



Phosphogypsum and Humic Acid Mixed with Saline Irrigation Water: A Strategy to Improve Some Chemical Properties of Soil and Cauliflower (*Brassica Oleracea* L.) Yield under Salt Stress Condition

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Article Info	ABSTRACT
Article type: Research Article	Using the saline water for irrigation purposes negatively affects soil properties; however, these effects can be mitigated through appropriate management practices A field experiment was conducted to determine the feasibility of mixing phosphogypsum and humic acid with saline irrigation water to mitigate its harmful effects on the soil chemical properties and cauliflower growth. The experiment was designed in a complete block design with three replications. The first factor involved three levels of water irrigation salinity, i.e., 2.70, 5.50, and 7.50 dS/ m. The second factor was the level of phosphogypsum-to-humic acid ratio, namely 0.0, 0.25, and 0.50 g/L for each of them. The treatment Phosphogypsum and Humic Acid were arranged as T1 (H0PG0) (control), T2 (H1PG1), T3 (H1PG2), T4 (H2PG1), and T5 (H2PG2), all applied Mixed with irrigation water, T4 (0.25 g/L phosphogypsum and 0.50 g/L humic acid) showed better performance over other treatments Specifically, such treatments decreased (EC, SAR, Na, Cl, HCO ₃) all soil depths; the highest reduction rate was observed at the 0.0–15 cm depth, reaching (26.52, 49.11, 38.70, 25.53, 15.46)% for each, respectively, while (Ca ²⁺) increased at 29.70% the same depth. Treatment T4 was the most effective treatment in terms of increasing cauliflower plant components)height, head weight, and yield(compared to the control treatment across all salinity levels; the increases recorded were 26.57% for height, 22.79% for head weight, and 22.67% for yield.
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INTRODUCTION

Water is the bedrock of life and a key component to the realization of the Sustainable Development Goals; it is also a common international problem of food security. Geographically, Iraq lands lies in arid and semi-arid geographical areas with low rainfall and high evaporation rates yearly. As a result, the issue of water scarcity has emerged among the key constraints of the agricultural sector in Iraq, which is largely due to frequent droughts and the fact that the nation heavily depends on the Tigris and Euphrates rivers to sustain its water needs, the vast majority of the sources of which are located beyond its borders (Al-Ansari, 2016). Moreover, the scarcity of surface water resources is aggravated by upstream policies of the neighboring nations, especially by building large dams that decrease the Iraqi water supply. Consequently, as water demand grows to support the farming sector, signs of water scarcity have become noticeable throughout the

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nation. Considering water availability is one of the main determinants of agricultural productivity, the alternative irrigation water source, which has been heavily used by many farmers, includes low-quality water sources like agricultural drainage water and groundwater. Nonetheless, irrigation with saline or low-quality water, which is indiscriminate, has adverse effects on the growth of plants and, therefore, on crop yields. This is largely attributed to high levels of salinity, which have a toxic effect on plants and modify chemical, physical, and biological characteristics of soil, hence retarding plant growth (Emdad et al., 2006). Thus, irrigation with saline water requires the introduction of relevant management practices that will ensure the concentration of salts is below the root zone and that salts do not accumulate with capillary rise (He-zhong, 2012). In this regard, phosphogypsum, a byproduct of wet-process production of phosphate fertilizers made out of phosphate rock, has received attention (Dehmel and Rogers, 1993). In the world, the annual production of phosphogypsum is estimated to be 280 million tons (Yang et al., 2009). Chemically, it consists of hydrated calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and serves as a direct source of calcium, which can reduce sodium adsorption in soils. In addition, it plays a significant role in improving soil properties by supplying calcium ions that replace sodium ions on the soil adsorption complex (Xue et al., 2019). Equally, humic acids are known to enhance soil fertility, enhance plant growth, productivity, and plant resistance to stresses caused by abiotic factors, such as water stress (Canellas and Olivares, 2014; Moghadam, 2015). Additionally, the humic materials have active functional groups, i.e., carboxyl and hydroxyl groups, which complex with the salt ions and hence leach out of the ground (Tan, 2003). Cauliflower is an excellent source of vitamins B-6, K and C, protein, folate, thiamine, riboflavin and pantothenic acid. It is also a very good source of dietary fiber, choline, omega-3 fatty acids and some elements, including biotin K, P, Ca, Mg, Fe and Mn (Islam et al. 2021). Thus, it is of great agricultural significance to enhance its growth and productivity in salty environments. The current research, thus, seeks to establish the best proportions of humic acid and phosphogypsum to counter the impacts of saline irrigation water on soil chemical properties, along with the growth and production of cauliflower plants.

