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Sulphur Compost Properties and its Amelioration Effect on Salt Affected Soil Characteristics and Productivity

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TWO consecutive experiments were conducted, the first one aims to find out the effect of elemental sulphur on the characteristics of the produced compost, and the second one was to study the effect of the compost produced from the first experiment on the chemical properties and soil fertility of a salt affected soil and its productivity of wheat (*Triticum aestivum*, Giza 12). These experiments were carried out at the greenhouse of Soil Science Department, Faculty of Agriculture, Menoufia University, Shebin El-Kom, Egypt during the winter growing season of 2020/2021. The S was mixed with compost raw materials (maize stalks and farmyard manure) at rates of 0.0 (CS0), 1.0 (CS1), 2.0 (CS2) and 3.0 % (CS3) which incubated for 60 days. Individually in pot trial, the produced composts were mixed with salt affected soil at 0.0, 0.5, 1.0, and 2.0 % application rates and sowed by wheat. The results estimated of the produced compost showed that, addition of S led to the improvement of compost chemical properties. Obtained results show that S addition to composted materials resulted in a decrease pH and organic matter (OM) values of S-treated compost compared to untreated type (CS0), while the compost values of electrical conductivity (EC) and available nutrients (N, P, K and S) increased. Moreover, addition of different types and rates of the produced sulphur compost to a salt affected soil led to significant improvements in soil chemical properties and its content of available nutrients. Soil pH, EC, exchangeable Na and exchangeable sodium percentage (ESP) values decreased with the increase of S in the applied compost, as well as with the increase its addition rate. Also, treating soil with compost that has a higher amount of S led to an increase in the soil value of OM, cation exchange capacity, exchangeable cation (Ca, Mg and K), S forms (soluble, available and organic) and available nutrients (N, P and K). Increasing rate of added compost either of unsulphur or sulphur form resulted in a significant increase in yields (straw, grains and biological) of wheat under saline soil conditions. In conclusion, the addition of sulphur improved the characteristics of compost, which by adding it to salt affected soil improved its chemical properties and productivity.

Keywords: Chemical properties, Salt affected soil, Sulphur, Compost, Wheat.

1. Introduction

Salt affected soils represent a large area of the Egyptian lands. These soils are placed mainly in two locations, the first one is in the valley and delta of the Nile River, which are known as the ancient lands, whose formation was influenced by flood irrigation and poor drainage (Kotb et al., 2000). While the second site occupies the large areas in deserts (eastern and western deserts), which are known as newly reclaimed lands, which affected the formation of the parent material from which these lands originated (Abd El-Kawy et al., 2011; Arnous and Green, 2015; Abdelaal et al., 2021). The presence of these soils is also associated with the arid and semi-arid climate regions as compared with the soil found in the rained regions (Carter, 1975).

The lack of fertile arable land and increase in population necessitated the reclamation of salt-affected soils in order to reduce the widening of the food gap and compensate for the shortfall in crop and food requirements (Wahba et al., 2019). Further, salt-affected soils are characterized by large amounts of soluble salts which have an electrical conductivity (EC) of more than 4 dSm^{-1} for their saturated extract (Richards, 1954). Also, as a result of drought conditions, these soils are also characterized by their low contents of organic matter (OM), low mineralization, and lack of

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available nutrients (Mohamed, 2017; Shao et al., 2019). In addition, lack of enough rain, high evaporation, and lack of proper soil and water management contributed to the increase in the salinity hazards (Meena et al., 2019). The proper sustainable management of salt-affected soils is therefore considered one of the important steps to treat with their problems and raise their productivity. There are many organic amendments such as compost, which may have positive impacts in treating salt-affected soil (Amer and Hashem, 2018; El-Ramady et al., 2022).

Application of compost improves the physicochemical and biological properties of salt-affected soils (Amer, 2017; Awwad et al., 2022). Compost is a source of organic matter resulting from the exploitation of organic waste such as plant residues through a controlled biotransformation process for all its factors such as C/N ratio, pH, temperature, humidity and aeration (Nada, 2015; Hussein et al., 2022).

The selection of agreed-upon residue elements and their complementary materials with optimal parameters will create a good environment for the development of microbial activity and, thus, an optimal biodegradation will be achieved in the active phase of the composting process (Mohajer et al., 2009). However, there is insufficient information on the effect of adding elemental sulfur on the decomposition rate of organic wastes and the chemical properties of the resulting compost. Abou Hussien et al. (2016) demonstrated that, addition of elemental S to maize stalks and farmyard manure as a compost raw materials led to an increase in their decomposition rates, decreased pH and increased available macronutrients (N, P, K, Ca, Mg, and S) content of the end products. Adding sulphur to the composting of green wastes treated with phosphate rock led to pronounced increase in soluble P, especially in the mixture that contains the lowest percentage of rock phosphate (Bustamante et al., 2016). The pH values of the compost mixture (olive mill waste and sheep litter) were reduced by one unit after two weeks from the addition of elemental S, which did not cause any negative effects on the quality of the final compost (Roig et al., 2004; Gu et al., 2011; Bohacz, 2019).

In general, there are many studies that confirmed that the addition of compost improves the physical, chemical and biological properties of saline soils (Amer and Hashem, 2018; Abou Hussien et al., 2019; Abdrabou et al., 2022; Awwad et al., 2022). However, there are few studies on the effect of sulfur compost on soil chemical properties, especially salt-affected soils. Abou Hussien et al. (2020) reported that, application of sulphur compost to saline soil decreased soil pH and increased soil available nutrients. Also, Ghodsi et al. (2015) noticed that, the application of sulphur coated by urban solid waste compost increased the availability of macronutrients (N, P, and K) and decrease the values of pH, EC and sodium adsorption ratio (SAR) in saline-sodic soil. Therefore, the potential hypotheses of the current study assume that the addition of compost produced in the presence of sulphur will have a positive effect on the properties of saline soils and its productivity.

Wheat was the first crop grown in Egypt, it is still very important and the most imported and consumed crop (FAO, 2020). Therefore, it is necessary to look for a way to reduce the large gap between production and consumption. One of the main reasons for this gap is the lack of cultivated land through the reclamation of desert lands. However, wheat yield in Egypt increased nearly 6-fold (6.8 billion kg) between 1961 and 2017. This happened because of using better farming methods, developing irrigation systems, increasing the cultivated area through the reclamation of new lands such as saline lands (Saied et al., 2017; Amer and Hashem, 2018; Abdelmageed et al., 2019).

From the aforementioned, the current study aims to investigate: (i) the effect of adding elemental sulphur on the chemical properties and available nutrients in the compost produced from mixing maize stalk and farmyard manure, (ii) Effect of sulphur treated compost on chemical properties, sulphur forms and available macronutrients of salt-affected soil, and (iii) Effect of sulphur treated compost on wheat yields (straw and grains) and their macronutrients content.

2. Materials and Methods

2.1. First experiment (Composting)

An experiment was carried out to evaluate the effects of elemental sulphur (S) additives during composting process of organic wastes on the produced compost chemical properties and its content of essential plant nutrients.

2.1.1. Compost raw materials

Two organic wastes i.e. maize stalks (MS) and farmyard manure (FYM) were brought from the research farm of the Crop Department and Animal Breeding Farm, respectively, Faculty of Agriculture, Menoufia University, Shebin El-Kom, Egypt. Samples of MS were collected, spread in the open-air conditions for drying, and then chopped into 2 - 4 cm segment using crushing machine. Also, the FYM was air-dried, homogenized and kept until starting compost experiment. In addition, the applied elemental sulphur (S) was obtained from El-Helb Pesticides and Chemicals Company, Damietta, Egypt that have a 99 % of purity S and pH (1:5 suspension) equal 6.42.

