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Improvement of Some Soil Properties and Productivity of Egyptian Cotton (*Gossypium barbadense* L.) Super Giza 94 under Salt Stress Conditions

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A Field experiment was performed throughout two summer seasons 2022 and 2023 at El - Hamoal, Kafr El- Sheikh Governorate, Egypt to explore the effect of phosphogypsum and agrochemical sulfur alone as well as their dual treatment in the main plots, in addition, applied of glycine betaine and ascorbic acid as plant spraying in the subplots on enhancing some physio-chemical characteristics of saline-sodic soil, cotton production and some biochemical constituents. The experiment was arranged in a split plot design with three replicates. The obtained results could be summed up as follow: The implementation of two soil amendments (phosphogypsum and sulfur) significantly reduced soil bulk density, but enhanced total porosity, hydraulic conductivity, field capacity and wilting point in both seasons. Additionally, all the used materials caused an increment in soil available phosphorus and the concentration of soluble calcium, magnesium ions. Meanwhile, it reduced soil pH, exchangeable sodium percentage, electrical conductivity and the concentration of soluble sodium ion in both seasons compared to untreated salinized plots. On contrast, the values of previous characters were not affected with foliar treatments singly during two seasons relative to control. Furthermore, data showed that all the used treatments increased seed germination % and plant growth parameters, Leaf chemical composition and Yield & its components. Regarding effects of stress mitigators, results revealed that glycine betaine or ascorbic acid significantly increased leaf content of photosynthetic pigments, chlorophyll a, b, total chlorophylls and carotenoids. Also, improved all studied growth parameters, number of fruiting branches per plant, plant height and leaf area per plant, and yield and its components, number of setting bolls, boll weight, number of open bolls and yield of seed cotton compared to control. Generally, glycine betaine was more effective than ascorbic acid in improving plant growth and yield. It could be concluded from these results that foliar spraying with glycine betaine and ascorbic acid positively mitigated the adverse effects on cotton growth and yield under salt stress.

Keywords: salinity, soil amendments, plant spraying, cotton.

1. Introduction

Salinity is one of the major problems which caused soil degradation with severe negative impacts on agricultural productivity. **Mukhopadhyay *et al*. (2020)** reported about 33% of all irrigated soils and 20% of the total global area under agriculture are affected by salinity; and this area is increasing at the rate 10 % annually due to change in climate. **Alcívar *et al*. (2018)** indicated that saline–sodic soils tend to accumulate salts (high Na^+ concentrations) in the top soil layers that change the chemical and physical characteristics, including hydraulic conductivity and soil structure. Furthermore, the negative effects of salinity on soil properties include raised soil pH, exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) **(Zhang *et al*., 2019; Abhayawickrama *et al*., 2020; Ihab *et al*., 2020)**. Additionally, salt stress disrupted the plants' physiological processes due to increase nutritional imbalance, osmotic pressure, oxidative stress **(Alnusairi *et al*., 2021)** and

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reduce nutrient uptake **(Nada *et al*., 2023)**and consequently decreased growth characteristics, yield components, weight & number of bolls and yield of seed cotton **(Ahmad *et al*., 2018; Shehzad *et al*., 2019)**.

Phosphogypsum (PG) is a by-product produced by sulfuric acid decomposing phosphate rock to produce phosphoric acid. At present, the world produces about 300 million tons of PG every year **(He *et al*., 2022)**. Phospho-gypsum contains large amounts of calcium, iron, zinc, phosphorus and sulfur therefore, when applied to agricultural soils, it improves nutrient availability to growing crops (**Raja *et al*. 2020**). Phospho-gypsum is cheap and available, thus could be used as saline sodic soil amendment and contains over 92% of ($CaSO_4.2H_2O$), where Ca^{2+} may effectively decrease sodicity by substituting exchangeable sodium (Na^+) to reclaim sodic soils through increasing the hydraulic conductivity to efficient enhancement of salt leaching from the root zone of crop and improvement of production, in addition, Gypsum assist on inverting the negative effect of salinity on P uptake **(Bello *et al*., 2021)**.

Sulfur (S) is a secondary nutrient element that plays crucial role to alleviate abiotic stresses in crop plants and improves salt-affected soils' productivity **(Ahmed *et al*., 2016).** The implementation of agrochemical sulfur is essential for healthy growth and it plays active role in the biosynthesis of chlorophyll, a few amino acids and protein **(Chowdhury *et al*., 2020)**. This essential nutritive is ready to plants as ionic form; hence most sulfur fertilizers consist of sulfate salts. Application of sulfate may help mitigate salt stress, as SO_4^{-2} plays an important role in the formation of H_2SO_4, which leads to a decrease in soil pH **(Mesbah, 2016)**.The wide spread S deficiency in soils may be due to the use of chemical fertilizers with high amounts but low sulfur content **(Kundu *et al*., 2020)**; hence may lead to damage growth, loss in productivity, sensibility to environmental stresses and decreased nitrogen utilization **(Fatma *et al*., 2016)**. Saline soils are varied in nature and demand specific strategies, i.e. the implementation of agrochemical sulfur combination with phosphogypsum to assist soil reclamation and their management for long-term production. Spraying antioxidants on crops can also protect by synthesis of free radicals and other reactive oxygen species, which are created in excess within the tissues of salt-stressed plants **(Ghazi *et al*., 2023)**.

Nawaz *et al*. (2021) referred that ascorbic acid is a major non-enzymatic antioxidant compounds generated endogenously in plant cells as solo molecules. It plays an essential role in enhancing the main functioning of plants under normal and saline conditions **(Xu and Huang, 2017)**. Ascorbic acid acts as a scavenger of reactive oxygen species (ROS) in plants, enhancing growth and raising tolerance of the harmful effects of salinity in plants **(Zandi and Schnug, 2022)**. **Xu *et al*. (2015)** indicated that ascorbic acid has a necessary role in plant cell division and expansion, flowering regulation, senility in leaves, photosynthesis, apical meristem formation additionally, being a cofactor for enzyme activity **(Soad *et al*., 2024**).

Glycine betaine (GB) is a secondary metabolite widely found in plants and animals **(Hasanuzzaman *et al*., 2019)**. It has a protective role as an osmoprotectanton mitigating the effects of salt stress **(Bai *et al*., 2022**; **Zhu *et al*., 2022)**. **Hamani *et al*. (2021)** said that exogenous spraying of glycine betaine in salinity-stressed plants can be an effective way to enhance plant acclimation and tolerance at environmental stress via regulating the water potential and amplifying the antioxidant defence system, improve plant growth, raise leaf number and chlorophyll content **(Tisarum *et al*., 2020; Hayam and Hammad, 2021)**.

Cotton is classified as moderately salt tolerant crop with salinity threshold level of 7.7 dS m^{-1} **(Zhang *et al*., 2013)**. **Niaz *et al*. (2020)** said that salt stress reduces boll formation per plant which finally reduces fiber yield and poor lint quality. On contrast, application of calcium is useful for restrict Na^+ uptake by plants **(Reid and Smith, 2000)**. **Niaz *et al*. (2020)** indicated that application of saline irrigation water increased already existent salts and retro gradation of soil production.

In this regard, the present study aims to evaluate the effects of different treatments (i.e. phospho-gypsum and sulfur as soil amendments) individually or in combination in addition, applied of foliar treatments i.e., glycine and ascorbic acid on improving some physical and chemical characteristics of saline sodic soil, growth, productivity of cotton super Giza 94 and some biochemical constituents.

2. Materials and methods

Experimental sites and soil

A field experiment was carried out at El -Hamoul, KafrEl- Sheikh Governorate, Egypt (31o18'13"5 N latitude and 31o03'30"8 E longitude), through two summer growing seasons 2022 and 2023to assess the effect of two different soil amendments (phosphogypsum and agrochemical sulfur)as well as their duality treatment in addition, applied of glycine betaine and ascorbic acid as foliar spray on improving some soil physio-chemical characteristics, growth, yield & its components of cotton plants (*Gossypium barbadense*, cv super Giza 94) and some biochemical constituents under salt stress condition.

Initial soil and water sampling

Before starting the field experiment of (2022 and 2023) seasons, representative soil samples were gathered at 0-30, 30-60 and 60-90 cm depths, samples were air –dried; ground and sieved through a 2 mm sieve for analyses. Some physio-chemical characteristics of the studied soil according to **Jackson (1973)** and **Kettler *et al.* (2001)** are shown in Table 1. The soil is clay in texture.

Water sample was taken before the agricultural season, filtrated using filter paper (No. 40); and subjected to chemical analysis according to **Jackson (1973)** as shown in Table 2.

Climatic conditions

The average data record of the past two years (2022 and 2023) including maximum and minimum air temperature, relative humidity, wind speed and rain fall from April until October (cotton growing season) are shown in Table 3. The prevailing climate of the area is semi-arid and the meteorological data during the growth period of the crop were obtained from the Meteorological station at Sakha Agricultural Research Station.