MATERIALS AND METHODS

The experiment was conducted under field conditions during the growing season of 2024-2025 in Anbar state, Iraq. A factorial experiment was conducted according to (RCBD) with three replications. first factor involved three levels of water irrigation salinity, i.e., 2.70, 5.50, and 7.50 dS /m, symbolized as S1, S2, and S3, respectively. The second factor was three levels of humic acid, namely 0.0, 0.25, and 0.50 g/L symbolized as H0, H1, and H2, while the third factor was phosphogypsum at three levels, i.e., 0.0, 0.25, and 0.50 g/L symbolized as PG0, PG1, and PG2. On 15 October 2024, cauliflower (*Brassica Oleracea* L.) seedlings were transplanted in rows of 4 m length, with a spacing of 0.50 m between the adjacent plants and 0.75 m between rows to provide a plant density of 26.666 plant/ ha. Irrigation was applied by a drip irrigation system with GR-type emitters (8 L/ h) and scheduled based on depletion 35% of the available soil water estimated based on Class A pan evaporation data. The humic acid used was completely soluble and consisted of 85% humic acid and 12% K_2O . The treatment Phosphogypsum and Humic Acid were arranged as T1 = H0PG0 (control), T2 = H1PG1, T3 = H1PG2, T4 = H2PG1, and T5 = H2PG2, all applied through irrigation water. Composite soil samples were taken from a 0–30 cm depth before the experiment, air-dried and sieved through a 2 mm mesh, and defined by their initial chemical and physical properties. Saline irrigation water was prepared as a mixture of river water with drainage water to obtain the required salinity levels according to the method described by Ayers and Westcot (1985), as shown below:

$$EC_m = \frac{(EC_1 \times V_1) + (EC_2 \times V_2)}{V_1 + V_2} \quad (1)$$

Table 1. Some properties of soil, irrigation water and phosphogypsum

Parameter	soil	irrigation water			phosphogypsum	Unit
		S1	S2	S3		
pH	8.14	7.93	7.70	7.66	5.80	-
Sodium Adsorption Ratio (SAR)	2.36	1.93	2.57	4.12	-	-
EC	1.80	2.70	5.50	7.50	3.80	dS/m
Organic matter	2.80					gm/kg
Lime (CaCO ₃)	225					gm/kg
Ca ⁺²	10.55	12.13	13.22	19.15	64.18	
Mg ⁺²	5.80	6.00	8.32	10.70	12.10	
Na ⁺¹	7.15	8.00	12.22	22.50	0.50	
K ⁺	0.92	0.16	0.30	0.49	2.25	
SO ₄ ⁻²	5.50	5.10	8.40	12.10		mmol/L
HCO ₃ ⁻	1.25	1.18	1.50	1.90		
Cl ⁻	3.80	17.20	19.00	20.32		
Bulk Density	1.32					mg/m ³
Soil Particles	Sand	500.00				
	Silt	200.00				
	Clay	300.00				g/kg
Texture Soil	Sandy Clay loam					

EC_m is the desired electrical conductivity of the mixed water; EC_1, EC_2 electrical conductivity of water sources 1 (river water) and 2 (drainage water), respectively; V_1, V_2 volumes of water sources 1 and 2, respectively. The required concentrations of phosphogypsum and humic acid were prepared and thoroughly mixed in 2000 L storage tanks through which irrigation water was passed. Also, electric pumps were used to drive the drip irrigation system to achieve uniformity in water distribution. Soil samples were also collected at three depths of 0–15, 15–30, and 30–45 cm for the determination of electrical conductivity (EC), soil pH, and major cations and anions. The EC and pH were determined in a 1:5 suspension of soil and water using calibrated EC and pH meters. Soil organic matter content was also determined by the method described by Jackson (1958). Finally, data were statistically analysed by using SPSS software version 20. Comparisons between treatment means were performed using the least significant difference (LSD) test at a significance level of $p \leq 0.05$. Chloride concentration was determined by titration with silver nitrate as described by Richards (1954). Furthermore, titration was used to measure bicarbonate (HCO_3^-). The sodium adsorption ratio (SAR) was estimated based on the concentrations of sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) in $mmol L^{-1}$ as shown in Eq. (1). In addition, sulfate (SO_4^{2-}) was determined by the turbidimetric method. Calcium and magnesium concentrations were determined by atomic absorption spectrophotometry and sodium and potassium by flame photometer, according to the procedures of Polemio and Rhoades (1977).

$$\text{Sodium Adsorption Ratio (SAR)} = \frac{N_a}{\sqrt{Ca + Mg}} \quad (2)$$

Some information about QA and QC of the analysis

Robust QA/QC protocols were applied to ensure analytical reliability. All analyses were performed in triplicates ($n = 3$), with a relative standard deviation (RSD) below (4.3) to confirm repeatability. Calibration curves demonstrated high linearity ($R^2 > 0.89$), Mean values were statistically compared using the (LSD) test at a significance level (0.05)

RESULTS AND DISCUSSION

Effect of phosphogypsum and humic acids on the soil electrical conductivity

Results in Table 2 showed that saline irrigation water caused a significant increase in soil

Table 2. Effect of phosphogypsum and humic acids on the soil electrical conductivity for the three different soil depths (0-15, 15-30 and 30-45cm) after planting.