2.1.2. Composting design and procedure

The experiment was established at the greenhouse of Soil Science Department, Faculty of Agriculture, Menoufia University, Shebin El-Kom, Egypt. Four treatments were created on the mixture of the prepared MS and FYM (as organic activators) at ratio of 65:35 by weight (Nada, 2011; 2015). These four treatments (piles) that repeated in three replicates were: (1) without sulphur additives (CS0), (2) mixed with 1 % sulphur (CS1), (3) mixed with 2 % sulphur (CS2), and (4) mixed with 3 % sulphur (CS3). The prepared four compost treatments were placed in plastic barrels of 50 cm diameter, 70 cm depth, and provided with holes (2 mm diameter) on the sides and the bottom of the barrel to improve aeration (Nada, 2015). Each barrel contained 20 kg of air dried MS and FYM mixture. Moreover, elemental S was mixed well by weight with CS1 (200 g S), CS2 (400 g S), and CS3 (600 g S) treatments. Individually, All barrels were treated with an activating mixture consisting of about 10 g $CaCO_3$, 3.20 g $Ca(H_2PO_4)_2$, 0.32 g urea (46 % N) and 100 ml suspension of fresh fertile soil (1:5, soil: water). Also, each barrel was properly moistened to reach about 55.0 % of its water holding capacity then left until 60 days **(**Nada, 2015; Elgezery, 2016**)**. The barrels were turned every 15 days starting from the top to bottom to promote the aerobic decomposition. By this method, the organic wastes were satisfactorily decomposed after 60 days. Representative sample of each barrels was taken air dried ground and analyzed for chemical properties (pH, EC, organic carbon, and total N) as well as the content of some available nutrients (N, P, K, and S) as described by Cottenie et al. (1982) and Page et al. (1982).

2.2. Second experiment (Planting)

The objectives of this experiment mainly were to determine the effect of the produced sulphur compost types on chemical properties of salt affected soil and their content of available nutrients and different S forms. Also, the productivity of wheat (*Triticum aestivum*, Giza 12) plant as well as its straw and grains content of some nutrients was a matter of concern.

2.2.1. Used soil location and sampling

Five surface soil samples (0-20 cm) were collected from different sites of salt affected soil at Experimental Farm, Agricultural Research Station Sakha, Kafr El-Sheikh Governorate, Egypt (31° 05' 16.7" N and 30° 56' 39.4" E). A sample of each site air-dried, ground and sieved through a 2 mm sieve. The sieved soils of the five locations were well mixed and kept for some physical and chemical properties and greenhouse experiment. A portion of the sieved soil was analyzed for its physicochemical properties and available macronutrients content using the procedures mentioned by Cottenie et al. (1982), Page et al. (1982) and Klute (1986) (Table 1).

TABLE 1. Some physical and chemical properties of the experimental salt affected soil.

Particle size distribution (%)				Texture class	WHC (%)	pH -	EC (dSm^{-1})
Coarse sand	**Fine sand**	**Silt**	**Clay**				
7.30	16.50	30.80	45.20	clay	31.50	8.85	6.32
OM (%)	**CEC** ($cmolkg^{-1}$)	ESP -	**Available macronutrient** ($mgkg^{-1}$)				
			N	**P**		**K**	**S**
1.30	38.30	22.50	64.10	6.13		754.0	9.15

pH = soil reaction measured in 1:2.5, soil: distilled water suspension**)**, **EC**= electrical conductivity (measured in 1:5, soil: distilled water extraction), **WHC**= Water holding capacity, **OM**= organic matter, **CEC**= Cation exchange capacity.

2.2.2. Experiment design and procedure

This experiment was carried out as a pot experiment at greenhouse in Soil Science Department, Faculty of Agriculture, Menoufia University, Shebin El-Kom, Egypt during the winter season of 2020 /2021 on prepared salt affected soil and wheat crop as a test plant. The studied treatments are arranged within the experimental units in two way completely randomized design in four replicates. Sixty four plastic pots having 30 cm in both inter diameter and height were used in this study. Each pot was filled with 5 kg of the prepared salt affected soil. These pots were divided into four main groups (16 pot/main group) representing the studied main factor or sulphur compost types (CS0, CS1, CS2, and CS3). Then the pots of each main group were divided into four sub groups (4 pot/sub group) representing the application rates of added sulphur compost i.e. 0.0, 0.5, 1.0 and 2.0 % (w/w). At the same time all pots were fertilized by ordinary superphosphate (15.5 % P_2O_5) as P fertilizer at rate 100 kg/fed (0.5 g pot^{-1}).

On the 15^{th} day of November 2020, 10 grains of wheat (*Triticum aestivum*, Giza 12) which brought from Field Crops Institute Research, ARC, Egypt, were planted in each pot. All pots were irrigated by tap water at moisture content of field capacity (FC, %) plus 20 % of this value was added as leaching requirements. After complete germination of wheat seeds (15 days), the plants of each pot were thinned to five plants. All pots were fertilized by ammonium nitrate (33.5 % N) and potassium sulphate (48 % K_2O) at rates of 150 and 100 (kg/fed) as N and K fertilizers (0.75 and 0.5 g/pot), respectively. Both N and K fertilizers were added with irrigation water in two equal doses after 20 and 40 days of planting. Irrigation process was carried out every three days based on the weight.

At maturity stage (150 days) wheat plants of each pot were harvested above the soil surface. On air-dried weight basis, the plants of each pot were weighted to measure the biological yield (g/pot) of wheat plant. After that, these plants were divided into straw and grains and weighted to obtain their yields (g/pot). A portion of each plant sample was taken separately, oven-dried at 70 °C for 48 hours, ground and kept in clear glass bottles for chemical analysis. Straw and grains contents of N, P, K, and S were measured by using the methods described by Cottenie et al. (1982) and Page et al. (1982).These measurements were carried out on plant materials digested which carried out using the procedure described by Chapman and Pratt (1961).

After plant harvesting the soil sample of each pot was taken, ground and sieved through a 2 mm sieve. The soil were analyzed for some chemical properties of pH, EC, organic matter (OM), exchangeable cations (Na, K, Ca, and Mg), and cation exchange capacity (CEC) by the methods reported by Cottenie et al. (1982) and Page et al. (1982). The exchangeable sodium percentage (ESP) was calculated by the following equation.

ESP = (Exchangeable Na/ CEC) * 100

Also, soil content of available macronutrients (N, P, K, and S) were measured (Page et al., 1982).

Moreover, different sulphur forms (soluble, available, and organic) were determined using methods mentioned by Tabatabai (1983) and Bashour and Sayegh (2007).

2.3. Statistical analysis

The data obtained from compost, soil and plant analysis were statistically analyzed (ANOVA) by using the method reported by Snedecor and Cochran (1989). Mean separation among the treatments was done by using the least significant difference (LSD) test at 5% level of probability.

3. Results

3.1. Characteristics of the prepared compost

The presented data in Table (2) show clear and wide variations within the chemical composition of the produced compost types. Obtained results show that S addition to composted materials resulted in a decrease pH values of S-treated compost compared to the untreated type (CS0). The pH values of the prepared composts types take the order of CS0 > CS1> CS2 > CS3 which was in line with S application rate to composted materials. Regarding to compost EC (dSm^{-1}), the EC values ranged between 1.86 and 2.13 dSm^{-1} (Table 2). Based on EC values, the prepared composts take the order CS3 > CS2 > CS1 > CS0 (Table 2). Data in Table (2) also showed that both OM and OC decreased in all four prepared types of compost. According to their content of OC and OM, the prepared composts take the order CS0 > CS1 > CS2 > CS3. The highest content (%) of total N (1.70 %) was found in CS3 followed by that in CS2 (1.58%), but the lowest one was found in CS0 (1.20%) (Table 2). Reversible order for these composts according their C/N ratios which was CS3 (15.98) < CS2 (17.64) < CS1 (18.57) < CS0 (23.96).

Data in Table (2) also reveals that, the increase in added S to the composted organic materials resulted in an increase of compost content (mg kg^{-1}) of available macro (N, P, K and S), where the highest content was found in CS3 followed by CS2 and the lowest one was found in CS1.

TABLE 2. Chemical properties and nutrients content of the studied sulphur compost types in relation with S applications.