TABLE 1: The mean values of some physical and chemical characteristics of the studied soil before cultivation in two growing seasons

Characteristic	Soil depths (cm)		
	0-30	**30- 60**	**60- 90**
Particle size distribution (%)			
Coarse Sand	5.3	6.2	9.6
Fine sand	11.4	10.2	16.1
Silt	36.4	35.1	34.0
Clay	46.9	48.5	40.3
Texture class		Clayey	
Bulk density (g/cm^3)	1.26	1.31	1.32
Hydraulic conductivity (cm/h)	0.38	0.36	0.35
Soil moisture parameters			
Field capacity (%)	39.1	37.85	37.5
Wilting point (%)	21.1	20.52	20.22
Available water (%)	18	17.33	17.28
Chemical analysis			
pH (1:2.5 soil: water suspension)	8.53	8.75	8.51
EC (dS/m) soil paste extracted	7.87	8.1	8.3
Soluble cations (meq/l)			
Ca^{++}	8.0	7.10	7.80
Mg^{++}	5.8	5.33	6.0
Na^{+}	63.78	67.51	68.5
K^{+}	1.12	1.06	0.7
Soluble anions (meq/l)			
CO_3^{--}	Not detected	Not detected	Not detected
HCO_3^{-}	0.70	0.60	0.5
Cl^{-}	69.68	71.28	76.9
SO_4^{--}	8.32	9.12	5.6
Available macro nutrients (mg/kg)			
Available nitrogen	22.15	23.45	20.65
Available phosphorus	6.2	4.86	4.2
Available potassium	181.6	209.5	211.4

EC: electrical conductivity

TABLE 2: Some chemical analyses of irrigation water used in the experiment

Variable	EC	pH	Soluble cations (meq/l)				Soluble anions (meq/l)			
			Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	CO_3^{-2}	HCO_3^{-}	Cl^{-}	SO_4^{-2}
Values	1.42	7.02	3.9	1.04	0.2	9.06	2.5	Not detected	10.9	0.8

TABLE 3: Mean Monthly agro-meteorological data of (2022 and 2023) from April until October (cotton growing season)

Month	Temperature (°C)				Wind Speed (km day^{-1})		RH (%)		Rainfall (mm month^{-1})	
	Max	Min	Max	Min						
	2022		2023		2022	2023	2022	2023	2022	2023
April	29.54	12.96	28.81	13.73	3.79	3.91	59.71	54.85	0	0.49
May	32.95	16.93	32.86	17.28	4.47	4.65	53.85	52.17	0	0
June	36.62	21.33	36.39	21.01	4.38	4.48	53.01	52.28	0	0
July	37.72	22.28	39.78	23.44	4.19	4.30	53.53	52.53	0	0
August	37.58	24.91	38.08	23.71	4.09	4.39	55.52	55.29	0	0
September	36.35	22.39	37.78	23.51	3.96	4.12	55.36	54.20	0	0
October	31.16	19.78	32.06	20.78	3.77	3.69	60.22	61.27	0	0

Source: Meteorological station at Sakha Agricultural Research Station.
Min Temp is (minimum air temperature), Max Temp is (maximum air temperature) and RH is relative humidity.

Phospho-gypsum requirements

The gypsum requirement of PG amendment (GRPG) was obtained by the saturated gypsum solution method **(Bao, 2005)**. Phosphogypsum requirement was calculated using the following equation:

GR_{PG}= ($[Ca^{2+}]_g$ - $[Ca^{2+} + Mg^{2+}]_f$)×BD×*D*×0.344(1)

where GR_{PG} is the gypsum requirement of PG amendment (t ha^{-1}), $[Ca^{2+}]_g$ is theCa^{2+}content of saturated PG solution (14.61 mmol l^{-1}), $[Ca^{2+} + Mg^{2+}]_f$ is the Ca^{2+} + Mg^{2+}content of filtrate (13.91mmol l^{-1}), BD is soil bulk density (1.26 g cm^{-3}), and *D* is soil depth (30 cm). To amend this saline-sodic soil to 30cm depth, 9.102 t ha^{1} of GR was required. Considering that the PG has only 88 % of pure gypsum (calcium sulfate), GR_{PG} was estimated to add about 10.3 t ha^{-1}.

The experimental design and treatments

The experiment was laid out in a split plot design with 12 treatments and three replicates. The treatments were divided into:

The main plots were treated with soil amendments as follows:

1- Control (ck) (without added.)

2- Gypsum requirement of PG (GR_{PG}) (PG at the rate 4.3 ton/fed.).

3-Agrochemical sulfur (S) (at the rate 200 kg/fed).

4- GR_{PG} + S

The subplots were treated with foliar application as follows:

Control (T) (spray with fresh water alone).

Glycine betaine (GB) (400 ppm)

Ascorbic acid (AsA) (200 ppm)

The used phosphogypsum (PG 88% purity) in the experiment was obtained from a fertilizer industry factory in El-Sharkia Governorate, Egypt. It was transported to the laboratory, ground, and passed through a 2-mm screen for analyzed the initial chemical characteristics Table 4.The soil used amendment (PG)was added at the rate 4.3 ton /fed and uniformly spread on the surface soil before cultivation except control.

TABLE 4: Some chemical analyses of phospho-gypsum (PG) used in the experiment

Parameters	EC (1:5 Soil: water extract) dS/m	pH (1:5 Soil: water suspension)	Ca^{2+} meq l^{-1}	Mg^{2+} meq l^{-1}	OM, %	CEC C moles kg^{-1}	S, %	P, %	K, %	Al, %	Cd, %
Phosphor-gypsum	3.95	3.65	28.11	3.99	5.68	59.87	14.3	2.32	0.09	0.13	2.12

The pH was measured with a digital pH meter, and the EC was measured by a conductivity meterin a 1:5 soil/water ratio (Richards, 1954). CEC: cation exchange capacity(C moles kg^{-1}) was determined by sodium acetate (NaOAC) method according to (Kim *et al*., 1996).OM: organic matter (%) was described by Bhattacharyya *et al*.(2015).The total contents of S, P, K, Al, and Cd in the PG were measured by coupled plasma–optical emission spectrometry (ICP-OES) (PerkinElmer Optima 4300 DV).

-Sulfur (S) is a commercial product from Agrimisr Co., Egypt. The soil used amendment (S) was added at the rate 200 kg fed^{-1} (except the control). The test material (S) is applied during soil preparation (before cultivation) and mixed with it during plowing **(Kabata-Pendias *et al*., 1995)**.

-Foliar spraying with glycine betaine and ascorbic acid was sprayed at two times after 30 and 45 days from planting at the rate 400 ppm and 200 ppm, respectively.

Culture practices

In the two growing seasons, cotton (*Gossypium barbadense*, cv super Giza 94) were used as a tested plant in saline sodic soil. The Department of Cotton Research, Agricultural Research Station, Sakha, Kafr El-Sheikh developed the seeds. Cotton seeds were sown on 25th and 30th April in 2022 and 2023 seasons. The experimental units consisted of 36 plots (4 soil amendments ×3 foliar application of growth promoters for plant×3rep.), each plot consisted of 5 rows,3.5 m long and 0.7 m width (plot area= 12.25 m^2).Seeds were sown manually in each hole, intra-hole spacing was 25cm apart, irrigated immediately after sowing, then thinned to one plant in each hole and irrigated regularly every 12 - 15 days. NPK was applied to the soil in the following amounts:

Nitrogen fertilizer was applied as urea (46.5% N) 60 kg fed^{-1}, in equal two doses, the first dose was at Mohayah irrigation (30 days after sowing); while the second addition was at the second irrigation after (20 days after the first addition). Phosphorus was applied through soil preparation as calcium superphosphate (15.5% P_2O_5) 23.2 kg P_2O_5 fed^{-1} (150 kg calcium superphosphate fed^{-1}). Potassium was applied as potassium sulfate (48% K_2O) 24 kg K_2O fed^1.The different agricultural practices of cotton plants were added according to the recommended dose of the Egyptian Ministry of Agriculture through the two growing seasons.

Soil measurements

At harvest, soil samples were gathered from each plot at both seasons of two consecutive depths (0-30, 30- 60 cm).The undisturbed soil samples were collected to evaluate some the physical characteristics, i.e., Particle size distribution of soil was measured using the pipette method according to **(Kettler *et al*., 2001)**. Bulk density (gcm^{-3}) and total porosity (%) was determined according to **(Campbell, 1994)**. Saturated hydraulic conductivity (HC) (cm/h) was measured using core samples; field capacity (FC) and permanent wilting point (PWP) were obtained by the pressure plate method according to **(Klute and Dirkoson, 1986)**. Soil available water content (AW) was calculated as the difference between soil field capacity and permanent wilting point. The disturbed soil samples were air-dried, sieved using a 2-mm sieve and analyzed to determine some the chemical characteristics, i.e., Soil pH values were determined in 1:2.5 soil: water suspensions **(Jackson, 1973)**. Total soluble salts were measured by electrical conductivity (EC) apparatus in the saturated soil paste extract as dS/m **(Jackson, 1973)**. Soluble cations and anions (Ca^{++}, Mg^{++}, Na+, K^+, $CO3^{--}$, $HCO3^-$, Cl^- and $SO4^{--}$as (meq/l) were also determined in soil paste extract **(Jackson, 1973)**. But $SO4^{--}$ was calculated by difference between soluble cations and anions. Exchangeable sodium percentage (ESP) was calculated by using the following Equation (2) **(Richards, 1954)** as follows:

$$\mathrm{ESP} = \frac{100(-0.0126 + 0.01475\mathrm{SAR})}{1 + (-0.0126 + 0.01475\mathrm{SAR})}$$

Soil available nitrogen (N) was determined according to **(Matsumoto *et al*., 2000)**, available phosphorus (P) and potassium (K) were determined according to **(Tian *et al*., 2021)**.