Levels of saline water (dS/m)	Soil depth (cm)	combinations of phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		ECe					
S1 (2.70)	0 - 15	2.85	2.16	2.99	1.5	2.92	3.10
	15 - 30	3.27	2.55	3.64	2.28	3.42	3.79
	30 - 45	3.58	2.78	3.86	2.49	3.79	4.12
S2 (5.50)	0 - 15	3.20	2.90	3.55	2.55	3.49	3.92
	15 - 30	3.50	3.14	3.78	3.00	3.66	4.27
	30 - 45	3.77	3.55	3.90	3.41	3.88	4.62
S3 (7.50)	0 - 15	3.80	3.50	4.22	3.20	4.10	4.70
	15 - 30	4.20	3.90	4.50	3.25	4.44	5.07
	30 - 45	4.40	4.00	4.96	3.90	4.48	5.43
Total Average of combinations of phosphogypsum and humic acids							
Average of combinations of phosphogypsum and humic acids	0 - 15	3.28	2.85	3.58	2.41	3.50	3.12
	15 - 30	3.65	3.19	3.97	2.84	3.84	3.49
	30 - 45	3.91	3.44	4.24	3.26	4.05	3.78

electrical conductivity at all studied soil depths, 0–15, 15–30, and 30–45 cm. The electrical conductivity of the soil, in general, increased with the increase in salinity levels and soil depth. The highest value of electrical conductivity was found at the salinity level S3 at the depth of 30–45 cm with the value of 5.43 dS/m, which was increased by 201.66% in comparison with the initial electrical conductivity of the soil, which was 1.80 dS/m. On the other hand, the minimum value of the electrical conductivity was obtained at the salinity level S1 and at the soil depth of 0–15 cm, reaching 3.10 dS/m, which is an increase of 72.00% compared to the initial soil condition. This enhancement of the electrical conductivity of the soil may be attributed to the continuous accumulation of soluble salts from saline irrigation water in the soil profile, particularly in the deeper soil layers. The combined use of humic acids and phosphogypsum also significantly influenced the electrical conductivity of the soil compared to the untreated control treatment T1. In particular, the treatment T4 showed the highest decrease in soil electrical conductivity at all soil depths. The highest reduction was 26.52% at depth 0–15 cm in comparison to the control treatment. On the other hand, at the same depth of control, treatment T3 increased the electrical conductivity by 9.14%. The increase in soil electrical conductivity with increasing phosphogypsum application rates maybe related to the relatively high electrical conductivity and sulfate content of phosphogypsum, as shown in Table 1. Phosphogypsum, when dissolved in soil solution, releases sulfate ions and thus provides a higher concentration of soluble salts. However, it is a good source of calcium. Phosphogypsum also contains calcium ions that displace exchangeable sodium ions from the soil exchange complex, thereby permitting leaching of sodium from the soil profile. However, over-application of phosphogypsum may cause an overall increase in soluble salts in the soil solution. On the other hand, the reduction in soil electrical conductivity observed at lower levels of phosphogypsum with higher levels of humic acid application may be associated with the beneficial effects of humic substances on soil chemical and physical properties. Humic acids have functional groups of carboxyl and hydroxyl that are especially active and increase the processes of ion exchange, adsorption, and chelation, which reduces the concentration of soluble salts in the soil solution ((Tchiadje 2007 and Al-Kubissi et al. 2024). Also, humic acids improve soil structure, reduce bulk density, and increase soil permeability, which allows salt leaching beyond the root zone (Nan et al. 2016). In the same way, phosphogypsum helps to improve the structure and permeability of the soil and therefore to leach excess salts from the soil profile (Agar 2011). In addition, phosphogypsum is

an available source of calcium that replaces the exchangeable sodium and increases the removal of these ions from the soil profile (Al-Hadethi and Al-Alwani 2020). The present findings are thus in agreement with those reported by (Khattak and Dost 2014 and Al-Falahi et al. 2022), who demonstrated that the application of organic and calcium-based amendments effectively improved soil salinity characteristics under saline conditions.

Effect of phosphogypsum and humic acids on the concentration of Ca^{2+} , Mg^{2+} , and Na^+ under saline conditions