SCT	pH -	EC (dSm^{-1})	OM (%)	OC (%)	TN (%)	C/N ratio
CS0	7.51	1.86d	45.15a	28.57a	1.20c	23.81a
CS1	7.48	1.91c	44.90b	28.42b	1.54b	18.45b
CS2	7.39	2.06b	44.32c	28.05c	1.60b	17.53c
CS3	7.29	2.13a	42.65d	27.00d	1.70a	15.88d
LSD $_{0.05}$	-	**0.033**	**0.110**	**0.101**	**0.061**	**0.706**

Available nutrients content (mg kg^{-1}) of the applied sulphur compost types

SCT	N	P	K	S
CS0	870d	705c	2010d	210d
CS1	898c	738b	2030c	1950c
CS2	932b	815a	2098b	2080b
CS3	992a	813a	2185a	2895a
LSD $_{0.05}$	**10.61**	**9.51**	**12.83**	**9.41**

SCT= Sulphur compost type, **CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, **pH=** soil reaction; measured in 1:5 (compost: water suspension), **EC**= Electrical conductivity; measured in 1:5 (compost: distilled water extraction), **OM**= organic matter, **OC**= Organic carbon, **TN**= Total nitrogen, means in a column with the same letter are not significantly different at the 5% level.

3.2. Characteristics of saline soil affected by sulphur compost

3.2.1. Chemical properties

a. Soil pH

The presented data in Table 3 and Figure 1 showed that, sulphur compost applications especially at high rates resulted in a significant decrease in soil pH compared with the control treatment. The obtained results revealed that all types of prepared compost resulted in significant decrease in soil pH. Maximum reduction if soil pH was associated with the application of compost type prepared with the high addition of elemental sulphur (CS3). At the same application rate of compost, the decrease in soil pH was increased with the increase of added S to compost. For example, soil pH was decreased from 8.85 in the control treatment to 8.75, 8.69, 8.60 and 8.40 with the application of CS0, CS1, CS2 and CS3, respectively at an application rate of 1.0 %. In addition, data in Figure 1 illustrated that, increasing rate of added compost in four types resulted in a significant decrease of soil pH.

b. Soil EC

The soil electrical conductivity (EC, dSm^{-1}) was significantly affected by both the type and application rate of the used composts (Table 3 and Figure1). Under the experimental treatments, soil EC ranged from 6.32 dSm^{-1} in the zero compost application to 5.50 dSm^{-1} at 2.0 % application rate of CS3. This range indicated that, application of zero sulphur-compost (CS0) reduced soil EC, but more decreases were resulted from sulphur compost applications. For example, soil EC was decreased from 6.32 dSm^{-1} in zero treatment of compost application to 6.05, 5.08, 5.65 and 5.50 dSm^{-1} at 2.0 % application rate of CS0, CS1, CS2 and CS3, respectively (Figure 1). The prementioned example also show that, the chemical composition of the used compost has clear effect on the changes of soil EC, where the found decrease of soil EC was associated with CS3 application and the lowest one was found with CS0 application (Table 3).

c. Soil organic matter

Data in Table 3 and Figure 1 show that soil organic matter was significantly affected by application of different compost types. Average values of soil organic matter affected by different compost types ranged from 1.39 % with CS0 type to 1.53 % with CS3. In addition, at the same application rate of added compost in the four types appeared a clear variation in their effect on the soil content of OM, where the highest content was found in the soil treated by CS3 followed by that treated by CS2, but the lowest content was found in the soil received CS0.

d. Soil cation exchange capacity

Soil cation exchange capacity (CEC, cmol kg^{-1}) of soil was significantly affected by application of studied compost types. The average values of soil CEC ranged from 38.74 to 40.54 cmol kg^{-1} in soil treaded by CS0 and CS3, respectively. Moreover, data in Table 3 and Figure 1 revealed that, increasing rate of added compost in any type resulted in a significant increase in the soil content of CEC. For example, increasing rate of added composts from 0.0 to 2.0 % resulted in an increase of soil CEC from 38.30 cmol kg^{-1} in the control treatment (zero compost application) to 39.50, 40.25, 41.76 and 42.10 cmol kg^{-1} in the soil manured by CS0, CS1, CS2 and CS3, respectively. This example reveals that, at the same application rate of added composts, the highest CEC value was found in the soil treated by CS3. Also, this example proves that, used compost in sulphur form is preferred than the other form.

TABLE 3. Individual effect of sulphur compost types and its application rates on the chemical properties of salt affected soil.

SCT & SCAR	pH -	EC (dSm^{-1})	OM (%)	CEC ($cmolkg^{-1}$)
a) Effect of SCT on soil chemical properties				
CS0	8.77	6.18a	1.39c	38.74d
CS1	8.74	6.05b	1.42bc	39.37c
CS2	8.67	5.95c	1.46b	40.24b
CS3	8.52	5.88c	1.53a	40.54a
LSD $_{0.05}$	-	**0.083**	**0.070**	**0.099**
b) Effect of SCAR (%) on soil chemical properties				
0.0	8.85	6.28a	1.32d	38.28d
0.5	8.70	6.14b	1.41c	39.56c
1.0	8.61	5.91c	1.49b	40.15b
2.0	8.55	5.74d	1.57a	40.90a
LSD $_{0.05}$	-	**0.059**	**0.051**	**0.061**

SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, **pH=** soil reaction; measured in 1:5 (compost: water suspension), **EC**= Electrical conductivity; measured in 1:5 (compost: distilled water extraction), **OM**= organic matter, **CEC**= Cation exchange capacity**,** means in a column with the same letter are not significantly different at the 5% level**.**

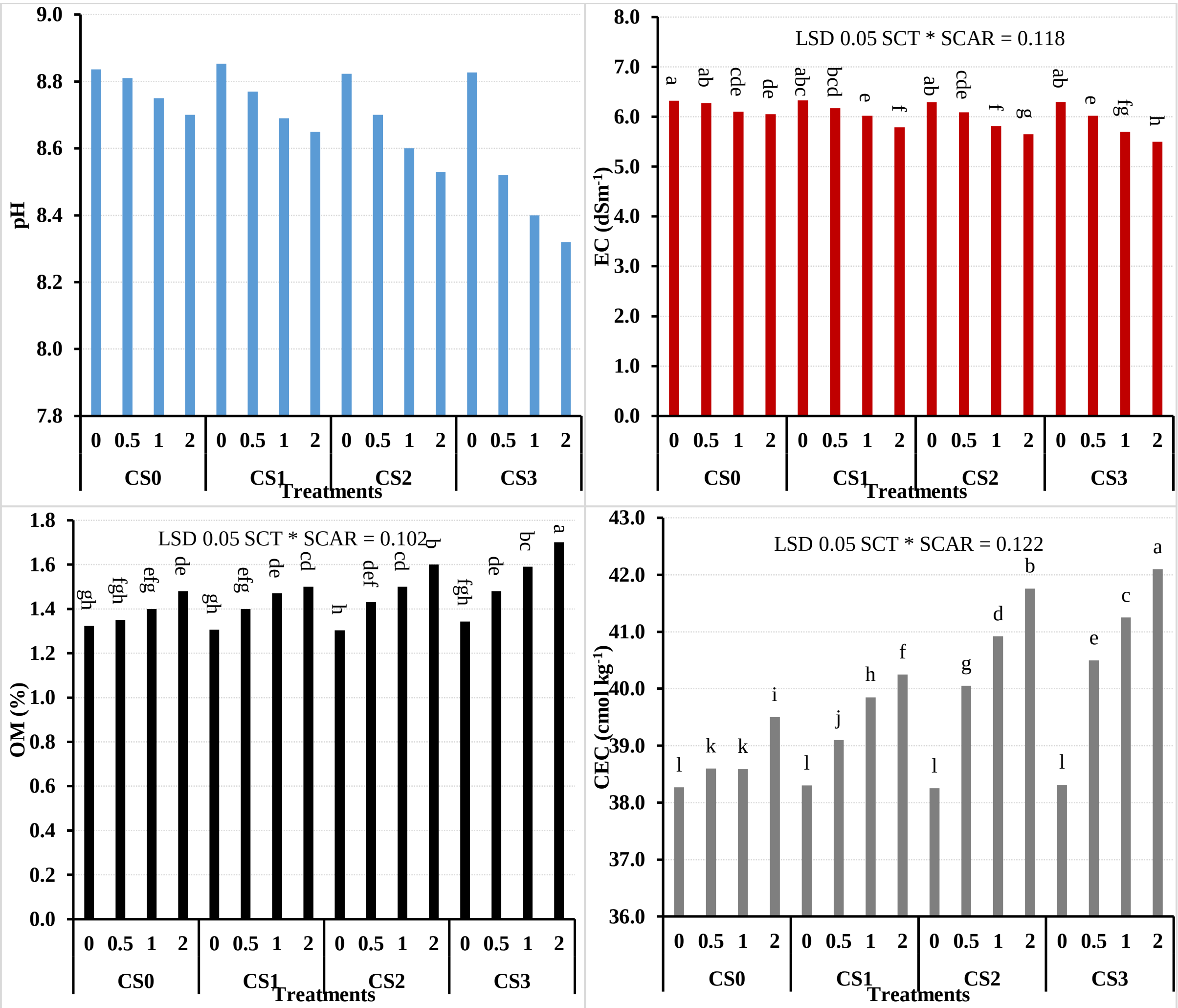

Fig. 1. Integrated effect of sulphur compost types and its application rates on the chemical properties of salt affected soil. SCT= Sulphur compost type, SCAR= Sulphur compost application rate, CS0= Compost produced without sulphur addition, CS1, CS2 and CS3= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, columns within the same attribute labelled with different letter are significantly different at 5 % level of probability.