Studied characters

Growth characters: Germination %, Plant height (cm), No. of fruiting branches, Leaf area (cm^2)

Chemical characters

Chlorophyll a (chl a), chlorophyll b (chl b) and carotenoid (carot.) of cotton were determined in the fresh leaves at different stages of plant growth, i.e. 85, 100 and 115 DAP using spectrophotometer method as described by **Wettstein (1957)**. Fresh weight of leaves (0.25g) was homogenized in 85 % aqueous acetone for 30 min. The homogenate was filtered and made up to 20 ml with aqueous acetone 85%. The extract was measured against a blanck of pure aqueous acetone 85 % at three wave lengths of 440, 644 and 662 nm and then calculated (as mg / L concentration) using the following formula as:

- Chl. a = (9.784 x E_{662}) - (0.99 x E_{644}).
- Chl. b = (21.426 x $E_{644)}$ - (4.65 x E_{662}).

-Carot. = (4.695 x E_{440}) - 0.268 (Chl. a + Chl. b).
Where E = optical density at the given wave length.

The concentrations were then calculated as mg / g dry weight of the differently treated plant leaves.

Proline: Proline concentration (mg/g f. wt) was measured in fresh leaves by using 5- Sulpho- Salicylic acid, Solvent and minhydrin reagent. It was expressed as mg/g fresh weight. The color intensity was red at 520 mm, using colorimetric, according to **Bates *et al.* (1973).**

Yield and its components

- **Number of setting bolls:** The number of squares and setting bolls / plant was measured during squaring and flowering periods of 6 days intervals until the harvest.
- **Number of open bolls**: Average number of mature bolls / plant.
- **Boll shedding %.**

$$\frac{\text{No. of setting bolls / plant} - \text{No. of total bolls at harvest / plant}}{\text{No. of setting bolls / plant.}} \times 100$$

- **Seed cotton yield. (kentar /fed),** (kentar = 157.5 kg of seed cotton).
- Boll weight (g).Average weight of open bolls / plant (g).

Statistical Analyses

The data were statistically analyzed according to the method described by **Snedecor and Cochran (1967)**. Duncan's multiple range test (**Duncan, 1955**) was used to compare between the treatments mean. The mean values within each column followed by same letter(s) are not significantly different at 5% level of probability.

3. Results and Discussion

3.1. Soil Physical Characteristics

3.1.1. Soil bulk density, total porosity and hydraulic conductivity

Data showed a remarkable decrease in BD of saline-sodic soil by applying PG, S and their duality treatment of both seasons compared to salinized untreated plots Table 5. Saline soils are described by high concentrations of soluble salts in the solution period (saline soil) or (sodic soils) which occupied by Na^+ on the cation exchange sites. A high sodium adsorption ratio causes clay minerals disperses, this in turn results in a poor soil structure and hence, high soil density, clogging of pores and surface crusts, making the soils impermeable to air and water. Thus, applied of amendments to saline-sodic soil could improve the soil bulk density. This might be as a result to replace of Na as monovalent on the exchange complex by Ca^{2+} from the soil solution **(Gharaibeh *et al*., 2009)**, to enhance the aggregates and macro-pores. Therefore, improved soil structure and soil water retention **(Bronick and Lal, 2005)**, soil porosity and permeability. Similar results were agreed by **Lastiri-Hernández *et al*. (2019)**. Phosphogypsum amendment was more efficient in decreasing BD, especially (0- 30 cm soil depth) than sulfur one.

TABLE 5: Effect of phosphogypsum (PG), sulfur (S) and their interaction (PG+S) on bulk density (BD), total porosity (TP) and hydraulic conductivity (HC) in saline- sodic soil during the two growing seasons after cotton harvest

Treatments	BD (gcm^{-3})		TP (%)		HC (cm/h)	
	0-30cm	30-60cm	0-30cm	30-60cm	0-30cm	30-60cm
			2022			
Ck	1.26a	1.31a	52.45b	50.57b	0.38c	0.36b
PG	1.16b	1.27b	56.23a	52.08a	0.76ab	0.63a
S	1.19b	1.29ab	55.09a	51.32ab	0.72b	0.61a
PG + S	1.15b	1.26b	56.60a	52.45a	0.80a	0.64a
LSD at0.05	0.05	0.03	2.193	1.329	0.06	0.06
			2023			
Ck	1.26a	1.31a	52.45c	50.57c	0.38c	0.36b
PG	1.13bc	1.26bc	57.36ab	52.45ab	0.75ab	0.61a
S	1.17b	1.29ab	55.85b	51.32bc	0.71b	0.60a
PG + S	1.12c	1.25c	57.74a	52.83a	0.80a	0.63a
LSD at 0.05	0.04	0.03	1.666	1.329	0.07	0.07

For instance, in the 0-30 cm soil depth, the decrement percentage of SBD was 10.32, 7.14 and 11.11% as a result of applied PG, S and their duality treatment at 2nd season, respectively compared to ck. It was noticed that the duality treatment of the used materials seemed to be the best one for decreasing the values of BD in the surface soil at 2nd season relative to ck. Concerning the TP and HC, the application of PG and S amendments as pretreated in saline-sodic soil single or together significantly improved the TP and HC values of both seasons compared to control Table 5. These results agreed with **Ondrasek and Rengel (2021)** who said that the hydraulic conductivity and porosity were enhanced by adding organic amendment in saline soil. Phosphogypsum amendment is superior to sulfur one in enhancing soil TP and HC. These improvements in the values of TP (0- 30 cm soil layer) at the 2nd season were more obvious than the first one. Meanwhile, the HC values were the highest at the 1st season. Phosphogypsum application inhibited the severe decline of HC at ESP levels, where PG placement plays a necessary role in gradual reduce of HC in saline soils **(Kazman *et al*., 1983)**. Additionally, **(Loveday, 1976)** investigated that mixing gypsum in saline soils was effective in displacing sodium as a result of high gypsum should be solubility. Moreover, the reduction of HC at 2nd season implies slaking of aggregates or dispersion which may be due to low rate of mineral dissolution through leaching or insufficient maintenance of flocculated conditions as a result of low electrolyte **(Shainberg *et al*., 1981)**. When the soil has the ability to retain and conduct water (soil hydraulic properties) in salt conditions, consequently improve HC, therefore, promoting yield. For instance, the duality treatment of the tested materials caused 7.912 and 110.53% increments in TP and HC values (0-30 cm soil depth) at the 1st season after cotton harvesting, respectively compared to ck.

3.1.2. Soil moisture constants

Data in Table 6 showed the effect of two soil amendments (PG and S) applied either separately or as alternatively on saline sodic soil moisture constants (field capacity (FC), wilting point (WP) and available water (AW)). Results indicated that the application of these tested materials increased significantly FC content. Meanwhile, the same materials had insignificant effect on WP and AW contents of both seasons except WP (0-30cm soil depth) at 2nd season compared to salinized untreated plots. Additionally, PG treatment is superior to S one in enhancing soil moisture constants especially at the 2nd season. This means that the rise of moisture in the top saline sodic soil might be due to improve water holding capacity **(Arie and Magaritz, 1986)**. **Bauder and Brock (2001)** indicated that available water was improved due to reduce osmotic forces around the salt affected soil particles, therefore, decreasing plant growth. These results of the maintenance on high moisture content in the top horizons of cultivated soils were in consistent with obtained by **Loveday (1976)** who suggested that the reason for enhanced seedling emergence in gypsum treated soils where, the application of gypsum reduced surface crusting. However, the gypsum application to saline soils improved the soil structure with leaching by non-saline water in addition; the applied of gypsum acidifies saline soils to improve water uptake and soil physical and chemical characteristics **(Abdelhamid *et al*., 2013)**. For instance, in 0- 30 cm soil depth, the increment percentage of (FC, WP and AW%) being 10.56, 4.33 and 14.10 % at the 2nd season due to application of PG, S and their duality treatment, respectively after harvesting cotton relative to untreated plots. It could be mentioned that the duality treatment of the used materials seemed to be the most efficient treatment for enhancing these characters compared to other treatments.

TABLE 6: Effect of phosphogypsum (P), sulfur (S) and their interaction (PG+S) onmoisture constants (FC, WP and AW %) in saline- sodic soil during the two growing seasons after cotton harvest

Treatments	FC%		WP %		AW %	
	0-30cm	30-60cm	0-30	30-60	0-30	30-60
			2022			
Ck	39.10b	37.85	21.10	20.52	18.00	17.33
PG	41.25ab	39.50	22.56	21.54	18.69	17.96
S	40.20b	38.75	21.91	20.90	18.29	17.85
PG + S	42.60a	40.60	23.51	22.11	19.09	18.49
LSD at 0.05	2.110	Ns	Ns	Ns	Ns	Ns
			2023			
Ck	39.00c	37.80b	21.02b	20.54	17.98	17.26
PG	43.12ab	40.11ab	23.61a	22.36	19.51	17.75
S	40.69bc	39.20ab	22.32ab	21.50	18.37	17.70
PG + S	44.50a	41.30a	24.23a	22.89	20.27	18.41
LSD at 0.05	3.520	2.310	2.310	Ns	Ns	Ns

ck= control, FC= field capacity, WP= wilting point and AW= available water, Ns= insignificant differences.