The data presented in Table 3 showed that saline irrigation water significantly increased the concentrations of Ca^{2+} , Mg^{2+} , and Na^+ in the soil at depths of 0–15, 15–30, and 30–45 cm. In general, concentrations of these cations increased progressively with increasing salinity levels and soil depth. The highest Ca^{2+} concentration was observed at the depth of 30–45 cm under the salinity level of S3, which was 38.20 mmol/ L, 262.08% higher than the initial soil concentration of 10.55 mmol/ L. Conversely, the lowest concentration of Ca^{2+} was found at the salinity level S1 at the depth of 0–15 cm, which was 25.61 mmol/ L, but an increase of 142.74% from the initial value. Similarly, the concentration of Mg^{2+} was significantly increased with the increase in salinity levels. The maximum Mg^{2+} concentration at salinity level S3 was observed at a depth of 30–45 cm, which was 27.71 mmol/ L, an increase of 377.75% over the initial soil concentration of 5.80 mmol/ L. Conversely, the lowest concentration of Mg^{2+} was found at 0–15 cm depth in S1 salinity level, which was 14.52 mmol/ L with an increase of 150.34% compared to the initial concentration. Similarly, Na^+ concentration followed a similar trend, progressively increasing with increasing salinity levels and soil depth. The highest concentration of Na^+ was found at salinity level S3 at a depth of 30–45 cm, where it was 26.38 mmol/ L, which was an increase of 328.94% from the initial concentration of 6.15 mmol/ L. On the other hand, the lowest level of Na^+ was found at salinity level S1 at the depth of 0–15 cm with the concentration of 14.00 mmol/ L (127.64% increase from the initial value). Because of the continued input of salts from saline irrigation water and the subsequent accumulation of these salts in the soil profile, probably deep in the soil profile, these increases in cation concentrations can be attributed. In addition, applying humic acids and phosphogypsum together also had a significant impact on the concentrations of Ca^{2+} , Mg^{2+} , and Na^+ in the soil. The amendment treatments generally resulted in higher levels of Ca^{2+} at all depths in the soil than the control treatment (T1). The concentration of Ca^{2+} in the depth of 30–45 cm of the treatment T5 (41.00 mmol/ L) was the highest, and the control treatment was 26.24 mmol/ L, which increased by 147.75%. This rise can be largely attributed to the phosphogypsum, which is a direct source of soluble calcium. Similarly, the concentration of Mg^{2+} was mostly higher than the control at all the soil depths in the amendment treatments. Also, the concentration of Mg^{2+} tended to rise with the increasing application rates of humic acid and to fall with the increasing levels of phosphogypsum. The highest concentration of Mg^{2+} was found in the treatment T3, which might be because Humic acid added to the soil increased the soil CEC and improved soil properties, which increased the magnesium content and availability in the soil solution. The amendment combinations, however, significantly lowered Na^+ concentrations relative to the untreated control treatment. T5, among all treatments, had the greatest effect in decreasing the Na^+ concentration in all soil depths. This decrease maybe attributed to the capacity of phosphogypsum to provide Ca^{2+} ions that displace exchangeable Na^+ ions on soil colloids, enabling sodium to leach out through the soil profile. Moreover, humic substances act as a soil conditioner, improve soil structure and permeability; promote water movement and removal of sodium from the root zone. Another reason for the increase in Ca^{2+} and Mg^{2+} concentrations after applying phosphogypsum and humic acids could be the chemical composition of phosphogypsum, where calcium concentration is high and is very soluble in the soil solution. Moreover, humic acids carry active carboxyl and hydroxyl functional groups, which lead to greater cation exchange and chelation reactions in the soil and

Table 3.Effect of phosphogypsum and humic acids on the concentration of Ca, Mg and Na for the three different soil depths (0-15, 15-30 and 30-45cm) after planting.

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		Ca, mmol/ L					
S1 (2.70)	0 - 15	17.71	23.00	29.92	26.43	31.01	25.61
	15 - 30	18.63	26.05	30.82	27.47	32.80	27.15
	30 - 45	20.34	26.29	33.60	31.01	35.30	29.30
S2 (5.50)	0 - 15	23.41	28.06	32.25	30.95	35.17	29.96
	15 - 30	25.10	29.67	32.80	32.35	37.10	31.40
	30 - 45	25.60	30.50	33.60	33.01	39.60	32.46
S3 (7.50)	0 - 15	28.07	30.95	34.50	32.35	40.50	33.27
	15 - 30	29.43	33.00	35.22	33.00	44.80	35.09
	30 - 45	32.80	35.58	37.40	37.10	48.12	38.20
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	23.06	27.33	32.22	29.91	35.56	29.61
	15 - 30	24.38	29.57	32.94	30.94	38.23	31.26
	30 - 45	26.24	30.79	34.86	33.70	41.00	33.32

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		Mg, mmol/ L					
S1 (2.70)	0 - 15	10.3	13.5	12.10	19.50	17.22	14.52
	15 - 30	12.2	15.2	13.4	21.22	18.50	16.10
	30 - 45	14.50	16.40	14.55	22.36	20.33	17.62
S2 (5.50)	0 - 15	13.55	17.15	15.11	25.44	22.5	18.75
	15 - 30	17.22	19.44	18.44	27.22	24.21	21.30
	30 - 45	19.44	22.33	21.50	27.40	25.81	23.29
S3 (7.50)	0 - 15	17.55	20.55	20.10	27.44	25.54	22.23
	15 - 30	22.4	26.40	24.11	30.22	28.22	26.27
	30 - 45	25.71	26.41	25.88	31.00	29.55	27.71
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	13.8	17.06	15.77	24.127	21.75	18.50
	15 - 30	17.27	20.34	18.65	26.22	23.64	21.22
	30 - 45	19.88	21.71	20.64	26.92	25.23	22.87

