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ORIGINAL PAPER

Effect of nano-zinc application combined with sulfur and compost on saline-sodic soil characteristics and faba bean productivity

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Abstract
Salinity considers a restricting agent for plant production in arid and semiarid regions of the world. A lysimeter experiment was carried out in the 2018–2019 growing season for faba bean in saline-sodic soil, to study the effects of different levels of nano-ZnO as a foliar application under the addition of sulfur (S) alone or combined with rice straw compost (C) on the chemical properties of the saline-sodic soil and faba bean (*Vicia faba* L.) productivity. The results indicated that the application of S alone or combined with C significantly increased removal sodium efficiency (RSE), exchangeable Ca, availability of nutrients (NPK), organic matter (OM), and faba bean yield as compared to control. A total yield of faba bean was increased by about 39.7% in the plots treated with the nano-ZnO foliar application at 2% as compared with the control. The decrease in soil ESP and EC under the S+C with nano-ZnO at 2 $g \cdot L^{-1}$ was 44.95% and 22.13% greater than the control treatment. The mixtures of S+C with nano-ZnO foliar application gave better results in increasing the plant height and total yield, especially the rate of 2% of nano-ZnO as compared to adding them individually. The experimental results concluded that the integration effect of nano-ZnO as a foliar application with organic fertilizer and sulfur as amendments to reclaim saline-sodic soil can be used as a promising strategy to improve its properties and increase the bean yield.

Keywords Saline-sodic soil · Foliar nano-ZnO · Compost · Sulfur requirement

Introduction

Salinity considers a limiting agent to crop production in arid and semiarid regions of the world. Munns and Tester (2008) reported that 800 × 10^6 million hectares of the world's land area is affected by salinity. In Egypt, more than 0.9 million hectares of arable land is affected by salts, and they represent about 24% of the total arable land (Ismail 2009, Mahmoud et al. 2019).

Salinity influences about 33% of the arable lands in the world (Artiola et al. 2019). In Egypt, the maximum parts of salt-affected soils are located around the Nile Delta in its northern central, eastern, and western sides counting about 0.9 million hectares of Egyptian irrigated lands (El-Sharkawy et al. 2017). Also, the main causes of soil salinity in the Nile Delta include sea water intrusion, use of traditional irrigation methods, impacts of climate change on water resources, rising water table levels, and reuse of wastewater for irrigation (Kheir et al. 2019b; Ding et al. 2020). Soil salinity and sodicity influences the structure of soils and its permeability and infiltration caused by Na-induced dispersal (Sparks, 2003; Day et al. 2019), increasing osmotic pressure, ion toxicity from excess accumulation of ions, and nutritional imbalance through disruption in the ion transport systems (Ellouzi et al. 2013). Therefore, it is necessary to look for management alternatives to improve the productivity of these soils (Fontalvo and Andrade 2018). In the saline and alkaline conditions, the availability of micronutrients like Zn, Fe, Cu, and Mo is decreased in the soil matrix due to their binding to the colloidal components of the soil; then, the plants show huge deficiency symptoms (Archangi et al. 2012).

Nanotechnology affects agricultural productivity by enhancing the efficiency of the inputs and reducing relevant losses (Shang et al. 2019). Nanomaterials propose an

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enormous specific surface area to fertilizers performance and are used as a magnificent carrier to introduce which called an intelligent delivery system of nutrients and increased plant protection. Nanofertilizers have been listed to encourage the capability of plants to absorb nutrients from the soil (Kahlel et al. 2020), therefore enhancing the plant growth and tolerance of plants to biotic and abiotic stresses and increasing the yield and plant biomass (Ekinci et al. 2014; EL-Henawy et al. 2018; Merghany et al. 2019). Application of nanofertilizers in the foliar system had been affirmed as appropriate for field use because it gradually feeds plants in a controlled status more than salt fertilizers (Kah et al. 2018), besides controlling the toxicity that may cause after soil amended with the same nutrients (Subramanian et al. 2015). Among nanoparticles, zinc oxide nanoparticles (nano-ZnO) are the most common metal nano-oxide used, as it listed as GRAS (Generally Recognized As Safe) by the USFDA (United States Food and Drug Administration) as mentioned by Tiwari (2017). The concentration of zinc in the soil solution is very low and is found in the form of different types of salts including ZnO zincite, sphalerite (ZnFe) S, smithsonite $ZnCO_3$, and ZnS; however, the uptake of this element by plants is affected by the $CaCO_3$ concentration and soil pH, which affects its availability for the plants (Mengel and Kirkby 1987). Prasad et al. (2012) reported that nano-scale zinc oxide increased stem and root growth and pod yield of peanut as compared with $ZnSO_4$ application. García-López et al. (2019) concluded the effect of nano-ZnO on the plant is due to changes in physical, chemical, and biological properties of the nanomaterials as well as their catalytic characteristics.