3.2. Soil Chemical Characteristics

3.2.1. Soil pH

The application of PG and S singly or as duality treatment reduced soil pH values in both depths of two growing seasons, these amendments promote the properties of saline-sodic soils and enhance the growth and productivity of cotton over to salinized untreated plots Fig.1.The phosphogypsum treatment was obviously greater than sulfur in reducing soil pH of two seasons. On contrast, the results demonstrated that GB and AsA as a plant spraying alone had no effect on the soil pH values over to controlFig.1. Similar results were in agreed with **Lastiri-Hernández *et al*. (2019)** who revealed that the application of $CaSO_4.2H_2O$ decreased the soil pH from 8.1to 7.64. **Haile *et al*. (2022)** referred that the applied of phosphogypsum emitted great amounts of H^+ ions into the soil solution, therefore, accelerating the reduction of pH in PG- treated sodic soils over to control. Moreover, **Zhao *et al*. (2018)** revealed that application of PG releases soluble Ca which substitutes the exchangeable Na^+ and also reacts with HCO_3^-+ CO_3^{-2} and alters sodic to neutral salt and thereby reducing the soil pH **(Zhao *et al*., 2018)**. Meanwhile, **Wiedenfeld (2011)** said that the saline soils are improved via the presence of S, which acidifies rapidly the soil and as it oxidizes to a strong acid (e.g., H_2SO_4), may further react with carbonates and bicarbonates in the soil to become leachable Na_2SO_4 **(Weil and Brady, 2017)**.Thus, reduce the soil pH. Also, the data indicated that the interaction effect between soil amendments and foliar treatments decreased soil pH values due to soil amendments Fig.1. For example, soil pH values were decreased with applied PG+ GB, S+ GB and their duality treatment by 4.45, 0.35 and 5.74% in 0- 30 cm soil depth at 1st season, respectively relative to control. It could be noticed that, the lowest pH values were observed in the duality treatment of the used materials at 2nd season in 0- 30 cm soil depth. Meanwhile, the highest one of this character was found in ck treatments.

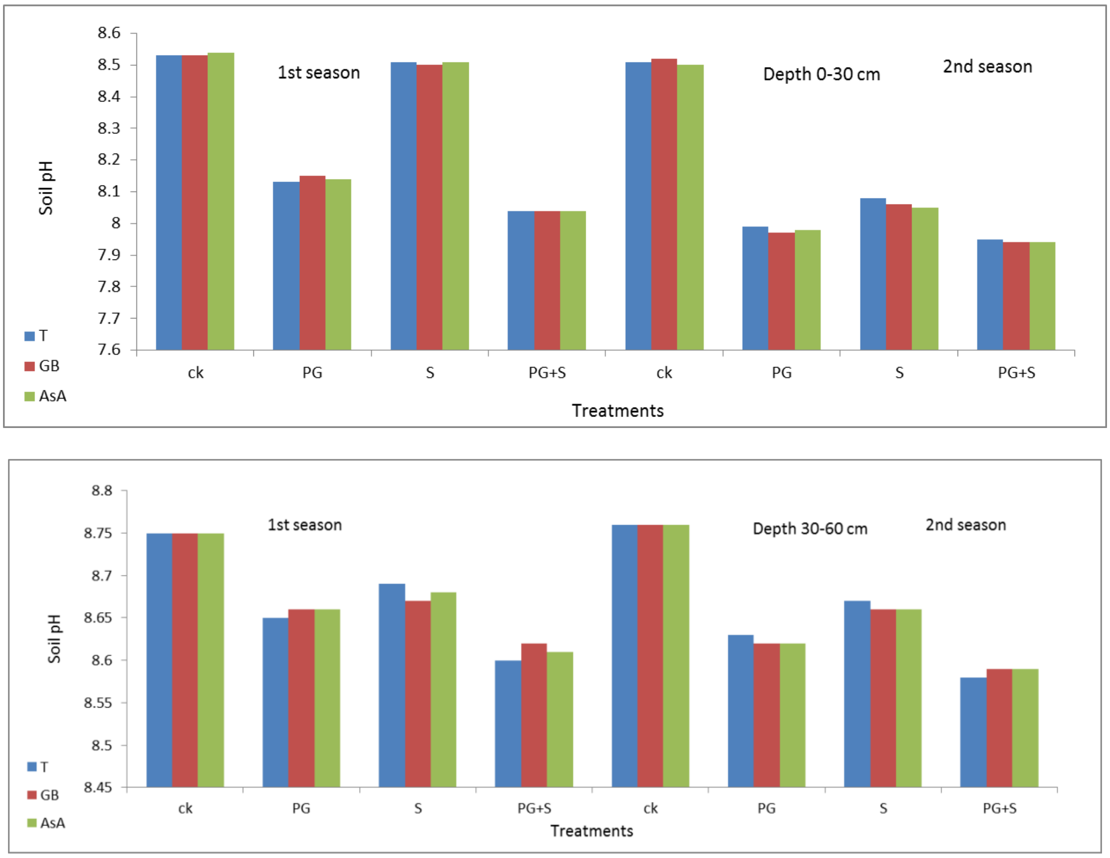

Fig. 1. Effect of interaction between phosphogypsum (PG), sulfur (S), glycine betaine (GB) and ascorbic acid (AsA)on soil pH compared to control during two growing seasons under salt stress condition after cotton harvest

3.2.2. Soil Electrical Conductivity (EC)

Results presented in Table 7 cleared the effect of two soil amendments as separately or alternatively treatments on soil EC in two depths (0- 30, 30- 60 cm) of both seasons after cotton harvesting. A significant decrement was detected on this character, because of the good effectiveness of PG and S application. The results investigated that PG treatment was superior to S one in decreasing soil EC compared to corresponding control values. On contrast, it could be observed that, the EC values in saline-sodic soil can be descended in order 30-60 > 0-30 cm depth of the two growing seasons. Similar results were in the same line as these obtained by **Outbakat *et al*. (2022)**. **Lastiri-Hernández *et al*. (2019)** indicated that the application of $CaSO_4.2H_2O$ reduced the soil EC from 6.21 to 2.39 dS m^{-1}.Phosphogypsum may be used as saline soil amendment on account of its contains over 92% of ($CaSO_4.2H_2O$), where Ca^{2+} may decrease salinity by replacing exchangeable sodium (Na^+)to reclaim sodic soils through increase the hydraulic conductivity in the interaction plots to efficient enhancement of salt leaching from the root zone, improved the soil permeability and hence, enhancement of production**(Lastiri-Hernández *et al*., 2019)**. Additionally, **Cifuentes and Lindemann (1993)** investigated that S presented in gypsum is an acid former that allows reducing soil electrical conductivity (EC) in a fast way at favorable temperatures and humidity conditions. Meanwhile, the data demonstrated that GB and AsA treatments singly had no effect on the soil EC over to control (Table 7). It could be observed that the applied of different sources of soil amendments ameliorated the deleterious effect of salinity in both seasons. For instance, in 0- 30 cm soil depth, at the 2^{nd} season, the application of the PG+ GB and S+GB and their duality treatments caused a decrement of soil EC represented by 35.89, 14.69 and 39.08 %, respectively. It could be observed that, the lowest EC value was reported by the duality treatment of the used materials at the 2^{nd} season in 0-30 cm soil depth compared to other treatments.

3.2.3. Water soluble ions

The concentration of three major water-soluble ions (Na^+, Ca^{2+} and Mg^{2+})in two studied soil depths (0- 30 and 30- 60 cm) as affected by different treatments was presented in Table 7. Applied of PG and S alone or as duality treatment increased significantly the concentration of Ca^{2+} and Mg^{2+}ions in soil, meanwhile, reduced significantly Na^+ concentration of two growing seasons relative to control. But, PG treatment was more effective in enhancing the concentration of Ca^{2+} and Mg^{2+} ions in soil than S one. Also, the increments were more pronounced in the top soil than the subsurface one. Similar results were agreed with those reported by **Outbakat *et al.* (2022)**. In saline–sodic soils, the expandable interlayer space of soil is occupied by sodium, causing soil swelling and clay dispersion. Sodium in the soil constituted a double layer due to low charge density **(Zocaand Penn, 2017)**, which decreases water flow in the soil. However, the application of PG brings high content of calcium. Sodium is easily replaced by calcium due to valence, great hydrated ionic radius, and low adsorption selectivity for the principal cations in the soil is: Ca^{2+}>Mg^{2+}> K^+≈ $NH4^+$>Na^+. Sodium ranked in the last position in this sequence, which means low electrical charges with clay fraction, which promotes its replacement **(dos Santos *et al.*, 2013)**, decreasing the sodic effect in the soil. Under an irrigation system, great contents of exchangeable Na were removed via leaching resulted high exchangeable Ca left in the soil profile. Moreover, the results investigated that GB and AsA as a plant spraying alone had no obvious impact on the concentrations of soil soluble ions in both layers compared to control (Table 7). Additionally, insignificant affected the concentrations of Ca^{2+}, Mg^{2+} and Na^+ ions in soil by applying all treatments (soil amendments + foliar spray) over to control. The use of $CaSO_4.2H_2O$ decreases Na^+ from the cations exchange sites, thereby decreasing its uptake by plants **(Gonçalo Filho *et al.*, 2019)**. Moreover, upon the applied of gypsum, it must be well-mixed with the soil followed by adequate water application to replace Na^+ from the rhizosphere. The increment of Ca^{2+}-to-Na^+ ratios on clay surfaces inhibit soil dispersion and improve a stable soil structure, as well as an promoted clay flocculation **(Aboelsoud *et al.*, 2020)**.This also makes more Ca^{2+} available for plant uptake. For instance, in 0-30 cm soil depth, at 1st season, the concentrations of soluble Na^+ and Ca^{2+} ions were 40.06 and 15.42 meq/l in the PG + AsA treatment and were 54.35 and 12.37 meq/l in the S+ AsA treatment, respectively. Meanwhile, the concentration of Na^+ was 54.97meq/l in the duality treatment of the same previous materials in 30-60 cm soil layer. It could be noticed that the duality treatment of the tested materials achieved the best results for enhancing the concentration of the soluble ions in soil compared to other treatments.