3.2.2. Soil exchangeable cations and ESP

The presented data in Table (4) and Figure 2 show effect of both sulphur compost types and application rates on salt affected soil content (cmol kg^{-1}) of exchangeable Na, K, Ca and Mg as well as its exchangeable sodium percentage (ESP). This data show that, using compost in sulphur and non-sulphur forms to improve the properties of saline soil is very important, where such S application resulted in decrease of both exchangeable Na and ESP, while resulted in an increases of exchangeable of K, Ca and Mg. Increasing application rate of added compost in any form resulted in further reductions in exchangeable Na and ESP as well as more increase in the exchangeable K, Ca and Mg (Table 4). Also this data show that, the chemical properties of these additives played a clear effect on salt affected soil content of exchangeable Na, K, Ca and Mg as well as soil ESP.

TABLE 4. Individual effect of sulphur compost types and its application rates on soil content of exchangeable cations and exchangeable sodium percentage (ESP).

SCT & SCAR	Na (cmol kg^{-1})	K (cmol kg^{-1})	Ca (cmol kg^{-1})	Mg (cmol kg^{-1})	ESP
a) Effect of SCT on soil content of exchangeable cations and ESP					
CS0	8.06a	15.86d	8.75c	6.08b	20.83a
CS1	8.08a	16.16c	8.90b	6.09b	20.56b
CS2	7.85b	16.39b	9.73a	6.29a	19.58c
CS3	7.74c	16.58a	9.78a	6.32a	19.16d
$LSD_{0.05}$	**0.072**	**0.095**	**0.078**	**0.142**	**0.127**
b) Effect of SCAR (%) on soil content of exchangeable cations and ESP					
0.0	8.63a	15.10d	8.32d	5.79c	22.56a
0.5	8.18b	15.85c	9.42c	6.21b	20.69b
1.0	7.61c	16.74b	9.57b	6.34a	18.97c
2.0	7.32d	17.29a	9.85a	6.43a	17.92d
$LSD_{0.05}$	**0.048**	**0.043**	**0.048**	**0.050**	**0.110**

SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0=** Compost produced without sulphur addition, **CS1, CS2 and CS3=** Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively**,** means in a column with the same letter are not significantly different at the 5% level**.**

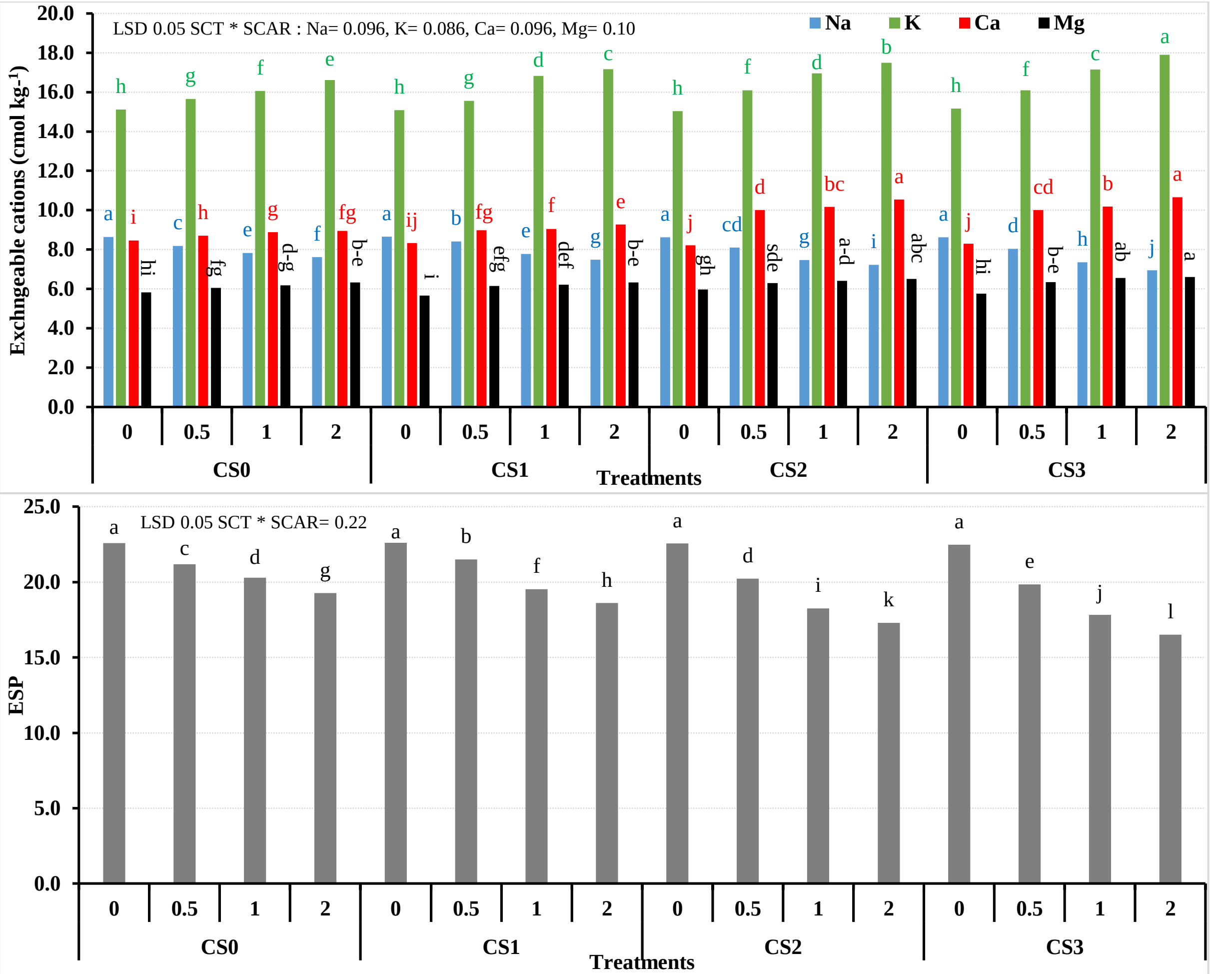

Fig. 2. Integrated effect of sulphur compost types and its application rates on soil content of exchangeable cations and exchangeable sodium percentage (ESP). SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0=** Compost produced without sulphur addition, **CS1, CS2 and CS3=** Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, columns within the same attribute labelled with different letter are significantly different at 5 % level of probability.

At the same application rate of added compost, the obtained data show that, increasing in mixed ratio of S in the compost resulted in increasing significant values of exchangeable K, Ca and Mg. The highest significant values of K (16.58 cmol kg^{-1}), Ca (9.78 cmol kg^{-1}), and Mg (6.32 cmol kg^{-1}) were recorded to CS3 treatment, while the lowest one were recorded for the control (CS0) (Table 4). However, exchangeable Na and ESP took an opposite trend of 7.74 cmol kg^{-1} and 19.16 for CS3 and 8.06 cmol kg^{-1} and 20.83 for CS0 treatment, respectively.

Regarding the combined effect of the types and rates of applied compost on the soil content of exchangeable cations (K, Ca, and Mg), the highest and lowest values were in favor of CS3 and CS0 treatment, respectively. Contrariwise, exchangeable Na and ESP observed with an inverse direction.