Fertilizers with an acid effect added to alkaline soils are important for enhancing plant productivity and improving their properties (Karimizarchi et al. 2014). Elemental sulfur (S), which is considered as an accepted and costless amendment for saline-sodic soils, as with the relief of soil microbes, will oxidize in the humidity of soil to form sulfuric acid, which will dissolve $CaCO_3$, resulting in available Ca^{2+} to replace the sodium on the soil exchangeable sites (Horneck et al. 2007; Tarek et al. 2013). Besides, it can mobilize nutrients from unavailable states to available pools, therefore increasing P and micronutrient availability (Ahmed et al. 2016). As well, sulfur is an essential nutrient for plant growth with various functions in both plants and soil like the creation of peptides, which contain cysteines like glutathione, vitamins (B, thiamine, and biotin), and chlorophyll, frustrate the uptake of unnecessary elements in saline-sodic conditions (Na^+ and Cl^-), and increase the selectivity of K/Na and discharge calcium ions to reduce the deleterious effect of sodium ions in plants (Zaman et al. 2002; Kacar and Katkat, 2007; Abdallah et al. 2010). Habtemichial et al. (2007) explored that application of S to soil has a potential effect in increasing the amount of N_2 fixed by the faba bean plants, thus improving the fertility status of the soil.

In addition to sulfur, the application of compost derived from plant residues and animal manure is another source of soil conditioner that has been used vastly to mitigate salinity in soil (Nayak et al. 2013, Cao et al. 2019), while organic acids formed during microbial respiration can solubilize $CaCO_3$ to facilitate Na displacement (Ahmad et al. 2013). Oo et al. (2013) reported that compost enhances soil water holding capacity and the infiltration rate of saline-sodic soils, as well as increases soil nutrient and organic matter contents. As for plants, the application of compost increased growth yield, yield components, and total crude protein of faba bean (Abdel-Monaim et al. 2017; Gad et al. 2017). It has been reported that the combination between sulfur and organic amendments could improve soil characteristics like salinity, organic carbon, and available NPK (Bharose et al. 2014; Sönmez et al. 2016; Fontalvo and Andrade 2018). Also, it increases faba bean pods, seed yields, and N, P, K, and Zn content in seeds (El-Galad et al. 2013).

Faba beans (*Vicia faba*) considers the first legume crop in the arable area of Egypt and a major source of protein (18%), carbohydrates (58%), vitamins, and other minerals as well as its impact on soil fertility (Mohsen et al. 2013; Hegab et al. 2014). A novel record released in 2019 by the Egyptian Central Agency for Public Mobilization and Statistics (CAPMAS) manifested that Egypt's cultivated area and production of faba beans had significantly decreased over the last 10 years. The beans productivity during 2016 was around 142 thousand tons, compared to about 413 thousand tons in 2005 (Zikrallah 2019). Faba bean tends to be exposed to various biotic and abiotic stresses, leading to yield instability which affects its planting decision (Abdalla and Darwish 2002). However, the integration effect of nano-ZnO as a foliar application with compost and sulfur as an amendment to reclaim saline-sodic soils was little addressed.

Therefore, this work aimed to study the integration effect of nano-ZnO as a foliar application with compost and sulfur as an amendment to reclaim saline-sodic soils and its reflection on faba bean plants' productivity.

Materials and methods

Lysimeter experiment was conducted during the winter season of 2018/2019 in Sakha Agric. Res. Station Farm, North Delta, Kafr El-Sheikh Governorate, Egypt, to clarify the role of foliar application with nano-zinc (N-ZnO), sulfur (S), compost (C), and its combinations on soil properties and faba bean (*Vicia faba* L.) variety (*Sakha 1*) productivity under saline-sodic soil conditions. The site lactated at 31°05'38" N latitude and 30°56′ 54″ E longitude with an elevation of about 6 m above sea level.

The experiments were conducted in split block design with three replications, the main plots were assigned as a foliar application of N-ZnO with three levels (0, 1, and 2 g·L^{-1}), and subplots were devoted to soil amendments as the following treatments: control (CK) without any additions and sulfur requirements (S) from commercial sulfur source, rice straw compost (C), and sulfur 50% + compost 50% (SC). Lysimeter (0.78 m2) was divided into 3 groups; each group includes 12 lysimeters.

Compost was added with the rate of 9.5 Mg·ha^{-1} as recommended by Sarwar et al. (2011). Sulfur requirements (purity 99%) were determined according to Lebron et al. (2002). These amounts are sufficient to reduce the initial ESP to 10% for the soil matrix in the surface layer according to the following equation:

$$SR = 0.00016\ x\ Ds\ x\ Pb\ (CEC)\ (ESPi–ESPf)/100\Big) \quad (1)$$

where SR is the amount of sulfur needed (kg m−2), Ds the depth of the soil to be reclaimed (30 cm in this study), ρb the soil bulk density (kg m^{-3}), ESPi the initial ESP value, ESP_f the final (target) ESP value, and CEC the soil cation exchange capacity (cmolc kg $soil^{-1}$).

Sulfur (0.153 kg $plot^{-1}$) and compost were thoroughly mixed with the surface soil layer (0–30cm) before cultivation, where the foliar applications of zinc treatments were applied in two doses: The first dose was after 45 days and the second after 60 days of sowing. The chemical composition of compost was given in Table 1.