TABLE 7 :Effect of interaction between phosphogypsum (PG), sulfur (S), glycine betaine (GB) and ascorbic acid (AsA) on electrical conductivity (EC dS/m) and the concentration of soluble ions (Ca^{2+} , Mg^{2+} and Na^+ meq/l) in saline sodic soil during the two growing seasons after cotton harvest

Treatments		EC (dS/m)		Ca^{2+} meq/l		Mg^{2+} meq/l		Na^+ meq/l	
		0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm	0-30 cm	30-60 cm
2022									
Ck	T	7.87	8.10	8.00	7.10	5.80	5.33	63.78	67.51
	GB	7.88	8.11	8.03	7.04	5.79	5.32	63.85	67.69
	AsA	7.89	8.12	8.06	7.05	5.81	5.34	63.90	67.75
	T	6.41	7.20	15.35	7.92	8.30	5.89	39.50	57.16
PG	GB	6.47	7.22	15.39	7.93	8.33	5.90	40.02	57.32
	AsA	6.48	7.19	15.42	7.96	8.35	5.92	40.06	56.98
	T	7.41	7.86	12.34	7.11	6.50	5.44	54.26	64.99
S	GB	7.39	7.84	12.33	7.11	6.54	5.40	54.02	64.83
	AsA	7.43	7.85	12.37	7.09	6.56	5.43	54.35	64.90
	T	6.10	7.08	16.97	8.61	8.65	6.05	34.44	55.13
PG + S	GB	6.07	7.09	16.99	8.60	8.62	6.07	34.14	55.21
	AsA	6.09	7.07	17.02	8.62	8.69	6.10	34.22	54.97
LSD at 0.05		Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns
2023									
Ck	T	7.82a	8.0a	8.01c	7.11c	5.80b	5.33a	63.27a	66.50a
	GB	7.83a	8.06a	8.04c	7.03c	5.82b	5.33a	63.33a	67.19a
	AsA	7.84a	8.05a	8.06c	7.04c	5.83b	5.35a	63.40a	67.06a
	T	5.10b	7.02a	17.53a	8.37ab	8.58a	6.61a	24.19c	54.20c
PG	GB	5.02b	7.09a	17.59a	8.39ab	8.60a	6.58a	23.30c	54.92c
	AsA	5.05b	7.10a	17.61a	8.4ab	8.63a	6.62a	23.54c	54.98c
	T	6.70a	7.60a	13.25b	7.7bc	6.98ab	5.84a	45.98b	61.41b
S	GB	6.68a	7.56a	13.27b	7.67bc	6.99ab	5.86a	45.75b	61.03b
	AsA	6.65a	7.58a	13.31b	7.68bc	7.01ab	5.89a	45.40b	61.19b
	T	4.79b	6.80a	18.06a	9.1a	8.90a	7.01a	20.34c	50.89c
PG + S	GB	4.77b	6.78a	18.1a	8.98a	8.92a	7.04a	20.06c	50.77c
	AsA	4.78b	6.79a	18.15a	8.99a	8.95a	7.05a	20.07c	50.84c
LSD at 0.05		Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns

Ca^{2+} = calcium ion, Mg^{2+} = magnesium ion and Na^+ = sodium ion, Ns= insignificant differences

3.2.4. Soil ESP

Data in Fig. 2 revealed that soil ESP values in both depths (0-30, 30-60 cm) were significantly reduced by applying two soil amendments either single or alternative at two growing seasons after cotton harvesting compared to ck. This decrement was more obvious at the top soil than the subsurface one. Similarly, PG amendment was more effective than S one in reducing soil ESP at two growing seasons. This might be due to PG amendment released a huge amount of soluble Ca into the soil solution which substituted excess exchangeable Na+ from exchange sites **(Ng *et al.*, 2022)**, which participated in reducing the soil ESP. The lowest values of soil ESP were found with the duality treatment of the used materials in 0- 30 cm soil layer at the 2nd season. On contrast, the highest values of the same character were recorded from control treatment. The values of soil ESP were not affected with GB and AsA treatments during two seasons relative to control Fig. 2. Additionally, results demonstrated no obvious different between soil ESP values in both depths because of the interaction effect between soil amendments and foliar application Fig. 2. These results were in agreed with those reported by **Haile *et al.* (2022)**. The sodic soils are described by high ESP and pH. High values of ESP cause deflocculating of clay particles and result in the deterioration of soil structure **(Shahid *et al.*, 2018)**. Similarly, **Wheaton *et al.* (2002)** demonstrated that the application of gypsum in a sodic soil assisted in the its reclamation by decreasing spontaneous dispersion and the ESP by 26% up to a depth of 0.5 m over a period of about 3.5 years. The application of $CaSO_4.2H_2O$ reduced the soil SAR from 42.39 to 9.39 (mmolcL-1)1/2 and ESP from 39.54% to 10.56% **(Lastiri-Hernández *et al.*, 2019)**.

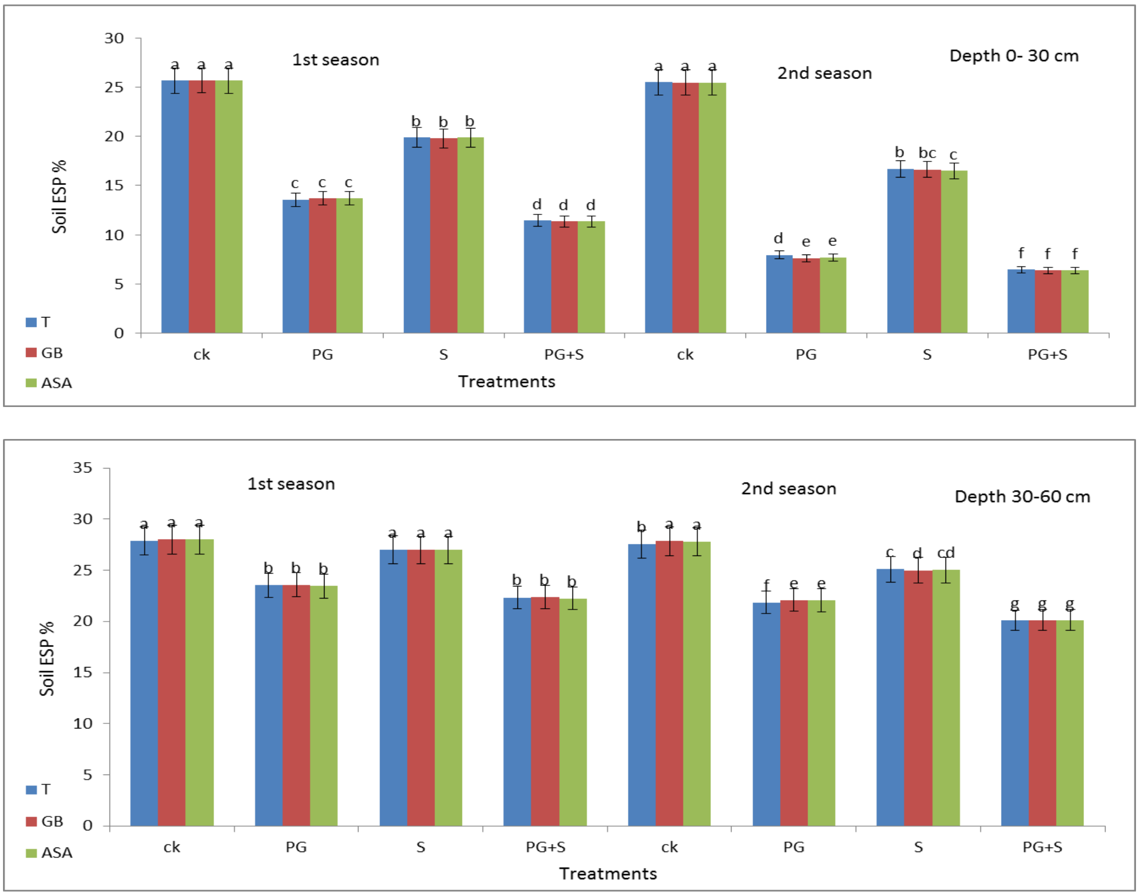

Fig. 2. Effect of interaction between phosphogypsum (PG), sulfur (S),glycine betaine (GB) andascorbic acid (AsA)on soil ESP %compared to controlduring two growing seasonsunder salt stress condition after cotton harvest.

3.3. Available phosphorus content

Data illustrated that the available P content in (0- 30, 30- 60 cm soil layer) was significantly improved as a result of PG and S treatments applied either separately or alternative of both seasons compared to salinized untreated plots Fig. 3. This is because of existence of sulfate (SO_4^{-2}) which pushes phosphate (HPO_4^{-}) from adsorption sites to soil solution, consequently promote available p after two seasons. Additionally, PG contains about 2% P_2O_5. Also, change of phosphorus from tricalcium phosphate to di and mono calcium phosphate due to the change in soil pH. These results are in the same line as these obtained by **Raja *et al.* (2020)** who indicated that the applied of PG amendments to cultivated soils improved nutrient availability to growing crops due to the existence of huge amounts of calcium, zinc, iron, sulfur and phosphorus, and enhances a balanced concentration of electrolytes in the soil solution **(Alcívar *et al.*, 2018)**. These increments were more pronounced in the top soil (0- 30 cm layer) than the subsurface one (30- 60 cm depth). Meanwhile, the soil available p values relatively reduced via the 2nd season compared to the first one under applied these amendments. **Havlin *et al.* (2017)** said that although the land preparation was done after the harvest, the practice might have mixed the P-PG with a large volume of soil, and hence improved P fixation Also, the increment of exchangeable Ca at the second planting might have enhanced the formation of insoluble calcium phosphate (Ca-P) **(Havlin *et al.*, 2017)**. It could be observed that application of foliar treatments (GB and AsA) separately had no effect on soil available P at two growing seasons compared to control Fig. 3. Insignificant increment in soil available P content was observed with application of all the tested materials. For instance, in 0- 30 cm soil depth, the increments of soil available P were 57.01and 56.96%for the PG + GB, PG + AsA treatments, also50and 50.24% for the S + BG, S + AsA treatments at 1st season, respectively in the same layer.