For example, increasing application rate of CS1 from 0.5 to 2.0 % resulted in decrease of exchangeable Na from 8.41 to 7.49 cmol kg^{-1} with recorded relative change (RC) values of -2.88 and -13.51%, respectively compared to control treatment (Figure 2). In addition, CS1 increased the exchangeable K, Ca and Mg from 15.56, 8.98 and 6.15 cmol kg^{-1} at 0. 5 % rate to 17.16, 9.27 and 6.33 cmol kg^{-1} at an application rate of 2.0 % with recorded RC values of 10.28, 3.23 and 2.93 %, respectively (Figure 1).

3.2.3. Soil available nutrients and sulphur forms

a. Soil available macronutrients

Data in Table 5 and Figure 3 show a clear effect of sulphur composts applications at different application rates on available N, P and K in the investigated soil. The content of these nutrients ranged from 64.08, 6.11 and 744.33 mg kg^{-1} in the uncomposted soil (CS0) to 71.50, 8.85 and 982.0 mg kg^{-1} in the soil treated by 2.0 % of CS3, respectively (Figure 3). Generally, these concentrations increased significantly with increasing the rate of added compost. For example, at the same type of added compost, available N, P and K increased from 64.09, 6.14 and 748.67 mg kg^{-1} to 68.74, 7.91 and 915.0 mg kg^{-1} at 0.0 and 2.0 % compost application rate, respectively (Table 5). Likewise, the highest available contents of N, P and K were found in the soil that received CS3 followed by the soil amended with CS2, while the lowest one was found in control treatment (CS0). For example, at treatment of CS0, CS1, CS2 and CS3, the soil content of available N, P and K was 65.22, 65.85, 66.72 and 67.56 mg N kg^{-1}, 6.59, 6.83, 6.96 and 7.49 mg P kg^{-1} and 787.33, 815.00, 842.08 and 876.50 mg K kg^{-1}, respectively (Table 5). As well as, the arrangement of added compost types effect on the increase of saline soil content of available N, P and K is in harmony with the added compost content of these nutrients (Table 2).

b. Soil sulphur forms

The data of the present study as listed in Table 5 and Figure 3 show that, there were a clear variations in the saline soil content (mg kg^{-1}) of the determined S forms i.e. soluble, available and organic with type and application rate of applied compost. With the same treatment of compost, the main S form in the soil is organic (more than 80 %), followed by available form (more than 12 %). Increasing rate of added four types of compost resulted in significant increases of S forms content in the soil. For example, soil content of soluble, available and organic S increased from 9.28, 102.22, and 616.29 mg kg^{-1} in the soil of control treatments (CS0) to 15.80, 137.96 and 693.78 mg kg^{-1} recording RC values of 70.26, 34.96, and 12.57 % in the soil treated by CS3, respectively (Table 5). Significant increases were found in the soil content of S forms, where the highest significant values were associated with soils that received 2.0 % compost (Table 5).

TABLE 5. Individual effect of sulphur compost types and its application rates on soil content of available macronutrients and sulphur forms.

SCT & SCAR	Macronutrients (mg kg^{-1})			Sulphur forms (mg kg^{-1})		
	N	**P**	**K**	**Soluble**	**Available**	**Organic**
a) Effect of SCT on soil content of macronutrients and S forms						
CS0	65.22d	6.59d	787.33d	9.28d	102.22d	616.29d
CS1	65.85c	6.83c	815.00c	10.60c	111.74c	629.90c
CS2	66.72b	6.96b	842.08b	12.97b	122.71b	658.81b
CS3	67.56a	7.49a	876.50a	15.80a	137.96a	693.78a
LSD $_{0.05}$	**0.091**	**0.074**	**6.183**	**0.085**	**0.105**	**1.39**
b) Effect of SCAR (%) on soil content of macronutrients and S forms						
0.0	64.09d	6.14d	748.67d	8.44d	96.35d	610.05d
0.5	65.39c	6.54c	798.00c	10.03c	107.72c	636.50c
1.0	67.13b	7.27b	858.75b	12.37b	127.08b	655.55b
2.0	68.74a	7.91a	915.00a	17.82a	143.48a	696.70a
LSD $_{0.05}$	**0.065**	**0.052**	**5.650**	**0.059**	**0.041**	**0.044**

SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively**,** means in a column with the same letter are not significantly different at the 5% level**.**

Regarding to the integrated effect of both type and rate of applied compost on soil content of S forms, the data reveals that, the highest significant values (26.33, 176.77, and 781.90 mg kg^{-1}) of soluble, available and organic S, respectively recorded to soil treated with 2.0 % and CS3 type. While, the lowest (8.47, 96.38, and 606.30 mg kg^{-1}) significant values of soluble, available and organic S, respectively were associated with 0.0 % and CS0 treatment (Figure 3).

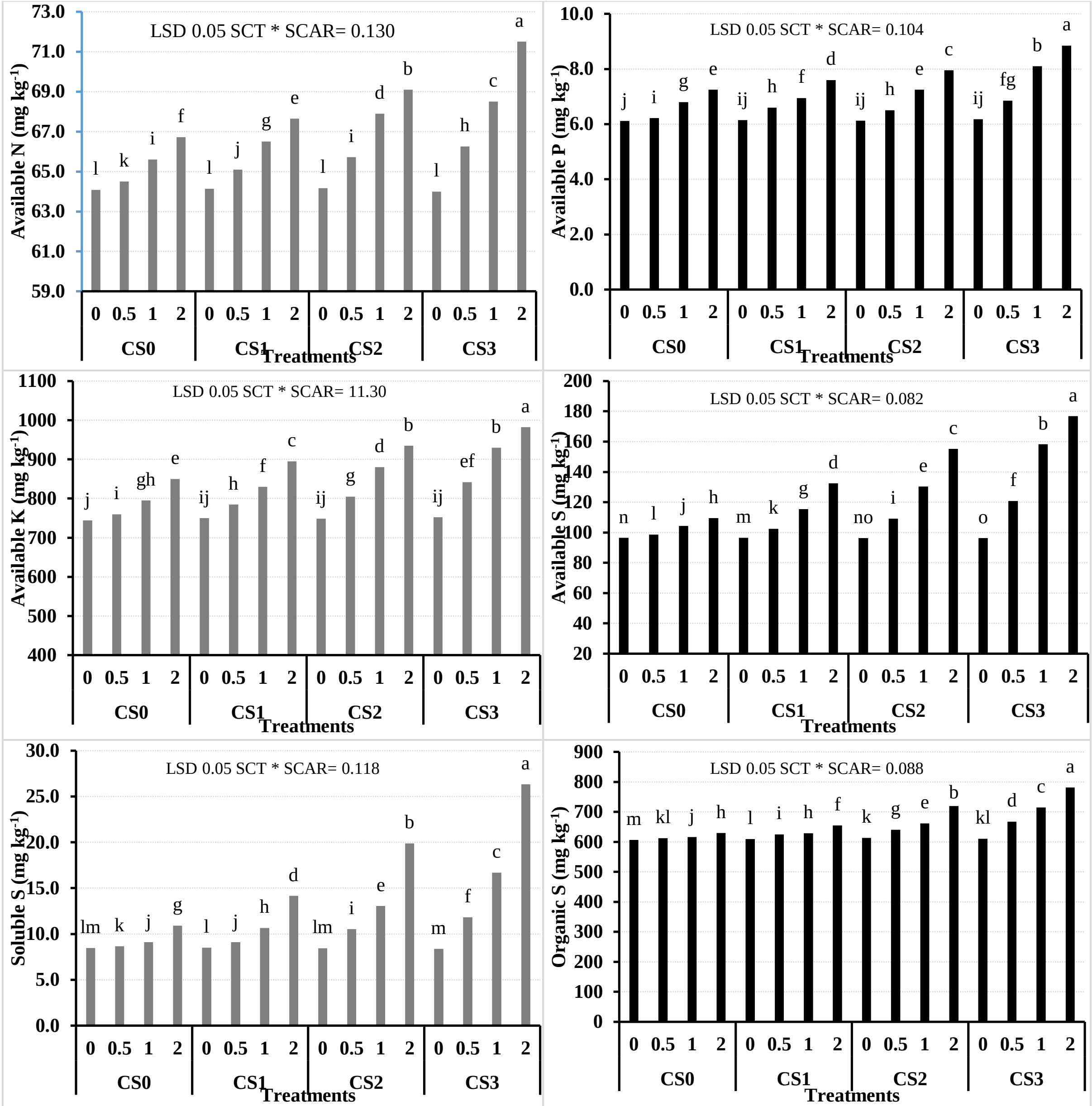

Fig. 3. Integrated effect of sulphur compost types and its application rates on soil content of available macronutrients and sulphur forms. **SCT=** Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, columns within the same attribute labelled with different letter are significantly different at 5 % level of probability.