Faba bean (*Vicia faba* L.) seeds variety (*Sakha 1*) was sown at the rate of 95 kg·ha^{-1} on November 21, 2018, and harvested after full maturity (April 9, 2019). Nitrogen fertilizer as urea (46% N) was applied at the rate of 142 kg N ha^{-1} in two doses; the first was following life watering irrigation, and the second dose was done with second irrigation. Phosphorus has applied field preparation as a super-monophosphate (18 %P_2O_5) with a rate of 71 kg P_2O_5 ha^{-1}; also 120-kg potassium sulfate ha^{-1} (48% K_2O) was applied twice with the first irrigation and at the flowering stage. Other agricultural practices were performed according to the Ministry of Agriculture recommendation for faba bean plants in the North Delta area. The irrigation water is applied to keep the moisture content up to 75% of field capacity.

Nano-ZnO synthesis and characterization

Zinc oxide nanoparticles were prepared using the zinc acetate precursor method via sol-gel technique according to Mohan and Renjanadevi (2016). In brief, zinc acetate (1M) and sodium hydroxide (2M) solutions were prepared separately. After complete dissolution, sodium hydroxide solution was added dropwise to zinc acetate solution with stirring for 18h, while precipitation was formed, which was filtered and dried in the oven (90°C/2h) and then calcined after grinding in the muffle at 400°C.

The structural phase of nano-ZnO was characterized by an X-ray diffractometer, while the size and particle morphology were visualized via transmission electron microscope (TEM) image technique.

Soil analysis

Surface soil samples (0–30 cm) were collected from the lysimeter experiment. The obtained soil samples were air-dried, crushed, and passed through a 2-mm sieve. The soil was analyzed for some physical and chemical properties according to the standard methods outlined by Page et al. (1982) and Klute (1986). Exchangeable calcium after harvesting is determined according to a method of Tobia and Milad (1956). The soil characteristics of the soil used for the experiment are shown in Table 2.

Sodium adsorption ratio (SAR) was calculated by the following equation according to Richards (1954), where the concentrations of cations are expressed in mmol as follows:

$$\mathrm{SAR} = Na/\sqrt{}((Ca + Mg)/2) \quad (2)$$

while exchangeable sodium percentage (ESP) was calculated according to the equation of Rashidi and Seilsepour (2008):

$$ESP = 1.95 + 1.03\ \mathrm{SAR} \quad (3)$$

Removal sodium efficiency (RSE) in percentage from soils at the end of the experiment was calculated as follows (Amer 2017):

$$RSE = (ESPi–ESP\ f)/ESPi \times 100 \quad (4)$$

Table 1 Some physicochemical properties of the rice straw compost

pH	EC dS m^{-1}	Total macronutrients (%)			Moisture content (%)	B.D (g cm^{-3})	O.M (%)	Total-C (%)	C/N ratio
		N	P	K					
7.58	4.02	2.40	1.10	1.30	16.70	0.57	26.89	15.60	11.14

B.D bulk density, *Total-C* total organic carbon

Table 2 Physical and chemical properties of the soil before cultivation

Chemical characteristics	Unit	Value	Physical characteristics	Unit	Value
EC_e	dS m^{-1}	7.48	Particle size distribution		
pH (soil suspension 1:2.5)		8.43	Clay	%	58.23
Soluble ions			Silt	%	29.71
Na^+	mmol·L^{-1}	39.22	Sand	%	14.03
K^+	mmol·L^{-1}	0.43	Texture class	Clayey	
Ca^{+2}	mmol·L^{-1}	10.01	Soil type	Saline-sodic	
Mg^{+2}	mmol·L^{-1}	4.43	O.M[a]	%	1.13
Cl^-	mmol·L^{-1}	30.20	$CaCO_3$[b]	%	2.43
HCO_3^-	mmol·L^{-1}	3.50	CEC[c]	$cmol_c$ kg^{-1}	37.44
SO_4^{-2}	mmol·L^{-1}	20.39	Bulk density	g cm^{-3}	1.26
SAR	%	16.23	Field capacity	%	38.96
			Wilting point	%	21.17
			Available macronutrients		
ESP	%	18.67	N	mg·kg^{-1}	19.33
			P	mg·kg^{-1}	6.29
			K	mg·kg^{-1}	248.96

O.M[a] soil organic matter was analyzed as described by Walkley and Black (1934), *CaCO3*[b] calcium carbonate determined using Bernard calcimetry method, *CEC*[c] cation exchange capacity determined by Bower et al. (1952) method

where ESPi is the initial ESP and ESP_f is the final ESP at the end of the experiment.

Plant sampling and analysis

Plant samples were randomly chosen from each lysimeter at the harvesting stage to determine the vegetative growth parameters. Plant biomass parameters were measured as total yield (Mg ha^{-1}) and seed yield (Mg ha^{-1}).

Seed samples of each treatment were oven-dried at 70°C to become a constant weight, ground, mixed, and wet digested with (H_2SO_4+H_2O_2) as described by Peterburgski (1968). Total N and P contents in seeds were determined according to the method described by Page (1982), while K content was determined using a flame photometer (Cottenie et al. 1982). Zinc content was determined using atomic absorption spectrophotometer as described by Chapman and Pratt (1961).