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		Na, mmol/ L					
S1 (2.70)	0 - 15	18.50	15.00	14.00	13.00	9.50	14.00
	15 - 30	19.00	15.50	15.00	14.16	10.00	14.73
	30 - 45	19.50	18.00	16.6	15.00	10.50	15.92
S2 (5.50)	0 - 15	23.50	18.5	15.22	15.00	11.47	16.73
	15 - 30	24.16	19.00	17.25	16.22	12.22	17.77
	30 - 45	26.00	21.10	18.60	18.20	12.30	19.24
S3 (7.50)	0 - 15	30.50	23.55	20.25	16.44	14.10	20.96
	15 - 30	33.00	28.22	22.5	20.20	18.20	24.42
	30 - 45	34.16	30.50	24.5	22.5	20.25	26.38
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	24.16	19.01	16.49	14.81	11.69	17.23
	15 - 30	25.38	20.90	18.25	16.86	13.47	18.97
	30 - 45	26.55	23.2	19.9	18.56	14.35	20.51

consequently increase the amount of Ca^{2+} in soil, which then can replace soil colloids exchangeable Na^+ ions and remove sodium from the root zone, especially in the improved soil permeability conditions with humic acid application (Al-Hadethi and Al-Alwani 2020). In general, the P: H ratio enhanced soil chemical balance under saline irrigation, increased the availability of

Ca^{2+} and Mg^{2+} in the soils, and lowered the Na^+ accumulation, thus reducing sodic hazards and improving soil quality. Phosphogypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) adds large quantities of Ca^{2+} and SO_4 to the soil system. The introduced Ca^{2+} displaces exchangeable Na^+ from the soil colloids into the soil solution. The chemical mass balance is altered as displaced Na^+ pairs with SO_4 to form soluble Na_2SO_4 which can then be leached out of the root zone. This process transforms the soil storage component by substituting harmful sodium with beneficial calcium. Humic acids introduce abundant carboxylic and phenolic functional groups, drastically increasing the soil's CEC. They chelate cations like (Ca^{2+}) preventing their premature precipitation with carbonates.

Effect of phosphogypsum and humic acids on the sodium adsorption ratio in the soil

Irrigation with saline water increased the soil sodium adsorption ratio at all tested soil depths of 0-15, 15-30, and 30-45 cm, as shown in Table 4. SAR values of soil increased progressively with an increase in salinity levels and soil depth. The highest SAR was at the salinity level S3 at the soil depth of 30–45 cm, which was 3.28, or increased by 118.66% compared to the SAR value before planting of 1.50. On the other hand, the lowest increase in SAR was noticed at salinity level S1 at depth 0–15 cm, where SAR reached 2.28, which is a 52.00% increase from the initial value. The increase of soil SAR under saline irrigation conditions can be attributed to the accumulation of sodium ions in the soil solution and on the cation exchange complex, especially under high salinity conditions. Moreover, excessive accumulation of sodium adversely affects soil structure, reduces soil permeability and water infiltration, and thus encourages further salt accumulation in the soil profile. In contrast, the integrated application of humic acids and phosphogypsum significantly reduced the soil SAR values at all soil depths in comparison to the untreated control treatment T1. Among the treatments applied, T5 was the most effective in reducing soil SAR, with the lowest value of 1.53 at 0–15 cm depth. The SAR value in treatment T1 reached 3.95, which is a reduction of 61.26 relative to the control. Likewise, SAR decreases were consistently observed for all soil depths as the application rate of humic acids and phosphogypsum increased. The decrease in soil SAR after the application of phosphogypsum and humic acids could be related to the high calcium content in the chemical structure of phosphogypsum (Table 1). When phosphogypsum dissolves, it increases the availability of calcium in the soil by releasing calcium ions into the soil solution. Furthermore, humic acids have active carboxyl and hydroxyl functional groups that can chelate calcium and magnesium ions, increasing their mobility and availability in the soil, as reported by Al-Hadethi and Al-Alwani 2020. This causes the sodium ions to be replaced by calcium ions on

Table 4. Effect of phosphogypsum and humic acids on the SAR for the three different soil depths (0-15, 15-30 and 30-45cm) after planting.

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		SAR					
S1(2.70)	0 - 15	3.49	2.48	2.15	1.91	1.36	2.28
	15 - 30	3.42	2.41	2.25	2.02	1.39	2.30
	30 - 45	3.30	2.75	2.39	2.05	1.40	2.38
S2 (5.50)	0 - 15	3.86	2.75	2.21	1.99	1.51	2.46
	15 - 30	3.71	2.71	2.40	2.10	1.56	2.49
	30 - 45	3.87	2.90	2.50	2.34	1.52	2.62
S3(7.50)	0 - 15	4.51	3.28	2.74	2.12	1.73	2.87
	15 - 30	4.58	3.66	2.92	2.54	2.12	3.16
	30 - 45	4.46	3.87	3.07	2.72	2.29	3.28
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	3.95	2.83	2.37	2.01	1.53	2.54
	15 - 30	3.90	2.92	2.52	2.22	1.69	2.65
	30 - 45	3.88	3.17	2.65	2.37	1.74	2.76

the soil exchange complex and promotes sodium leaching below the root zone. This in turn decreases the sodium dominance in the soil solution, thus reducing the sodium adsorption ratio. Furthermore, the improved soil structure and permeability induced by humic acid application may further promote water movement and salt leaching, thus leading to lower SAR values under saline irrigation conditions. In conclusion, the combined application of phosphogypsum and humic acids proved to be effective for the mitigation of sodium hazards and enhancement of soil chemical properties under saline irrigation, suggesting that these amendments could be a sustainable approach to manage salt-affected soils.