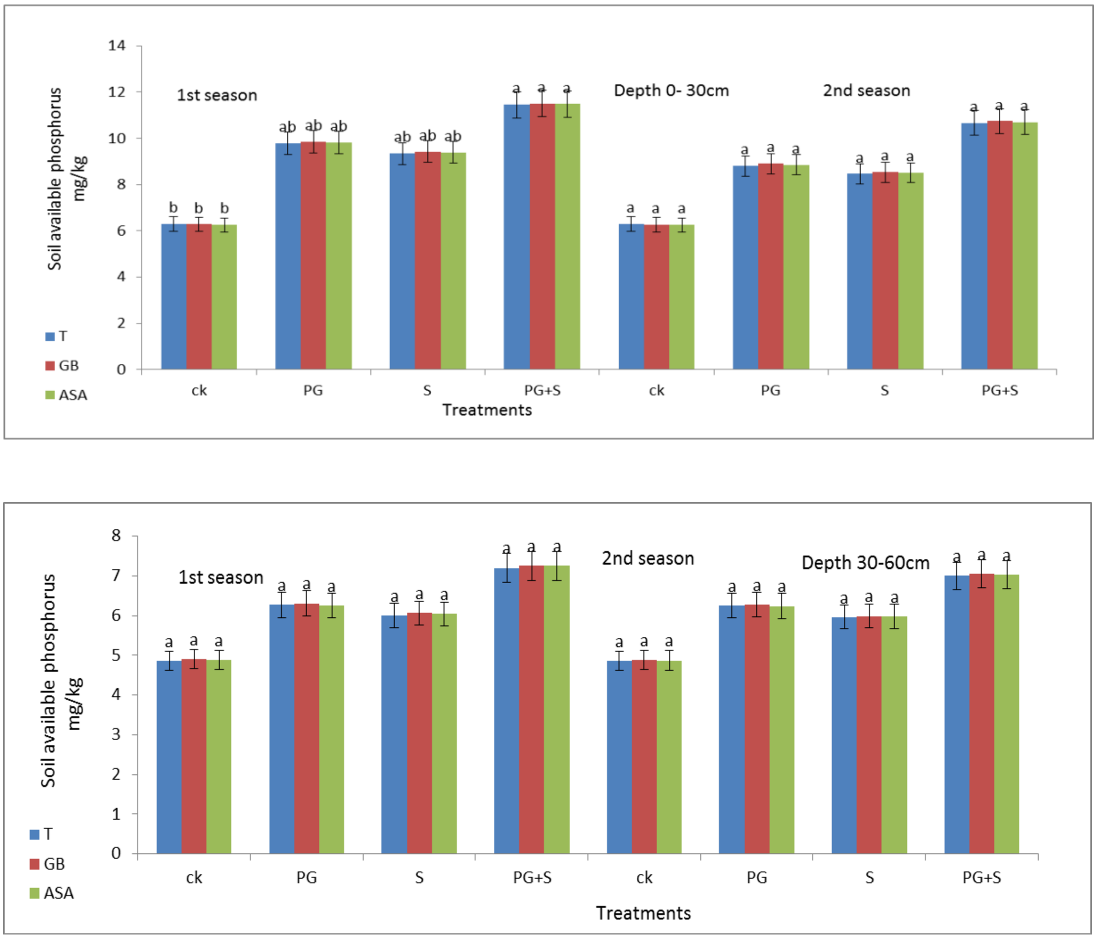

Fig. 3. Effect of interaction between phosphogypsum (PG), sulfur (S),glycine betaine (GB) and ascorbic acid (AsA)on soil available phosphorus content (mg/kg)compared to control during two growing seasons under salt stress condition after cotton harvest.

3.4. Effects on cotton plant

3.4.1. Seed germination % and plant growth parameters

Results shown in table (8) reveal that seed germination % was significantly affected by only soil amendments in both seasons. No significant effects were found for either stress mitigators or the interaction soil amendments x stress mitigators on germination % in both seasons. A general trend was obtained to increase seed germination % by the used soil amendments, but the significant increase was reached by only the combined application of phosphogypsium (PG) and sulfur (S) in both seasons, and by PG alone in 2022 season only in comparison with the control. The application of sulfur alone failed to exert any significant effect on seed germination as over to control in both growing seasons. Seed germination reached its maximum value by the combined application of PG + S followed by PG alone. The positive effects for soil amendments on seed germination % may be attributed to their improvement in soil physiochemical properties as discussed above, which enhance soil structure and improve the water availability and nutrients, creating favorable conditions for seed germination. Several studies showed that salt stress has a hard effect on seed germination of cotton. The weak seed germination in the presence of excess salt can be due to low osmotic pressure that leads to poor water absorption capacity of seed water, and /or abnormal embryo development due to absorption of harmful ions from the soil **(Bibi *et al*., 2016, Sharif *et al*., 2019; Chaudhary *et al*., 2024)**. Recent studies confirm that both sulfur and phosphogypsum play critical roles in improving seed germination under saline and sodic conditions. Sulfur primarily improves soil pH, enhances nutrient availability, and reduces salinity-induced oxidative stress, while phosphogypsum improves soil structure, reduces sodicity, and increases calcium availability. When used together, these amendments have synergistic effects, creating an optimal environment for seed germination by reducing osmotic stress and improving water availability for seeds to imbibe water, a crucial step in the germination process, enhancing essential nutrients availability, and correcting soil compaction and permeability issues that commonly hinder seed germination in saline and sodic soils **(Chen *et al*., 2021; Wang *et al*., 2022)**.

Results showed that all studied parameters of plant growth were affected significantly by soil amendments, stress mitigators and their interaction in both seasons (Table 8). It is observed that the applied of PG and S singly or alternatively, increased plant growth parameters i.e. plant height, No. of fruiting branches per plant and leaf area per plant compared with the control in two growing seasons. The applied of PG + S gave the maximum values of studied growth parameters, followed by PG alone in the different studied seasons. These results could be due to the corresponding effects for the soil amendments used in this study on physiochemical properties of the soil as discussed above (tables, 5, 6, 7). It could be observed that growth parameters decreased by salinity because of interaction between osmotic stress and sodium chloride toxicity. Salt stresses reduce turgor pressure, leaf area, photosynthesis activities, stomatal conductance, and transpiration rate, reducing assimilates accumulation within plant which leads to an inhibition in cell division and cell expansion **(Sharif *et al*., 2019; Zahra *et al*., 2022)**. **Shehzad *et al*. (2019)** showed that cotton growth was highly reduced by soil salinity through nutrient ion imbalance, with increasing Na^+ and Cl^- and reducing N, P and K, and osmotic stress which inhibits water availability. **Bibi *et al*. (2016)** reported that growth traits i. e. leaves per plant and area, fresh/dry weights of shoot and root, and general growth of cotton were significantly reduced under salinity. Also, spending more energy in salinity mitigation processes instead of building plant tissues may contribute to further growth inhibition under salinity conditions. Sulfur and phosphogypsum play critical roles in improving soil properties under saline and sodic conditions. Sulfur reduces soil pH, enhances microbial activity, and improves nutrient availability, while phosphogypsum displaces sodium, improves soil structure, and enhances water infiltration. In plant S offers multiple benefits; mitigating ionic imbalance and improving the osmotic balance under salinity conditions via regulating the uptake of K^+ and Ca^{+2} while limiting Na^+ accumulation, thereby improving the plant ionic homeostasis, and boosting antioxidant defence as S involves in glutathione synthesis which plays an essential role in reducing oxidative damage. Previous studies have shown that the combined or individual application of phosphogypsum and sulfer shows great potential in mitigating the adverse effects of salinity on cotton growth and productivity by promoting osmotic adjustment, enhancing antioxidant defense and improving nutrients and water uptake **(Chen *et al*., 2021, Afsheen *et al*., 2022)**.