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using PROC GLM of SAS 9.4 (SAS Institute Inc., Cary, NC). Replications were considered random and all other variables were considered fixed effects. Means of all variables were separated using Fisher's protected LSD test at a probability of 5% according to Snedecor and Cochran (1980).

Results

Characterization of prepared nano-ZnO

XRD and TEM image

Figure 1 showed the crystallite size and purity of synthesized nano-ZnO. The peaks demonstrated that the prepared N-ZnO lied in the nano range.

Peaks with the diffraction angle (2θ) of 31°, 34°, 36°, 47°, 56°, 62°, and 68° match the reflection form [100], [002], [101], [102], [110], [103], and [112] crystal plans when compared with quartzite structure corresponding to JCPDS cards (Morkoc and Ozgur 2009). The average particle size was found to be 35 nm of the hexagonal quartzite structure (Yang et al. 2004). Figure 2 indicted the TEM image of synthesized nano-ZnO and confirmed that nano-ZnO could be a rod-like shape but are not exactly circular and their average size is about 40–50 nm. Moezzi et al. (2012) illustrated that the rod structure considers the best nanostructure as compared to other one-dimensional nanostructures.

Soil properties

Results in Table 3 illustrated that foliar application of nano-ZnO with/without application of sulfur, compost, and its combinations had positive effects on soil salinity (ECe), soil sodicity (ESP and RSE), and exchange Ca comparing to the untreated plots.

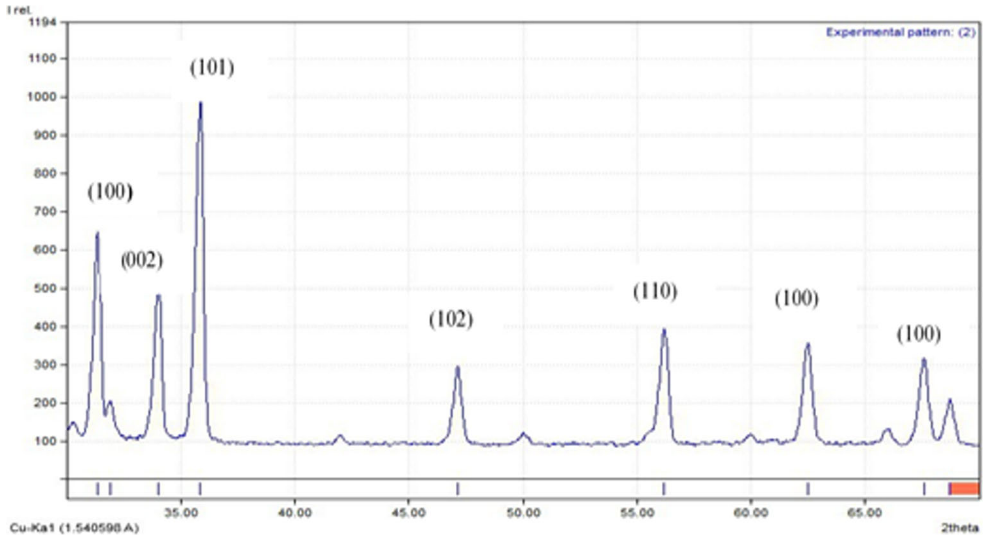

Fig. 1 X-ray diffraction pattern of nano-ZnO powder

Soil salinity

Data in Table 3 showed that soil applications (compost and/or sulfur) had a significant effect (p>0.01) on soil salinity. It is noticed that foliar application of nano-ZnO has no effects on soil salinity with the rate of 1 $g{\cdot}L^{-1}$ in comparison to control. Table 3 and Fig. 3 demonstrate that the combination of sulfur with compost (S+C) recorded the lowest ECe and the highest changes of salinity compared to individual application of sulfur or compost, while more efficiency recorded with foliar application of nano-ZnO at the rate of 2 $g{\cdot}L^{-1}$ with the value of 5.49 $dS{\cdot}m^{-1}$.

Increasing the density and reactivity of the specific surfaces of nanoparticles led to enhanced plant physiology and performance, thus increasing its ability to mitigate salinity (Hussein and Abou-Baker 2018).

Soil alkalinity (ESP, RSE %, and exchangeable Ca)

The results related to soil ESP, RSE, and exchangeable calcium are given in Table 3 and Fig. 4. Analysis of variance data in Table 4 illustrated that both foliar nano-ZnO and soil amendments (S and C) affected significantly ($p < 0.001$) and its combination ($p < 0.01$) in soil sodicity resulting in reducing soil ESP and RSE. The ESP decreased from 18.33 in the check plots to 17.99 or 17.89 in plots supplemented by the foliar application of nano-ZnO at the rate of 1 or 2 $g{\cdot}L^{-1}$, respectively. Adding sulfur and/or compost resulted in decreasing ESP, while the combination (S+C) recorded the lowest ESP in all traits. Increasing the concentration of nano-ZnO led to decrease in the ESP and the lowest value recorded with S+C treatment with the value of 10.09 %. As for RSE, the magnitude of RSE takes the same direction as for ESP.