3.3. *Wheat yield and its content of nutrients*

3.3.1. Straw, grain and biological yields

Data in Table 6 and Figure 4 show the effect of compost types and their application rate on straw, grains and biological yield of wheat plants. These data show that, increasing rate of added compost either of unsulphur or sulphur form resulted in a significant increases in yields (straw, grains and biological) of wheat plants under saline soil conditions. Likewise, increasing the rate of S in compost led to significant increases in wheat yield components (Table 6). For example, straw, grains and biological yields of wheat plant increased from 1.68, 0.98 and 2.66 g pot^{-1} for the plants grown in CS0 to 1.89, 1.34 and 3.25 g pot^{-1} with RC values of 12.50, 36.73 and 22.18 % for the plants fertilized by CS3 (Table 6). Also the same data in Table 6 showed, the highest significant values (2.09, 1.43, and 3.52 g pot^{-1}) of straw, grains and biological yields, respectively were recorded to the high rates of applied compost (2.0 %), while the lowest one were found in plants grown in un-manured soil. Also data show that, the applied composts showed a clear effect on yields (straw, grains, and biological) of wheat plants, where these yields ranged from 1.52, 0.92 and 2.45 g pot^{-1} in untreated soil (0.0 %) and CS0 treatment to 2.40, 1.86 and 4. 26 g pot^{-1} with recorded RC values of 57.89, 102.17 and 73.88 % in the plants grown in the soil treated by 2.0 % and CS3, respectively (Figure 4).

TABLE 6. Individual effect of sulphur compost types and its application rates on straw, grains and biological yields and biological index of wheat plant grown on salt affected soil.

SCT & SCAR	SY (g pot^{-1})	GY (g pot^{-1})	BY (g pot^{-1})	BI (%)
a) Effect of SCT on straw, grains, biological yield and biological index				
CS0	1.68d	0.98d	2.66d	36.84c
CS1	1.74c	1.05c	2.79c	37.85bc
CS2	1.82b	1.18b	3.00b	39.11b
CS3	1.89a	1.34a	3.25a	40.73a
LSD $_{0.05}$	**0.062**	**0.045**	0.039	1.31
b) Effect of SCAR (%) on straw, grains, biological yield and biological index				
0.0	1.54d	0.91d	2.43d	37.44c
0.5	1.68c	1.04c	2.73c	37.95bc
1.0	1.83b	1.17b	3.00b	38.84b
2.0	2.09a	1.43a	3.52a	40.29a
LSD $_{0.05}$	**0.041**	**0.037**	**0.046**	**1.33**

SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, **SY**= Straw yield, **GY**= Grains yield, **BY**= Biological yield, **BI**= Biological index**,** means in a column with the same letter are not significantly different at the 5% level**.**

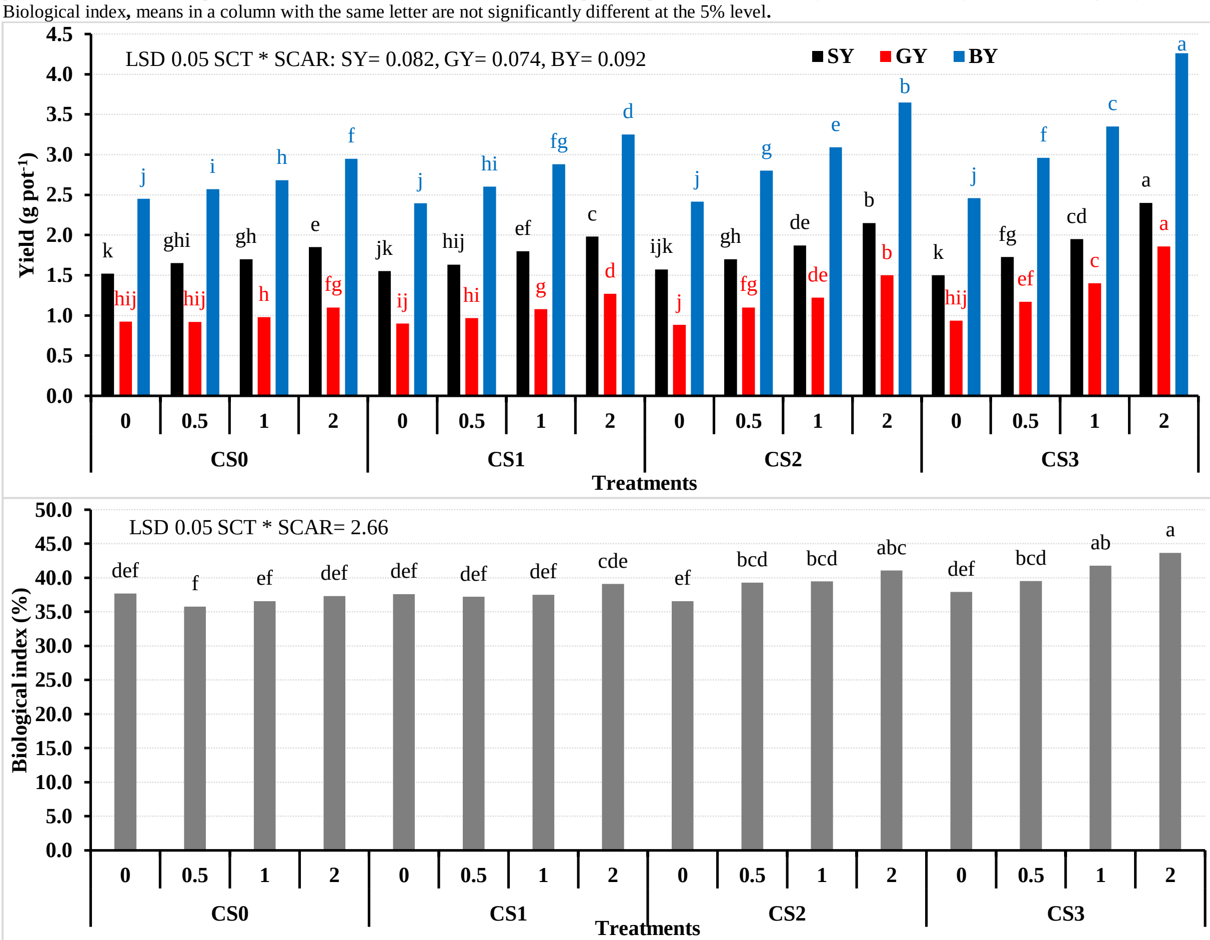

Fig. 4. Integrated effect of sulphur compost types and its application rates on straw, grains and biological yields and biological index of wheat plant grown on salt affected soil. **SCT=** Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, **SY**= Straw yield, **GY**= Grains yield, **BY**= Biological yield, columns within the same attribute labelled with different letter are significantly different at 5 % level of probability.

Moreover, data in Table 6 and Figure 4 show that, biological index (BI) of wheat plants grown on saline soil revealed a significant response to the studied treatments of both type and application rate of added compost, where its values ranged between 37.68 % for the plants grown on the soil under zero compost application (control) and 43.67 % in the plants fertilized by 2.0 % and CS3 (Figure 4). These data also illustrated that, increase rate of added rate of the used four compost types as well as increase in S mixed ratio with the composted materials resulted in a significant increase of BI of wheat plant (Table 6).