Concerning the effect of stress mitigators on plant growth, data illustrated in Table (5) clarify that both glycine betaine (GB) and ascorbic acid (AsA) improved the studied growth characteristics in comparison to control, but the level of significance was not always reached by AsA. The maximum values of growth parameters were scored by GB in both seasons. Salt stress negatively affects cotton growth and development through imposing osmotic potential, nutritional deficiencies and ionic toxicity **(Caudhary *et al*., 2024)**. Salt stress, called also hyper ionic concentration stress, promotes Na^+ and $Cl^−$, reduces the level of Mg^{2+}, K^+ and Ca^{2+} in leaves of cotton and decreases N and P uptake by cotton roots **(Qamer *et al*., 2021)**. Enhancement of plant growth for GB could be owing to its role in maintaining cellular turgor and water content by regulating osmotic pressure within plant tissues, preventing wilting and ensuring continued cell expansion and growth. Also, the promotive effect for AsA on plant growth may be its role as a powerful antioxidant in alleviating salt- induced oxidative stress, enhancing both physiological and biochemical processes and ensuring that the plant metabolic processes function normally under salinity stress. Other workers obtained an increases in plant growth characteristics i.e.; plant height, leaf area ,root and shoot biomass and total dry weight by foliar application of GB **(Gohram *et al*., 1998),** or AsA **(Kamal *et al*., 2017).**

TABLE 8: Effect of soil amendments and stress mitigation on cotton growth and growth parameters

Main (soil amendments)	Sub (plant growth)	Germination %	Plant height/ cm	No. of fruiting b.	Leaf area / cm^2
			2022		
Without	Control	76.38 e	92.82 i	8.79 e	871.10 k
	Glycine	78.11 d	100.22 g	9.36 e	885.13 i
	Ascorbic acid	76.52 e	96.86 h	8.76 e	876.00 j
	Mean	**77.25 c**	**96.65 d**	**8.93 d**	**877.40 d**
Sulfur	Control	78.68 d	111.06 f	9.62 de	904.02 h
	Glycine	78.85 d	114.13 e	10.80 cd	989.94 f
	Ascorbic acid	78.87 d	112.25 f	9.90 de	925.86 g
	Mean	**78.65 bc**	**112.42 c**	**10.15 c**	**940.15 c**
Phosphogypsum	Control	79.08 d	115.73 d	10.86 cd	990.43 f
	Glycine	80.45 bc	118.32 c	12.05 bc	1062.82d
	Ascorbic acid	79.14 cd	116.85 d	11.60 bc	1004.20 e
	Mean	**79.35 b**	**117.36 b**	**11.43 b**	**1019.01 b**
Sulfur +phospho.	Control	80.95 b	119.46 bc	12.64 ab	1140.62 c
	Glycine	83.50 a	122.16 a	15.35 a	1315.41 a
	Ascorbic acid	81.26 b	120.36 b	13.43 ab	1185.55 b
	Mean	**81.93 a**	**120.23 a**	**13.20 a**	**1213.80 a**
LSD at 5%	A	1.74	0.99	0.26	23.63
	B	0.70	1.14	0.41	35.49
	AXB	1.38	1.37	2.57	22.70
			2023		
Without	Control	80.36 a	108.16 e	11.46 h	800.33 g
	Glycine	82.35 a	109.20 e	11.70 g	842.43 f
	Ascorbic acid	82.00 a	109.01 e	11.88 g	822.66 fg
	Mean	**74.04 b**	**118.53 c**	**11.06 c**	**997.62 d**
Sulfur	Control	81.31 a	110.06 de	12.08 f	900.11 e
	Glycine	80.49 a	111.61 d	12.59 e	930.14 e
	Ascorbic acid	82.38 a	110.86 de	12.08 f	922.58 e
	Mean	**74.87 b**	**118.72 c**	**11.49 c**	**1017.85 c**
Phosphogypsum	Control	83.55 a	113.50 c	13.36 d	945.52 d
	Glycine	85.66 a	114.80 c	14.05 c	1070.80 bc
	Ascorbic acid	86.55 a	114.03 c	13.50 d	1050.45 c
	Mean	75.00 b	120.61 b	12.45 b	1134.74 b
Sulfur +phospho.	Control	86.53 a	116.02 b	14.06 c	1100.66 b
	Glycine	88.65 a	118.76 a	14.82 a	1257.13 a
	Ascorbic acid	87.47 a	117.80 ab	14.48 b	1140.52 b
	Mean	**78.39 a**	**122.33 a**	**14.79 a**	**1250.11 a**
LSD at 5%	A	3.61	2.27	1.34	38.92
	B	1.13	3.50	0.67	33.81
	AXB	N.S	1.00	0.33	40.26

The interaction soil amendments x stress mitigators significantly affected all studied growth parameters in two growing seasons. The highest values of plant height, No. of fruiting branches / plant and leaf area / plant were recorded by soil application of PG + S and plant spraying with GB while the lowest ones were obtained from the control treatment with neither soil application nor plant spraying in both seasons.

3.4.2. Leaf chemical composition

Data in Table (9) exhibit that soil amendments affected significantly leaf contents of chl.b, total chls and proline in both seasons, chl. an in 2022 only and carotenoids in 2023 only. Soil amendments, in general, increased leaf content of pigments and decreased leaf content of proline in comparison with the control. These effects were more consistent and pronounced by the combined application PG + S, followed by the application of the application of PG alone. The increase in leaf pigments content by the used soil amendments may be due to their enhancement in nutrients availability and absorption by plant. Other studies obtained increases in leaves content of essential nutrients and pigments by the application of PG and/or S **(Abdelhamid *et al*., 2013)**.

It is obvious from Table (9) that all studied leaf constituents were affected significantly by stress mitigators, except for carotenoids in 2022 season and chl.a and ch.b in 2023 season. GB increased leaf pigments contents and decreased proline content as compared with either AsA or the untreated control. The salinity-sressed treatment (control) gave significantly lower leaves chemical constituents, indicating the degradative effects of salinity on photosynthetic pigments.GB is mainly localized in chloroplasts and plays a necessary role in chloroplast adjustments and the protection of thylakoid membranes, which assists to maintain the photosynthetic efficiency of the plant **(Massange-Sanches *et al*., 2021)**. In this regard, the restrained effects of salinity on chlorophyll pigments could be due to inhibition of specific enzymes responsible for the synthesis of the green pigments **(Dawood *et al*., 2021)**. Additionally, salt stress raised the degradation of chlorophyll through improved the activity of the proteolytic enzymes such as chlorophyllase. Moreover, Salt stress, called also hyper ionic concentration stress, improves Na^{+} and Cl^{-}, reduces the level of Mg^{2+}, K^{+} and Ca^{2+} in cotton leaves and decreases N and P uptake by cotton roots **(Qamer *et al*., 2021)**. GB and/or AsA were reported to mitigate such salt-induced negative effects via their role in osmotic adjustment, antioxidant promotion and ionic balance, maintaining pigments and photosynthetic apparatus. Since ascorbic acid is a detoxifier and neutralizer of super oxide radicals, it can inhibit chlorophyll degradation and indirectly improve leaf chlorophyll content. Similar results were in the same line by **(Gohran *et al*., 1998, Namish, 2003** and **Hamani *et al*., 2021)**. The interaction between soil amendments and stress mitigators significantly affected total chlorophyll and proline in both seasons and chl.b in 2023 season only, as the highest values of these traits were obtained by applying PG + S as soil amendments with spraying plant with GB, while the lowest ones was for the un treated control with no soil amendments or stress mitigators.

TABLE 9: Effect of soil amendments and stress mitigators on leaf chemical components

Main (soil Amendments)	Sub (plant growth)	Chl. a (mg/ g fresh weight)	Ch. B (mg/ g fresh weight)	Total chlorophyll	Carotenoids (mg/ g fresh weight)	proline (µg/g FW)
				2022		
Without	Control	2.12 a	1.23 a	3.41 b	1.12 a	645.53 a
	Glycine	2.13 a	1.34 a	3.58 b	1.13 a	600.80 b
	Ascorbic acid	2.10 a	1.40 a	3.69 b	1.16 a	551.71 c
	Mean	**2.12 b**	**1.43 d**	**3.54 d**	**1.14 a**	**599.33 a**
Sulfur	Control	2.12 a	1.50 a	3.76 b	1.10 a	425.64 g
	Glycine	2.10 a	1.66 a	3.94 b	1.11 a	384.96 i
	Ascorbic acid	2.11 a	1.72 a	4.12 b	1.22 a	403.54 h
	Mean	**2.21 b**	**1.72 c**	**4.06 c**	**1.24 a**	**466.92 b**
Phosphogypsum	Control	2.31 a	1.80 a	4.13 b	1.20 a	473.70 d
	Glycine	2.35 a	2.13 a	4.50 ab	1.21 a	467.56 f
	Ascorbic acid	2.30 a	1.80 a	4.12 b	1.22 a	467.53 e
	Mean	**2.22 b**	**1.90 b**	**4.19 b**	**1.23 a**	**404.00 c**
Sulfur +phospho.	Control	2.41 a	2.10 a	4.56 ab	1.26 a	363.91 j
	Glycine	3.30 a	2.32 a	5.68 a	1.35 a	315.04 l
	Ascorbic acid	2.62 a	2.23 a	4.79 ab	1.32 a	345.95 k
	Mean	**2.71 a**	**2.21 a**	**4.96 a**	**1.20 a**	**341.63 d**
LSD at 5%	A	**0.29**	**0.09**	**0.16**	**N.S**	**23.26**
	B	**0.15**	**0.07**	**0.21**	**N.S**	**23.31**
	AXB	**N.S**	**N.S**	**1.61**	**N.S**	**30.20**
				2023		
Without	Control	2.00 a	1.55 f	3.52 e	1.43 a	565.81 a
	Glycine	2.13 a	1.52 f	3.61 e	1.32 a	533.91 b