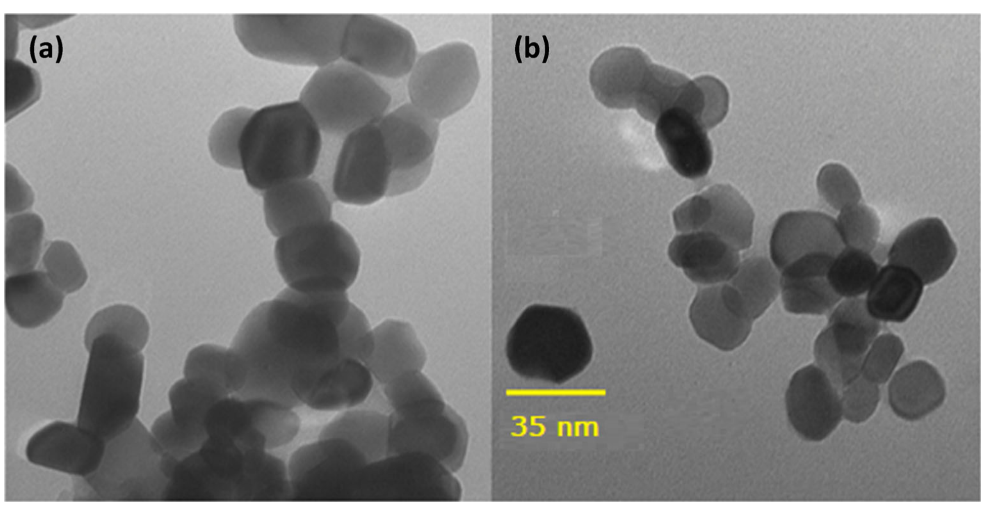

Fig. 2 The TEM images of nano-ZnO. **a** Displays the diffusion and structural characteristics of N-ZnO particles and **b** shows that laboratory prepared N-ZnO particles are not exactly circular with size ranged from 30 to 35nm

Table 3 Effect of soil application of sulfur, compost, and foliar application of nano-ZnO and its combinations on soil salinity and sodicity after harvesting

Nano-ZnO foliar app.	Soil amendment	ECe ($dS\cdot m^{-1}$)	ESP (%)	RSE (%)	Exch. Ca ($cmol\cdot kg^{-1}$)
0	Control (CK)	7.05 ± 0.02	18.33 ± 0.03	1.82 ± 0.16	6.46 ± 0.01
	Sulfur (S)	6.57 ± 0.02	12.50 ± 0.30	33.05 ± 1.61	11.72 ± 0.03
	Compost (C)	6.89 ± 0.01	11.06 ± 0.02	40.76 ± 0.11	8.02 ± 0.02
	S+C	5.51 ± 0.01	10.94 ± 0.01	41.40 ± 0.05	13.74 ± 0.04
1 g/l	Control (CK)	6.94 ± 0.04	17.99 ± 0.01	3.64 ± 0.05	6.66 ± 0.02
	Sulfur (S)	6.54 ± 0.02	12.43 ± 0.03	33.42 ± 0.16	11.75 ± 0.03
	Compost (C)	6.87 ± 0.02	11.02 ± 0.02	40.97 ± 0.11	8.04 ± 0.01
	S+C	5.51 ± 0.02	10.91 ± 0.04	41.56 ± 0.21	13.86 ± 0.01
2 g/l	Control (CK)	6.85 ± 0.04	17.89 ± 0.01	4.18 ± 0.05	6.42 ± 0.02
	Sulfur (S)	6.52 ± 0.02	12.39 ± 0.01	33.64 ± 0.05	11.80 ± 0.10
	Compost (C)	6.87 ± 0.02	11.02 ± 0.02	40.97 ± 0.11	8.06 ± 0.03
	S+C	5.49 ± 0.01	10.09 ± 0.03	45.95 ± 0.16	13.98 ± 0.02
Source of variation	Degrees of freedom				
Foliar nano-ZnO	2	0.079	0.101**	2.907**	0.030**
Soil amendments	3	0.606**	1009.08**	2155.518**	101.930**
Foliar nano-ZnO and soil amendments	6	0.030	0.027*	0.766*	0.023**
LSD (0.05)		0.139	0.073	2.391	0.033

*Significant at P < 0.05. **Significant at P < 0.01

ANOVA analysis in Table 3 showed the significant effects ($p< 0.05$) of foliar application with nano-ZnO and soil amendments and significant effects ($p< 0.01$) with its combination. Foliar application with nano-ZnO at the rates of 1 and 2 $g\cdot L^{-1}$ resulted in increasing the RSE to reach 3.64 and 4.18 %, respectively, in comparison to control. The combination between compost and sulfur resulted in the enhancement of RSE to reach 45.95% with treatment sprayed with 2-$g\cdot L^{-1}$ nano-ZnO. Table 3 showed that foliar application of nano-ZnO increases the exch. Ca with an increment of its concentration to reach 6.66 $Cmol\cdot kg^{-1}$ with 2-$g\cdot L^{-1}$ nano-ZnO compared to 6.42 $Cmol\cdot kg^{-1}$ in the control treatment.