Effect of phosphogypsum and humic acids on the concentration of SO_4^{2-} , Cl^- , and HCO_3^- in the soil

Table 5 indicated that irrigation with saline water caused a significant increase in the concentrations of SO_4^{2-} , Cl^- and HCO_3^- in the soil at different depths of 0–15, 15–30 and 30–45 cm. In general, the concentrations of these ions increased gradually with the increase of salinity levels and soil depth. The highest SO_4^{2-} concentration was found at salinity level S3 and soil depth of 30–45 cm, which was 59.27 mmol/L, an increase of 1217.11% compared to the pre-planting concentration of 4.50 mmol/L. In contrast, the lowest SO_4^{2-} concentration was observed at a depth of 0–15 cm in the salinity level S1, which was 12.40 mmol/L, an increase of 175.55% compared to the pre-planting value. Similarly, salinity and soil depth had a significant effect on the concentration of Cl^- , which increased considerably with the increase in salinity and soil depth. Maximum concentration of Cl^- of 25.14 mmol/L was found at salinity level S3 and depth of 30–45 cm. On the other hand, the lowest concentration was found in S1 at 0–15 cm depth (15.24 mmol/L), while the initial concentration of the soil was 2.80 mmol/L. Similarly, the concentration of HCO_3^- was very much higher under saline irrigation treatments. The highest concentration of HCO_3^- (9.13 mmol/L) was observed at salinity level S3 and depth level of 30–45 cm, which was an increment of 730.00% compared to the initial concentration. The lowest value of HCO_3^- (4.18 mmol/L) was reported for salinity level, S1 (0–15 cm). This was 280.00% higher than the initial value. These soluble ion increases may be due to the continual application of salts via saline irrigation water and their build-up in the soil profile, especially at lower depths. Moreover, humic acids and phosphogypsum applications, along with saline irrigation water, had a significant effect on the soil concentration of these ions. Application of the combined amendments, in particular, led to an increase in post-harvest SO_4^{2-} concentration as compared to the control treatment, T1. The higher concentration of SO_4^{2-} came in T2 at 30–45 cm (46.92 mmol/L) compared to that of the control (22.56 mmol/L) with an increase of 107.97%. The rise of the SO_4^{2-} content in such soil may be due to the high sulfate content of the phosphogypsum, which releases sulfate ions into the soil solution, as mentioned by Al-Hadethi and Al-Alwani (2020). However, humic acids and phosphogypsum decreased Cl^- and HCO_3^- levels in soils compared to control treatments. Besides, the decrease was more significant at higher levels of humic acid and phosphogypsum treatments, as the treatment T5, in which the highest levels of humic acid and phosphogypsum was used, showed the lowest concentration of both Cl^- and HCO_3^- at all soil depths. This decrease can be attributed to the effect of phosphogypsum providing sulfate ions to the soil solution, which will be replaced by the chloride and bicarbonate ions, allowing their leaching. Moreover, the phosphogypsum also increases the bulk density and porosity of the soil, thus facilitating water infiltration and salt leaching from the root zone, as observed by Agar 2011. Similarly, humic acids also enhance the physical properties of soil, such as soil structure and bulk density, which in turn enhances soil permeability and promotes the leaching of salt beyond the root zone as was reported by Nan et al. (2016) and Al-Hadethi and Al-Alwani (2020). Therefore, the use of phosphogypsum and humic acids together contributed to a decrease in the concentration of destructive ions like Cl^- and HCO_3^- , and improved the chemical and physical quality of soil in the saline conditions.

Table 5. Effect of phosphogypsum and humic acids on the concentration of SO_4 , Cl, and HCO_3 for the three different soil depths (0-15, 15-30 and 30-45cm) after planting.

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		SO ₄ (mmol/ L)					
S1 (2.70)	0 - 15	5.22	12.21	18.60	10.77	15.20	12.40
	15 - 30	7.11	21.33	24.75	15.30	18.15	17.32
	30 - 45	10.14	24.30	27.82	18.90	21.30	20.49
S2 (5.50)	0 - 15	10.15	22.83	31.83	28.83	30.33	24.79
	15 - 30	15.22	33.15	37.83	32.19	31.50	29.97
	30 - 45	19.14	34.65	45.21	33.69	33.54	33.24
S3 (7.50)	0 - 15	30.11	57.31	63.30	52.71	60.15	52.71
	15 - 30	34.20	60.37	67.65	55.65	65.25	56.62
	30 - 45	38.40	63.30	67.74	60.15	66.76	59.27
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	15.16	30.78	37.91	30.77	35.22	29.97
	15 - 30	18.84	38.28	43.41	34.38	38.30	34.64
	30 - 45	22.56	40.75	46.92	37.58	40.53	37.66