3.3.2. Straw and grains uptake of essential nutrients

Data in Table 7 and Figure 5 show straw and grains of wheat uptake (mg pot^{-1}) of N, P, K and S were affected by both type and application rate of the used compost. These data show a wide variations among the uptakes values of N, P, K and S by both straw and grains of wheat plants grown on saline soil that received the four types of compost which were applied at rate of 0.5, 1.0 and 2.0 %. With the same treatment under study, grains uptake of N, K, and S were higher than those found in the straw, while the uptake P took an opposite trend with the highest values were found in straw yield (Table 7 and Figure 5). The uptake of these nutrients followed reversible trend that resulted from the high straw yield compared with that of grains (Tables 6).

In both straw and grains of wheat plants treated by four compost types (CS0, CS1, CS2, and CS3) at different application rates (0, 0.5, 1.0 and 2.0 %) the uptake (mg pot^{-1}) of the determined nutrients takes the order K > N > S > P.

Increasing application rate of any one type of added compost resulted in significant increases of both straw and grains uptake of N, P, K and S. For example, N, P, K and S uptake by straw increased from 6.82, 3.35, 7.60 and 5.48 mg pot^{-1} in the plants of control treatment to 18.74, 10.32, 20.38 and 17.30 mg pot^{-1} in the plants received 2.0 % and CS3, where with the grains uptake of these nutrients increased from 11.54, 2.77, 16.44 and 5.62 mg pot^{-1} in the uncomposted plants (control) to 31.26, 10.42, 42.22 and 20.45 mg pot^{-1} in the plants fertilized by 2.0 % and CS3 for the same nutrients, respectively (Figure 5). In addition, data in Table (7) showed that, at the same application rate of the added four composts, the highest content (mg pot^{-1}) of N, P, K and S were found in the plants grown on the soil treated by CS3 followed by these found with the application of CS2, while the lowest values were found in the plants grown in the control treatment (CS0).

TABLE 7. Individual effect of sulphur compost types and its application rates on the uptake of essential nutrients by the straw and grains of wheat grown in salt affected soil.

SCT & SCAR	**Straw nutrients uptake** (mg pot^{-1})				**Grains nutrients uptake** (mg pot^{-1})			
	N	**P**	**K**	**S**	N	**P**	**K**	**S**
a) Effect of SCT on nutrients uptake								
CS0	8.84c	4.33c	9.82d	7.43c	12.94d	3.37c	18.61d	6.29d
CS1	9.53c	4.84bc	10.82c	7.71bc	14.29c	3.78c	20.64c	7.42c
CS2	10.96b	5.48ab	11.96b	8.98b	16.53b	4.75b	23.80b	9.02b
CS3	12.29a	6.13a	13.36a	10.76a	19.93a	5.91a	28.06a	11.87a
$LSD_{0.05}$	**0.71**	**0.78**	**0.83**	**1.35**	**0.72**	**0.53**	**0.83**	**0.53**
b) Effect of SCAR (%) on nutrients uptake								
0.0	6.70d	3.38c	7.66d	5.61d	11.38d	2,72d	16.19d	5.55d
0.5	8.82c	4.08c	9.40c	7.27c	13.83c	3.50c	19.88c	7.15c
1.0	11.26b	5.34b	12.51b	9.16b	16.37b	4.58b	23.76b	8.97b
2.0	14.64a	7.99a	16.40a	12.84a	22.11a	6.99a	31.26a	12.95a
$LSD_{0.05}$	**0.70**	**0.76**	**0.78**	**1.29**	**0.64**	**0.54**	**0.72**	**0.48**

SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, means in a column with the same letter are not significantly different at the 5% level.

4. Discussion

4.1. Characteristics of the prepared compost

Addition of elemental S to composted materials resulted in a decrease pH values of S-treated compost compared to the untreated type (CS0). This reductions may be attributed to presence of S in the composted materials which oxidized to produce H_2SO_4 and free H^+ ions. Addition of S, an acidic chemical, could effectively reduce the compost pH at a relatively lower cost (Nasser, 2007; Aiad, 2010). Addition of elemental S during the nutrition phase of the composting process was evaluated as suitable method to reduce pH of compost. Roig et al. (2004) reported that the pH values of the composting mixture decreased by one unit after 2 weeks after adding elemental S causing no negative effect on the final compost quality. Also, the increase in compost EC values with the addition of S, especially with higher S levels, might be due to the high degradation rates, release of mineral salts and formation of organic acids in composted materials mixed with elemental S (Roig et al., 2004). These findings are similar with those obtained by Abou Hussien et al. (2016).

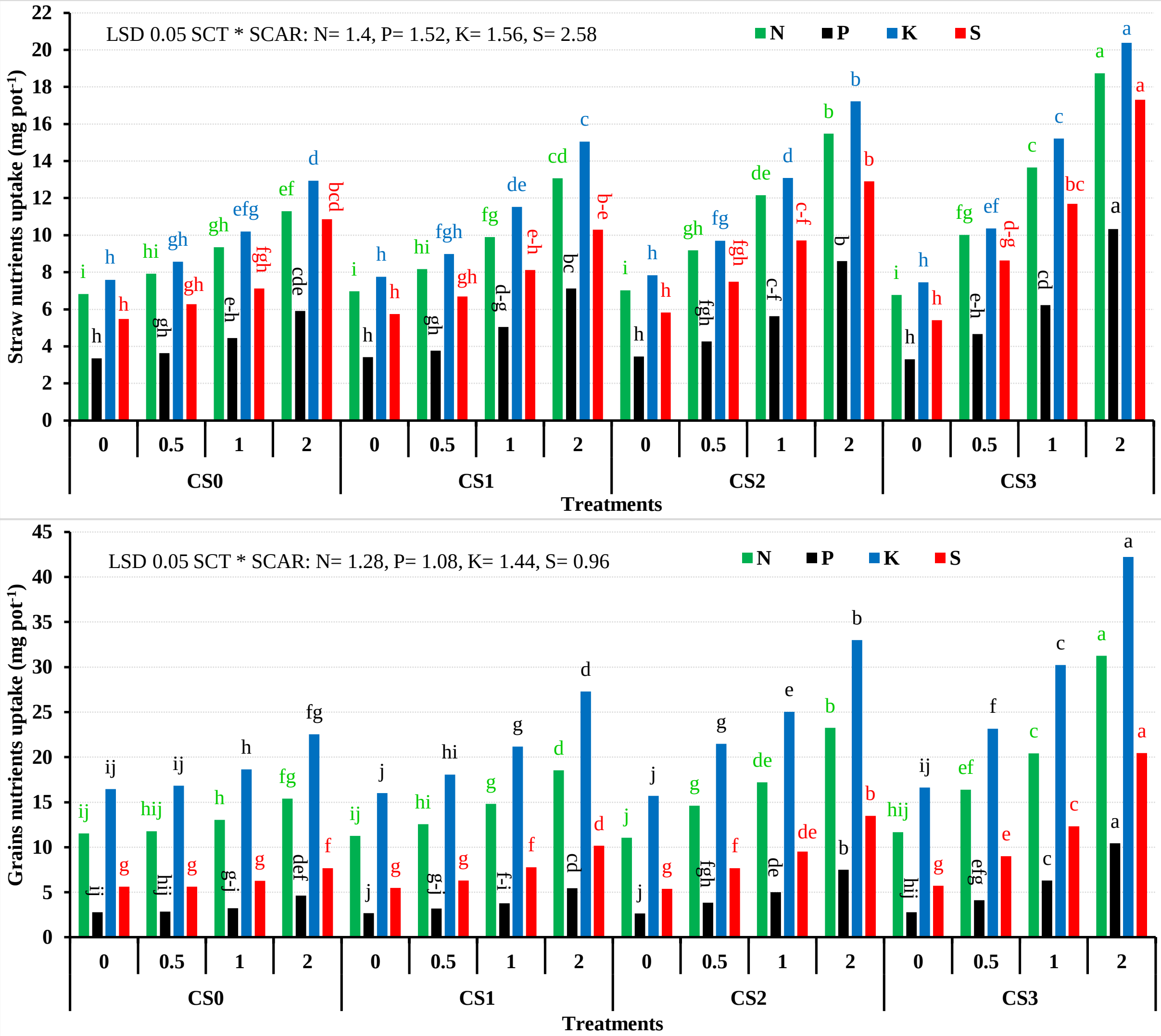

Fig. 5. Integrated effect of sulphur compost types and its application rates on the uptake of essential nutrients by the straw and grains of wheat grown in salt affected soil. SCT= Sulphur compost type, **SCAR=** Sulphur compost application rate**, CS0**= Compost produced without sulphur addition, **CS1, CS2 and CS3**= Compost produced from mixed compost raw materials with 1, 2 and 3% elemental sulphur, respectively, columns within the same attribute labelled with different letter are significantly different at 5 % level of probability.