Sulfur supplements resulted in an accretion of calcium in soil to vary from 82.5% over the check plot treatment to reach 82.5% and 77.2% with 1- and 2-$g\cdot L^{-1}$ nano-ZnO treatments, respectively.

Soil fertility

The data representing soil organic matter (%) and available N, P, and K as affected by the soil application of sulfur, compost, and foliar application of nano-Zn and its combination after faba bean harvest are shown in Table 4.

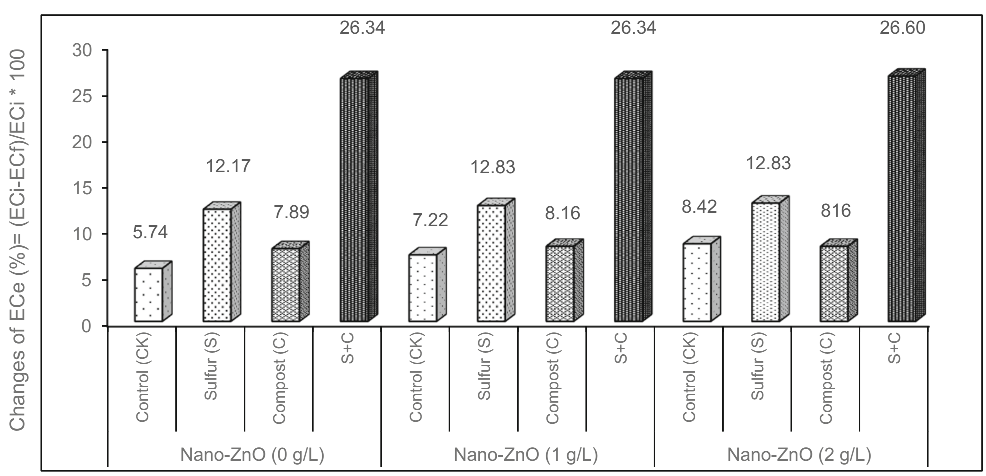

Fig. 3 Changes of electrical conductivity (ECe) as affected by sulfur (S), compost (C), and its combination under different nano-ZnO foliar concentrations after faba bean harvesting

Table 4 Effect of soil application of sulfur, compost, and foliar application of nano-ZnO and its combination on soil organic matter (%) and available N, P, and K

Nano-Zn foliar app.	Soil amendments	O.M (%)	N (mg·kg^{-1})	P	K
0	Control	1.13 ± 0.03	20.45 ± 0.01	6.37 ± 0.02	270.32 ± 0.02
	Sulfur (S)	1.19 ± 0.02	23.12 ± 0.04	6.95 ± 0.02	295.12 ± 0.02
	Compost (C)	1.36 ± 0.02	25.31 ± 0.01	7.94 ± 0.02	337.28 ± 0.07
	S+C	1.39 ± 0.01	26.05 ± 0.03	8.12 ± 0.02	344.72 ± 0.02
1 g/l	Control	1.09 ± 0.01	20.58 ± 0.02	6.37 ± 0.02	270.32 ± 0.02
	Sulfur (S)	1.19 ± 0.01	23.17 ± 0.02	6.95 ± 0.01	295.12 ± 0.02
	Compost (C)	1.36 ± 0.01	25.31 ± 0.01	7.94 ± 0.01	337.28 ± 0.01
	S+C	1.39 ± 0.01	26.11 ± 0.02	8.12 ± 0.02	344.72 ± 0.03
2 g/l	Control	1.09 ± 0.04	20.48 ± 0.03	6.60 ± 0.10	280.24 ± 0.04
	Sulfur (S)	1.20 ± 0.05	23.28 ± 0.02	7.01 ± 0.01	297.60 ± 0.10
	Compost (C)	1.36 ± 0.01	25.36 ± 0.03	7.94 ± 0.03	337.28 ± 0.03
	S+C	1.39 ± 0.01	26.23 ± 0.01	8.12 ± 0.03	344.72 ± 0.02
Source of variation	Degrees of freedom				
Foliar nano-ZnO	2	0.0003	0.033**	0.024**	419.450
Soil amendments	3	0.167**	56.997**	5.732**	11717.495**
Foliar nano-ZnO and soil amendments	6	0.0005	0.009**	0.011**	292.96
LSD (0.05)		0.021	0.020	0.031	14.116

*Significant at P < 0.05. **Significant at P < 0.01

All treatments received compost alone or in combination with sulfur increased soil organic matter recording 1.39% with S+C treatment in all traits.

Concerning to available N, P, and K in the soil, data in Table 4 illustrated that foliar nano-ZnO and/or soil amendments with sulfur and/or compost significantly affected (p>0.01) soil available N and P, while soil amendments only affected soil (p>0.01) soil available (K). Treatment (S+C) recorded the highest values in available N, P, and K in soil with average values of 26.23, 8.12, and 344.72, respectively, compared to control treatment. These results are in agreement with Skwierawska et al. (1997).