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		Cl (mmol/ L)					
S1 (2.70)	0 - 15	21	16.72	13.77	15.3	9.45	15.24
	15 - 30	21.44	17.88	14.814	16.15	9.65	15.98
	30 - 45	22.46	18	15.396	17.05	10.10	16.60
S2 (5.50)	0 - 15	26.86	22.32	18.858	19.40	12.08	19.90
	15 - 30	27.32	22.6	19.122	20.02	12.29	20.27
	30 - 45	29.41	22.83	19.746	20.92	13.23	21.22
S3 (7.50)	0 - 15	30.86	27.88	22.248	23.93	13.88	23.75
	15 - 30	31.12	28	22.848	24.45	14.00	24.08
	30 - 45	33.56	28.77	23.1	25.21	15.10	25.14
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	26.24	22.30	18.29	19.54	11.80	19.63
	15 - 30	26.62	22.82	18.92	20.20	11.98	20.10
	30 - 45	28.47	23.2	19.41	21.06	12.81	20.99

Levels of saline water (dS/m)	Soil depth (cm)	phosphogypsum and humic acids					Average of saline water
		T1	T2	T3	T4	T5	
		HCO ₃ (mmol/ L)					
S1 (2.70)	0 - 15	5.50	4.50	4.19	3.50	3.22	4.18
	15 - 30	6.22	5.00	4.25	3.75	3.55	4.55
	30 - 45	8.14	5.50	4.30	3.90	3.60	5.08
S2 (5.00)	0 - 15	7.10	7.00	6.80	6.70	6.40	6.80
	15 - 30	8.54	7.60	6.95	6.88	6.10	7.21
	30 - 45	9.22	8.10	7.55	7.90	5.80	7.71
S3 (7.50)	0 - 15	8.55	8.10	8.00	7.70	6.90	7.85
	15 - 30	9.70	9.15	8.25	7.85	7.00	8.39
	30 - 45	11.22	10.85	8.60	7.90	7.10	9.13
Total Average of phosphogypsum and humic acids							
Average of phosphogypsum and humic acids	0 - 15	7.05	6.53	6.33	5.96	5.50	
	15 - 30	8.15	7.25	6.483	6.16	5.55	
	30 - 45	9.52	8.15	6.81	6.56	5.5	

Effect of phosphogypsum and humic acids on some growth and yield components of cauliflower

The results shown in Table 6 reveal the effects of irrigation water salinity on plant height, head weight, and total yield of Cauliflower plants, as affected by Phosphogypsum and humic acid. Generally, salinity had a significant negative effect ($P \leq 0.05$) on all growth and yield parameters. Especially, a reduction in Cauliflower plant height was noticed with increasing

Table 6. Effect of phosphogypsum and humic acids on some growth and yield components of cauliflower

Levels Of combinations	Plant height, cm				Head weight, g /plant				Plant yield, t/ha			
	Salinity levels (dS/m)			Average combinations	Salinity levels (dS/m)			Average combinations	Salinity levels (dS/m)			Average combinations
	S1	S2	S3		S1	S2	S3		S1	S2	S3	
T1	29.42	20.89	15.84	22.05	327.11	232.50	165.97	241.86	8.71	6.19	4.42	6.44
T2	32.83	25.4	16.9	25.04	367.50	263.99	168.49	266.66	9.79	7.03	4.48	7.10
T3	26.84	17.1	11.21	18.38	253.66	195.82	127.97	192.48	6.75	5.21	3.83	5.26
T4	37.22	27.21	19.32	27.91	405.88	311.00	174.06	296.98	10.81	8.28	4.63	7.90
T5	28.23	18.29	13.44	19.98	299.53	211.03	144.05	218.20	7.98	5.62	3.40	5.66
Average of Salinity	30.90	21.77	15.34		330.73	242.86	156.10		8.808	6.46	4.15	
LSD _{0.05}												
S			0.934				10.27				0.274	
T			1.206				13.26				0.353	
S*T			2.089				22.97				0.612	

S1, S2, S3 is the salinity levels; T1 to T5 is the phosphogypsum, humic acids and saline irrigation water, LSD is least significant difference

