58	2.52	2.55
I_2	2.32	2.45	2.85	2.54	2.53	2.55	2.54
I_3	2.16	2.37	2.52	2.35	2.36	2.33	2.35
Mean	2.24	2.45	2.75	2.48	2.49	2.47	2.48
CD (p = 0.05)	I = NS	G = 0.15	I × G = NS		M = NS	I = 0.15	M x I = NS

I, Irrigation; G, Gypsum; M, Mulching; NS, Non-significant. Treatment details are given under Materials and Methods.

comparable with I_2. This suggested that moderate deficit irrigation under drip can sustain yield while improving water use efficiency. Gypsum application further enhanced yield from 34.38 q/ha (G_1) to 40.64 q/ha (G_3) due to improved soil structure, root growth, and nutrient uptake (Singh *et al.* 2009). The interaction of I × G was significant with the I_1G_3 combination yielding the highest productivity (48.26 q/ha). This underscores the synergistic benefit of simultaneous physical and chemical reclamation (Minhas *et al.* 2021). Mulching had a non-significant yet positive effect, with slightly higher yield in mulched plots (37.71 q/ha) due to better soil moisture conservation.

Gypsum application also had a significant effect on wheat chlorophyll content (Table 4). The highest mean chlorophyll concentration (2.75 mg/g) occurred under G_3, indicating better nutrient availability, particularly nitrogen and magnesium, which are crucial for chlorophyll synthesis (Yadav *et al.* 2025). Irrigation and mulch effects were non-significant, suggesting that moderate deficit irrigation (I_1) under drip maintained sufficient physiological activity for chlorophyll synthesis. The combined results demonstrated that gypsum is critical for restoring photosynthetic efficiency and yield potential of wheat under sodic conditions.

Rice grain yield and chlorophyll content: The yield of DSR was primarily governed by gypsum application, while irrigation and mulch effects were statistically non-significant (Table 5). The highest mean yield (29.33 q/ha) was obtained with G_3, significantly higher than other treatments. The improvement in yield with gypsum reflects its role in reducing exchangeable sodium percentage, enhancing soil structure, and promoting root proliferation and nutrient uptake. Although irrigation levels had no significant effect, slightly higher yield under I_1 (28.93 q/ha) compared to I_3 (27.62 q/ha) suggested that micro-irrigation can sustain rice productivity under sodic groundwater while improving water use efficiency. Mulching showed minor yield enhancement due to reduced evaporation and moderated soil microclimate.

Similarly, gypsum application significantly increased total chlorophyll content in rice leaves (Table 5) from 1.52 mg/g (G_1) to 1.87 mg/g (G_3). This improvement might be associated with enhanced root activity, reduced Na^+ toxicity, and improved uptake of N and Mg, leading to better photosynthetic performance (Meen *et al.* 2025). Irrigation and mulch had no significant impact on chlorophyll content, though slightly higher values under drip irrigation and mulching indicate favourable physiological responses under improved soil conditions.

The study demonstrated that sodic groundwater can be utilised safely and productively when coupled with suitable management interventions. Drip irrigation substantially improved soil chemical health by reducing alkalinity and enhancing nutrient availability compared to flood irrigation. Gypsum application emerged as the most effective amendment for sodic soil reclamation, with 50% gypsum requirement providing optimal results. The combination of drip irrigation (80% ETc in wheat and 150% ETc in rice) and 50% GR gypsum (I_1G_3) maximised soil organic carbon, nutrient availability, and yields of both wheat and direct-seeded rice, while improving physiological indicators such as chlorophyll content. The mulching effect on most of the parameters was not significant. This may be attributed to the use of high RSC irrigation water applied based on crop evapotranspiration along with the relatively short duration of the experiment.

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Table 5 Effect of irrigation, gypsum and mulch on the direct seeded rice yield (three years pooled data)

Levels of irrigation	Levels of gypsum application				Level of mulch		
	G_1	G_2	G_3	Mean	M_1	M_2	Mean
Rice yield (q/ha)							
I_1	27.68	28.32	30.80	28.93	29.02	28.84	28.93
I_2	28.79	28.53	29.15	28.82	29.12	28.52	28.82
I_3	26.90	27.93	28.05	27.62	27.73	27.52	27.62
Mean	27.79	28.26	29.33	28.46	28.62	28.30	28.45
CD (p = 0.05)	I = NS	G = 0.91	I × G = NS		M = NS	I = 0.86	I × M = NS
Rice chlorophyll content (mg/g)							
I_1	1.52	1.70	2.00	1.74	1.76	1.72	1.74
I_2	1.57	1.66	1.92	1.72	1.71	1.72	1.72
I_3	1.46	1.60	1.70	1.59	1.60	1.58	1.59
Mean	1.52	1.65	1.87	1.68	1.69	1.67	1.68
CD (p = 0.05)	I = NS	G = 0.11	I × G = NS		M = NS	I = 0.11	

I, Irrigation; G, Gypsum; M, Mulching; NS, Non-significant. Treatment details are given under Materials and Methods.

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