Faba bean yield and its biomass

The statistical analysis of the data presented in Table 5 indicated that foliar nano-ZnO incorporated with soil application of sulfur, compost, and its combinations affected significantly (p>0.01) on faba bean biomass. Foliar application of nano-ZnO positively affected the plant height (Fig. 5), and the

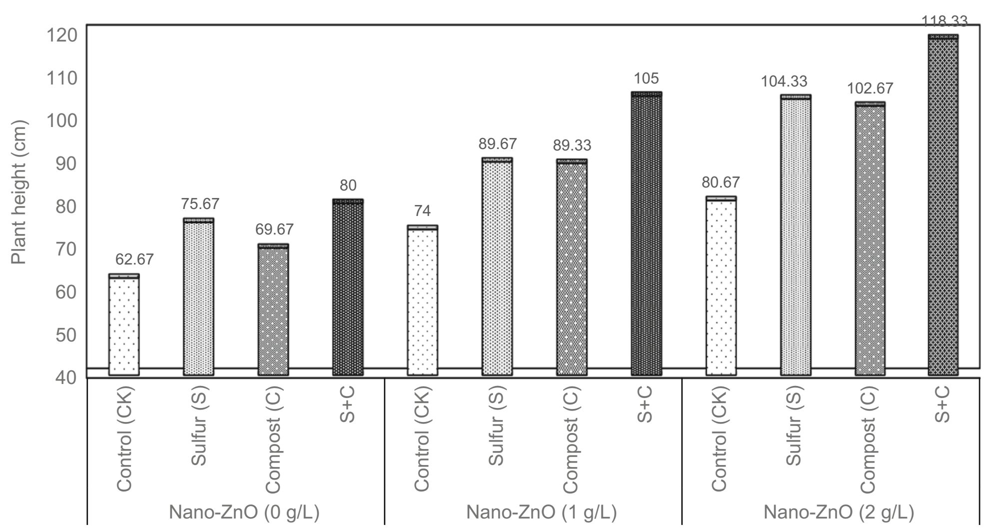

Fig. 4 Effect of sulfur (S), compost (C), and its combination under different nano-ZnO foliar concentrations on plant height (cm) after faba bean harvesting

tendency impacted with increasing nano-ZnO concentration recording 18.07% and 28.72% with 1- and 2-g·L^{-1} nano-ZnO, respectively, in comparison to check plots. Concerning soil amendments, the sulfur application performed a significant difference (p>0.01) in faba bean plant height recording about 20% over the control treatment, while the integration with nano-ZnO increased the plant height to reach 89.67 and 104.33 cm with 1- and 2-g·L^{-1} nano-ZnO, respectively. However, the mixture of S+C with the magnitude of increasing nano-ZnO was superior in increasing plant height recording 118.32 cm.

Data in Table 5 showed that the magnitude of the enhancement of plant biomass was observed with treatments received rice straw compost in combination with sulfur. The orientation of promoting faba bean productivity was elucidating with increasing foliar nano-ZnO concentrations. The S+C treatment that received foliar nano-ZnO at the rate of 2 g·L^{-1} recorded the highest plant biomass via total yield (8.46 Mg ha^{-1}), 100 seeds weight (65.74 g), and seed yield (6.15 M g^{-1}).

Chemical components of faba bean seeds

Data in Table 6 clearly indicated that foliar nano-ZnO with/without soil additives significantly (p>0.01) affected faba bean seed components. With regard to nano-ZnO, the magnitude of increasing N, P, K, and Zn in seeds takes the trend of increasing nano-ZnO concentration recording percentage of 103, 120, 112, and 90 % of N, P, K, and Zn, respectively, over the control treatment. Concerning to soil amendments, the addition of sulfur seems to have a potential impact in inducing faba bean seed components. However, the combination of S+C and foliar nano-ZnO had superior effects in boosting N, P, K, and Zn content in seeds of faba bean plants with average values of 2.17%, 0.59%, 1.25, and 26.30 mg kg^{-1}, respectively.

Discussion

Soil characteristics

Soil salinity and sodicity

Application of sulfur in recommended dose led to decrease soil ECe recording 6.54 and 6.52 dS·m^{-1} with the application of nano-ZnO (1 and 2 g·g·L^{-1}, respectively) compared to untreated nano-ZnO treatment which recorded 6.57 dS·m−1. These results are in agreement with those reported by Tarek et al. (2013) and Ahmed et al. (2016). It has been reported that inorganic conditioners application combined with organic materials decrease electrical conductivity (Bayoumy et al. 2019). As for soil alkalinity, results from Table 3 and Fig. 4 demonstrated that foliar application of nano-ZnO could alleviate soil sodicity with average (1.85 and 2.4 %) at a rate of 1 or 2 g·L^{-1}, respectively. It could be explained as the result of improvement of the plant root system as reported by Hassanpouraghdam et al. (2019). The combination of sulfur and compost with increasing nano-ZnO levels causes the

Table 5 Effect of foliar nano-ZnO incorporated with soil application of sulfur, compost, and its combination on faba bean biomass