Moreover, the reduction of OM and OC upon composting resulted from mineralization of composted organic materials and has been widely reported. Before that, Aiad (2010) and Belal (2011) found a decrease in the composted materials content of OM, where the rate of this decrease related mainly with the sources of the composted organic materials. Also, the decrease in the compost content of OM as a result of S additions could be due to high oxidation rate in the composted materials mixed with S. These findings are similar with these obtained before that by Elgezery (2016). The increases in the compost content of total N and reduction of C/N ratios, particularly after adding sulfur are well in agreement with the findings of Kenawy (2003), Aiad (2010), and Elgezery (2016). They showed that, the content of total N increased and more increases were found with the increase of S in the composting materials. Also, Gu et al. (2011), Elgezery (2016) and Abou Hussien et al. (2016) pointed out that, mixed elemental S with the composted organic materials resulted in an increase in the produced compost content of N especially that in NH_4 form due to reduced N loss. The C/N ratio of the composted organic materials tended to be narrow due to gaseous loss of carbon as CO_2 with the nitrogen remained higher bound in organic form (Nasser, 2007; Ali et al., 2008). The augments in the compost content of available N, P, K, and S may be attributed to decomposition of organic materials, urea addition and biological fixation by compost microorganisms. Taha (2007)) found a significant increase in the compost content of N, P, and K during composting process because of mineralization of organic matter. Also, Gu et al. (2011) found that, compost content of S increased in the composted materials at maturity stage. Elgezery (2016) mentioned that, the produced compost content of available macronutrients (N, P, K, Ca, Mg and S) and micronutrients (Fe, Zn, Mn and Cu) were augmented with the increase of added S and composting period.

4.2. Characteristics of saline soil affected by sulphur compost

4.2.1. Chemical properties

These reductions of soil pH after additions of compost might be related with the percent of S in compost, where these decreases were increased with the increase of added S. These reductions also could be attributed to the presence of organic acids which were produced from chemical and biological degradation of added compost and from free H^+ ions, which were mainly produced from organic acids hydrolysis and decomposition. As well as, the effect of increasing rate of applied compost on soil pH was associated by an increase of added S during composting, which converted through oxidation process to H_2SO_4. These results are similar with those obtained by Elgezery (2016) and Abou Hussien et al. (2017). El-Gamal (2015), Abou Hussien et al. (2017) and Nada et al. (2023) mentioned that application of elemental S and sulphur compost resulted in a decrease of soil pH, which resulted from S oxidation and produced H_2SO_4 as a final product of this reaction.

Decreasing soil EC, compost applications and their degradation resulted in more solublization of soil compounds which leached (downward) with irrigation water as well as its bioremediation by growing plants through water uptake. Before that, decrease in soil EC followed by compost and other organic manures was noted by El-Gamal (2015), Elgezery (2016) and Rabie (2019). Abou Hussien et al. (2021) found that, the decrease in soil EC resulted from compost applications related mainly with the chemical composition of added compost. Similar findings were obtained before that by Rabie (2019), Abou Hussien et al. (2020) and Nada et al. (2023).

The positive impact of additive compost on soil OM and CEC values depending on the chemical composition of added compost especially its content of OM and S. Elgezery (2016) mentioned that, increasing compost content of S was associated by more increase in the soil content of OM. The observed values of soil CEC are in harmony with the effect of the studied treatments on soil content of OM which have a high surface negative charge density (CEC) compared with that on soil mineral particles. Elgezery (2016) and Abou Hussien et al. (2017) pointed out that, added compost in sulphur form have a significant increase in soil CEC and its content of OM.

4.2.2. Soil exchangeable cations and ESP

Application of compost resulted in increasing soil exchangeable cations of Ca, Mg and K, while more reductions of soil exchangeable Na and ESP observed. Before that Sweed (2012) pointed out that, applications of organic acids materials resulted in solublization of carbonates compounds followed by an increase in both soluble and exchangeable Ca and Mg. This trend may be attributed to the high acidity (low pH) of sulphur compost compared to unsulphur compost which resulted in more release of Ca and Mg from soil compounds. El-Gamal (2015) suggested that, S applications to salt affected soils of Egypt resulted in a decrease of exchangeable Na as well as its ESP, but these applications resulted in an increase of exchangeable Ca, K and Mg. Recently, Abou Hussien et al. (2021) obtained similar effect of added composts in different forms on more increase of released Ca from calcareous soil manured by compost.

4.2.3. Soil available nutrients and sulphur forms

The increases of soil available nutrients (N, P, and K) and S forms resulted from the increase in the soil content of OM followed by compost application as mentioned before that by Rabie (2019) and Abou Hussien et al. (2021 and 2022). As well as, the arrangement of added compost types effect on the increase of saline soil content of available N, P and K is in harmony with the added compost content of these nutrients. These findings means that, the chemical composition of added compost had a remarkable effect on soil content of available macronutrients. These results are similar with those obtained before that by Abou Hussien et al. (2021) and Ghazi et al. (2021). This means that using compost enriched with sulphur is more preferable as a soil amendment than the non-sulphur enriched compost especially under saline soil conditions.

Sulphur is present in soil mainly in the form of organic compounds like ester sulphate and carbon bounded sulphur and also in organic form like sulphate and sulphite but is primary uptake the plants as sulphate (SO_4^{2-}) ions (Mengel et al., 2001). The significant increases in the soil content of S forms, which were mainly attributed to the concurrent increase in the proportion of S mixed with the added compost. These results are in similar with the results obtained before by Abou Hussien (1999) in clay soil with different S sources and Elgezery (2016) in the calcareous soil treated by sulphur compost. It is preferable to use compost in the form of sulphur than that prepared without sulphur, as the first form produced high and sufficient amounts of both soluble and available S (Abou Hussien et al., 2020).

4.3. Wheat yield and its content of nutrients

The addition of compost especially that produced from adding sulphur led to an increase in the wheat yields grown in saline soil and their contents of nutrients. These findings of increasing of wheat plant yield may be resulted from increase in the soil content of OM and available essential nutrients as well as the decrease in soil pH, EC and ESP as a result of increase in added rate of compost (Rabie, 2019; Abou Hussien et al., 2020; Nada et al., 2023). Moreover, these increases resulted from the improve effect of added compost (organic manure) on all saline soil conditions and growth media as mentioned before that by El Sanat (2003), El-Gamal (2015) and Ghazi et al. (2021). Elemental S mixed with the composted organic materials enhanced plant growth and its uptake of N, P, K and S (Abou Hussien, 1999; El Sanat, 2003; El-Gamal, 2015; Elgezery, 2016; Abou Hussien et al., 2020; Nada et al., 2023).

5. Conclusion

In compost experiment, the addition of elemental S during composting led to an improvement in the chemical properties (pH, EC, OM, OC, TN and C/N ratio) and the content of available nutrients (N, P, K, and S)) of the produced compost. In the planting experiment, the following results were summarized after treating soil with compost produced from the compost experiment: (1) Soil chemical properties, especially pH, EC, OM and CEC were improved, (2) Soil content of available nutrients (N, P, K, and S) also were increased, (3) Under the effect of compost, especially in sulphur form, the soil content of exchangeable Na decreased, while its content of exchangeable Ca, Mg and K increased, (4) Soil content of S forms were positively affected by the addition of compost especially sulphur compost, and (5) The soil productivity of wheat (straw, grains, and biological yield) increased after being treated with compost especially that treated with sulphur during composting. In conclusion, the addition of the elemental S led to the improvement of the properties of the produced compost, which by adding it to the salt affected soil led to the improvement of its chemical properties and its available nutrients, as this was positively reflected on its productivity of the wheat.

Conflicts of interest

There is no conflict of interest between the authors or any donor or funding agency.

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