	Ascorbic acid	2.55 a	1.71 e	4.23 d	1.23 a	540.33 b
	Mean	**2.43 a**	**2.05 b**	**4.43 bc**	**1.12 c**	**545.72 a**
Sulfur	Control	2.65 a	1.83 e	4.41 d	1.21 a	500.52 c
	Glycine	2.00 a	2.01 d	4.01 d	1.41 a	498.53 c
	Ascorbic acid	2.11 a	2.00 d	4.11 d	1.51 a	499.63 c
	Mean	**2.52 a**	**2.02 b**	**4.51 bc**	**1.31 bc**	**500.83 ab**
Phosphogypsum	Control	2.31 a	2.14 cd	4.42 d	1.37 a	453.72 d
	Glycine	2.52 a	2.31 c	4.82 c	1.16 a	428.52 e
	Ascorbic acid	2.73 a	2.20 c	4.92 c	1.23 a	450.73 d
	Mean	**2.63 a**	**2.12 b**	**4.73 b**	**1.56 b**	**456.62 b**
Sulfur +phospho.	Control	3.00 a	2.53 b	5.52 b	1.35 a	420.42 ef
	Glycine	3.21 a	2.76 a	5.94 a	1.53 a	400.06 f
	Ascorbic acid	3.02 a	2.55 b	5.55 b	1.46 a	413.84 ef
	Mean	**2.81 a**	**2.42 a**	**5.24 a**	**1.77 a**	**423.74 c**
LSD at 5%	A	**N.S**	**0.56**	**0.52**	**0.17**	**27.60**
	B	**N.S**	**N.S**	**0.28**	**0.23**	**10.82**
	AXB	**N.S**	**0.15**	**0.32**	**N.S**	**20.81**

3.4.3. Yield and its components

Results in Table (10) indicate that soil amendments significantly affected No. of setting bolls, No. of open bolls, boll weight and seed cotton yield in two growing seasons. The application of sulfur or phosphogypsum, either individually or in combination, increased yield and its components compared to control with the maximum values of studied traits of yield & its components were realized by the combined treatment PG + S , followed by PG alone. Such enhance in yield & its components because of used soil amendments could reflect their overall positive effects on soil properties and their improvements in seed germination, leaf chemical composition and plant growth. These cumulative improvements in soil conditions translated into a significant increase in yield and yield components. It is a well-established fact that salinity decreased crop productivity through imposing oxidative, osmotic and ionic stresses, which all disrupt plant functions and metabolic pathway at biochemical, cellular and physiological levels, and ultimately decreased crop productivity **(Zhang *et al.*, 2014; Qamer *et al.*, 2021** and **Caudhary *et al.*, 2024)**. Soil application of PG and/or S improved soil properties, created favorable condition for better germination, seedling growth, root growth and overall plant growth and subsequently increased crop yield. Previous studies have emphasized that the combined or individual application of sulfur and phosphogypsum shows great potential in mitigating the adverse effects of salinity on plant growth and productivity by promoting osmotic adjustment, enhancing antioxidant defense and improving nutrients and water uptake **(El-Sayed and Hamid, 2020; Chen *et al.*, 2021** and **Wang *et al.*, 2022).**

Concerning the effect of stress mitigators on yield and yield components, it is clear from Table (10) that stress mitigators in general increased No. of open bolls, boll weight and seed cotton yield in two growing seasons as comparing to control. Such increases in yield and its components were more consistent and pronounced for GB as compared with AsA. These results could be attributed to the sum of their positive effects on leaves chemical composition and plant growth which may ensure regular supply of assimilates to the developing bolls, increasing number and weight of bolls and seed cotton yield. Both GB and AsA have the potential to alleviate the adverse effects of salinity due to their roles in enhancing antioxidative activity and osmotic adjustment, both compounds are thought to have positive effects on enzyme and protect cellular components along with adaptive roles in mediating osmotic adjustment in plants grown under stress conditions **(Kaya *et al.*, 2013** and **Qamer *et al.*, 2021)**. **Giri (2011)** showed that the presence of glycine betaine (GB) remarkably decreased heavy metals concentrations in the stem, roots, and leaves of cotton plant owing to its defensive role in the cell membrane, and concluded that GB is considered an important osmolyte that empowered the cotton plant to cope with certain environmental factors. **Kaya *et al.* (2013)** indicated that GB alleviated some of the harmful effects of salinity and maintaining membrane permeability. The positive effects of ascorbic acid in overcoming the adverse effects of salinity were due to the stabilization and protection of photosynthetic pigments and the photosynthetic apparatus from oxidative damage Similarly, AA has significant effects on crop plants under stress conditions by acting as an antioxidant that scavenges ROS therefore, improving cotton production **(Kamal *et al.*, 2017)**.

As for effect of the interaction soil amendments x stress mitigations on yield & its components, data in Table (10) clarify that all studied traits of yield & its components were affected significantly by the interaction effect between soil amendments and stress mitigators in both seasons, except for boll weight in 2022 season.

The highest values of yield & its components were obtained by the treatment including the applied of PG + S as soil amendments and GB as stress mitigators, while the lowest values of these traits were obtained by the control treatment with no application of soil amendments or stress mitigators. These results could be attributed to the positive effects for the combined application of sulfur and phosphogypsium on soil properties, creating a favorable environment for better plant growth and productivity under saline conditions, while glycine betaine complement these amendments by enhancing the plant physiological tolerance to salt stress through osmotic regulation and antioxidative defense mechanisms.

TABLE 10: Effect of soil amendments and stress mitigators on cotton yield and its components

Main (soil Amendments)	Sub (plant growth)	No. of Setting bolls	No. of open bolls	Boll shedding %	Seed cotton yield /kent.	Boll weight (g)
				2022		
Without	Control	18.52 f	14.83 d	21.00 a	6.21 e	1.91 a
	Glycine	19.81 def	15.75 bcd	20.83 ab	7.44 de	2.02 a
	Ascorbic acid	19.12 ef	15.16 cd	20.46 abc	6.96 e	2.01 a
	Mean	**18.43 c**	**15.54 b**	**19.82 a**	**6.84 d**	**2.01 d**
Sulfur	Control	20.74 bcd	16.16 abcd	20.33 abc	7.42 de	2.15 a
	Glycine	21.02 bcd	16.46 abc	20.23 abcd	8.42 cd	2.33 a
	Ascorbic acid	21.03 bcd	16.13 abcd	20.26abcd	8.33 cd	2.34 a
	Mean	**20.42 b**	**16.45 a**	**20.02 a**	**8.12 c**	**2.22 c**
Phosphogypsum	Control	19.73 def	16.53 abc	20.02 abcde	8.75 bcd	2.53 a
	Glycine	20.36 cde	16.80 ab	19.73 abcde	9.16 abc	2.74 a
	Ascorbic acid	20.22 cde	16.65 ab	19.52 bcde	9.12 abc	2.62 a
	Mean	**20.24 b**	**16.55 a**	**20.42 a**	**9.24 b**	**2.63 b**
Sulfur +phospho.	Control	21.42 bc	16.93 ab	19.32 cde	10.00 ab	2.81 a
	Glycine	25.24 a	17.43 a	18.93 de	10.20 a	2.82 a
	Ascorbic acid	21.73 b	17.42 a	18.72 e	10.21 a	2.80 a
	Mean	**22.92 a**	**16.86 a**	**19.56 a**	**9.80 a**	**2.72a**
LSD at 5%	A	**1.94**	**0.90**	**N.S**	**0.51**	**0.11**
	B	**N.S**	**0.89**	**N.S**	**0.44**	**0.13**
	AXB	**6.53**	**3.21**	**2.29**	**3.21**	**N.S**
				2023		
With out	Control	14.30 e	11.81 f	17.80 b	5.51 d	1.52 g
	Glycine	15.02 e	12.73ef	15.31 c	6.33 c	1.80 e
	Ascorbic acid	14.51 e	12.04 f	17.22 b	7.84 b	1.71 f
	Mean	**17.52 d**	**12.63 c**	**20.14 b**	**6.56 d**	**1.91 c**
Sulfur	Control	15.50 de	13.05 ef	16.13 bc	7.92 b	1.82 e
	Glycine	16.53 d	14.04 d	15.22 c	8.24 b	2.00 d
	Ascorbic acid	16.01 d	13.23 e	17.50 b	8.03 b	2.06 d
	Mean	**19.63 c**	**14.01 bc**	**20.51 b**	**7.05 c**	**2.03 c**
Phosphogypsum	Control	18.00 c	14.82 c	17.80 b	8.63 ab	2.01 d
	Glycine	20.54 bc	15.76 b	19.53 a	8.22 b	2.32 c
	Ascorbic acid	18.65 c	15.09 c	18.44 ab	7.51 c	2.36 c
	Mean	**22.56 b**	**15.65 b**	**22.62 a**	**8.02 b**	**2.33 b**
Sulfur +phospho.	Control	19.92 bc	16.06 b	17.03 b	8.06 b	2.42 b
	Glycine	22.43 a	18.55 a	18.66 ab	9.03 a	2.50 a
	Ascorbic acid	20.34 b	17.26 ab	17.92 b	8.72 ab	2.44 b
	Mean	**24.82 a**	**17.15 a**	**21.02 b**	**8.53 a**	**2.51 a**
LSD at 5%	A	**2.11**	**1.51**	**0.43**	**0.48**	**0.23**
	B	**1.32**	**0.89**	**2.12**	**0.43**	**0.49**
	AXB	**1.80**	**0.70**	**1.82**	**0.55**	**0.12**

4. Conclusion

It could be concluded from this study that the application of soil amendments (sulfur and phosphogypsium) either separately or alternatively enhanced physical and chemical characteristics of saline- sodic soil, cotton growth and productivity as well, with the best results were achieved by the combined application of sulfur and phosphogypsium. The foliar spraying of glycine betaine and ascorbic acid enhance cotton growth and productivity, while glycine betaine gave the best results. The significant interaction between soil amendments and stress mitigators on seed cotton yield indicate that the most positive integrative was between the combined application of sulfur and phosphogypsium and foliar spraying of glycine betaine which synergistically gave the highest seed cotton yield.

5. Conflicts of interest

There is no conflict of interest

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