water salinity for the irrigation. Similarly, the lowest plant height, 15.34 cm, was observed at salinity level S3, which was about 50.34% less than the plant height at S1, 30.90 cm. The plant height at salinity level S2 was 21.77 cm, which was about 29.54% less than at S1. The decline in plant height under conditions of salinity may be due to salinity effects that are osmotic, ion toxic, or a combination of these effects, and the rising electrical conductivity of the soil due to salt accumulation in the plant root zone. In addition, salinity has negative impacts on different nutrient balances and nutrient uptake efficiency, which eventually slows down the growth and developmental process of plants. However, the plant growth affected by the amendments applied to the plants differed between treatments; the plant height of T2 and T4 was significantly increased compared to the plant height of T1, while the plant heights of T3 and T5 decreased compared to T1. The greatest plant height was achieved in T4 with 27.91 cm, and the least in T3 with 18.38 cm, which was 26.57% and 16.64% higher or lower than the control value, respectively. The above increase might be related to the positive response of humic acid to soil chemical, physical, and biological properties as mentioned by Gholami et al. 2013. Humic substances also have active functional groups, such as carboxyl and hydroxyl groups, that improve sodium leaching and stabilize calcium in the soil solution. Therefore, the ability to release nutrients is thereby enhanced, and plant growth is stimulated as mentioned by Tan 2003 and Tchiadje 2007. Furthermore, Canellas and Olivares 2014 showed that humic acids enhance plant resistance to salinity stress and their capacity to reduce the toxicity of harmful ions. In the same way, phosphogypsum also had a positive contribution in reducing sodium hazards, decreasing the pH of soils, making nutrients more available, and increasing plant growth (Al-Naser 2018). But, excess application of phosphogypsum can lead to soil salinization due to the accumulation of CaSO_4 and other Ca^{2+} and SO_4^{2-} ions in the soil solution, consequently causing an increase in soil electrical conductivity (EC) and adversely influencing plant growth as reported by Aftan and Al-Hadethi (2021). As for the interaction effects, the highest plant height (37.22 cm) was obtained in treatment T4 under salinity level S1, while the lowest (11.21 cm) was obtained in treatment T3 under salinity level S3. Moreover, salinity negatively and significantly affected Cauliflower head weight. S3 gave the lowest head weight (156.10 g/plant), and it decreased by 52.80% from S1, which had the highest head weight (330.73 g/plant). Similarly, head weight of plants under salinity level S2 was (242.86 g/plant), which was 26.56% less than S1. These decreases may be related with the increased salinity, osmotic pressure, and ion toxicity in soil, which affect nutrient uptake, photosynthetic activity, and assimilate distribution to the developing heads, according to (Ragab 2008 and Liu et al. 2016.) In the treated plants, T4 significantly increased the head weight with the highest value of 296.98 g plant⁻¹ (+22.79 % compared to the control treatment). T3 in comparison gave the lowest head weight, one of 192.48 g/plant, showing a decrease of 20.41% from the control. The increasing head weight

associated with the application of humic acid might be related to the increase in soil fertility, available nutrients, and reduction in electrical conductivity, which manifests overall better plant growth and productivity. Similarly, irrigation water salinity significantly affected the yield of Cauliflower. The lowest yield was observed at S3 of 4.15 t/ha, meaning there was 52.88% less yield than at S1 of 8.81 t/ha. In the same manner, the salinity level S2 resulted in a yield of 6.46 t/ha, which equals 26.65% less than S1. The decrease in yield could be largely attributable to osmotic stress, nutritional imbalances, and toxicity of ions, which all have an inhibitory effect on plant productivity in conditions of salinity. On the other hand, application of treatments T2 and T4 significantly increased the yield of Cauliflower compared to the control, while other treatments T3 and T5 significantly decreased the yield performance. The yield of treatment T4 was maximum with 7.90 t/ha (22.27% higher than the control 6.44 t/ha). However, T3 produced the lowest yield (5.26 t/ha), which was 18.32% less than the control. In general, the positive effects of humic acid and phosphogypsum can be explained by the synergism of humic acid in the soil properties and the alleviation of salinity stress by the phosphogypsum. Humic acids lower the sodium toxicity, reduce any soil degradation from salinity, and make more nutrients available to plants, while phosphogypsum makes the soil less sodic, improves soil structure and calcium availability, and makes plants more tolerant to salinity. However, its overuse may increase soil electrical conductivity due to high soluble calcium and sulfate ions, resulting in poor soil productivity. Overall, the joint use of phosphogypsum and humic acid proved to be a successful method for lowering soil electrical conductivity, sodium, chloride, sulfate, and bicarbonate levels, and for enhancing calcium and magnesium in the soil. Thus, the growth and productivity of Cauliflower plants were enhanced under saline irrigation through these amendments. Hence, mixing of phosphogypsum and humic acid might be a good management for reducing the negative impacts of saline irrigation water on Cauliflower production. These results were consistent with Al-Falahi et al. 2023.

CONCLUSIONS

The present research showed that saline water irrigation was significantly deleterious to the chemical properties of the soil, as well as the plant growth and yield parameters of Cauliflower, such as plant height, fruit weight, and overall production. In particular, the soil salinity caused an increase in soil electrical conductivity, soil sodium adsorption ratio (SAR), and soluble ions and negatively affected plant performance. However, the combination of phosphogypsum and humic acid proved to be effective in reducing the negative effects of saline irrigation. In particular, the following amendments enhanced the soil chemical balance, decreasing EC, SAR, chloride, bicarbonate, and sodium levels in the soil, and at the same time guaranteeing the availability of more calcium and magnesium in the soil. More so, the relationship between phosphogypsum and humic acid considerably improved the growth features and yield factors in Cauliflower. The combination of treatments at optimal levels gave good results in the form of plant height, fruit weight, and total yield over the control and other treatments. Overall, the combined application of phosphogypsum and humic acid is a promising soil amendment strategy to enhance soil quality and support the production of Cauliflower under saline irrigation conditions.

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AUTHORS' CONTRIBUTIONS

Muneer N. A. Al-Falahi designed the research and wrote the article. Data analysis was done by Khdyar Y. K. Al-Kubissi. Jabbar Sh. E. Al-Esawi conducted the research in the field. Chemical analysis was done by Saad Jabir Hafi.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interests.

ETHICAL APPROVAL

All ethical guidelines concerning chemical safety and security in fertilizer manufacturing—issued by both national and international organizations have been fully adhered to within the scientific framework of this report.

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