Nano-Zn foliar app.	Soil amendment	Plant height (cm)	100 seeds weight (g)	Total yield# (Mg ha^{-1})	Seed yield (Mg ha^{-1})
0	Control (CK)	62.67 ± 3.06	27.25 ± 1.34	3.42 ± 0.27	2.03 ± 0.13
	Sulfur (S)	75.67 ± 4.51	33.91 ± 1.04	4.72 ± 0.21	2.82 ± 0.06
	Compost (C)	69.67 ± 1.53	32.82 ± 1.84	4.51 ± 0.36	2.69 ± 0.23
	S+C	80.00 ± 5.29	41.80 ± 3.25	4.50 ± 0.64	3.80 ± 0.52
1 g/l	Control (CK)	74.00 ± 4.00	37.92 ± 1.42	4.31 ± 0.32	3.40 ± 026
	Sulfur (S)	89.67 ± 5.13	48.67 ± 2.30	7.17 ± 0.34	4.38 ± 0.27
	Compost (C)	89.33 ± 4.16	45.92 ± 5.16	6.07 ± 0.20	4.61 ± 0.11
	S+C	105.00 ± 3.61	55.39 ± 1.01	7.15 ± 0.36	4.59 ± 0.36
2 g/l	Control (CK)	80.67 ± 2.52	46.46 ± 1.07	4.78 ± 0.15	4.23 ± 0.11
	Sulfur (S)	104.33 ± 4.51	57.00 ± 2.50	7.97 ± 0.10	6.03 ± 0.40
	Compost (C)	102.67 ± 5.69	53.80 ± 2.69	7.07 ± 0.33	6.15 ± 0.32
	S+C	118.33 ± 2.52	65.74 ± 1.40	8.46 ± 0.12	5.62 ± 0.20
Source of variation	Degrees of freedom				
Foliar nano-ZnO	2	2641.00**	1444.49**	21.976**	21.419**
Soil amendments	3	1252.81**	447.398**	13.339**	3.93**
Foliar nano-ZnO and soil amendments	6	62.26**	4.336	0.74**	3.001**
LSD (0.05)		3.124	1.990	0.274	0.245

Total yield = seed yield + straw yield, *Significant at P < 0.05. **Significant at P < 0.01

enhancement of soil sodicity, and reduction of ESP, RSE, and exch. Ca levels could be a result of improvement of soil porosity or may be a cause of decreasing Na+ or an increase of Ca+2 (Kim et al. 2017). It has been reported that the combination of organic and inorganic amendments to sodic soil resulted in reducing SAR and therefore ESP of soil (Sarwar et al. 2011; Abdel-Fattah et al. 2015; Sundhari et al. 2018; Khan et al. 2019). Amer (2017) demonstrated that the combination between organic and inorganic amendments resulted in boost of the RSE by 71.59%, while the combination of foliar application with plant growth regulators with organic and inorganic amendments raised the RSE to vary from 0.13 to 0.57%. Mahdy (2011) also reported that RSE was affected by the combination of NPK and compost combination in two different soils to reach at the end of the experiment 76 % in both soils. This could be explained as a result of reduction of soil bulk density and increasing of soil porosity (Scheuerell and Mahaffee 2004; Nasef et al. 2009) with the addition of sulfur leading to an increase of the percentage of removal sodium. Simultaneously, regarding the exchangeable calcium, Fig. 5 showed that foliar application of nano-ZnO increases the exch. Ca with an increment of its concentration to reach 6.66 Cmol·kg^{-1} with 2-g·L^{-1} nano-ZnO compared to 6.42 Cmol·kg^{-1} in the control treatment. In this concern, the growth of the root zone may attribute in the increase of calcium transportation in soil and the stabilization of aggregates and ditto exchangeable calcium with sodium ions on colloids (Suriadi 2001; Gill et al., 2009).

Soil amendments tended to increase exch. Ca significantly (p>0.01) to record up to 25% compared to control in all traits. These results are in good agreement with those reported by Kheir et al. (2019a) who showed the good impact in a correlation between nanoparticles incorporated with plant residues on soil properties like soil compaction, bulk density, hydraulic conductivity, soil salinity, and soil nutrient contents which induced calcium content in the soil. Ghafoor et al. (2008) demonstrated that the addition of organic-like materials to soil increases CO_2 in soil and liberates hydrogen from hydrocarbonic acid. The released H^+ dissolves $CaCO_3$ and releases more calcium for sodium exchange. With regard to the combination of sulfur + compost +foliar, application of nano-ZnO at the rate of 2 g·L^{-1} achieved the highest exch. Ca value (13.98 cmol kg^{-1}). Jaggi et al. (2005) reported that sulfur in soil exposed to oxidation converted to SO4, and when further oxidation happens, it is converted to H_2SO_4 and finally to $CaSO_4$ (Abd El-Hady and Shaaban 2010), which dissolves more Ca in soil solution and increases the exchangeable calcium (Abdelhamid et al. 2013, Ding et al. 2021).

Soil fertility

Soil organic matter (OM) did not affect by Nano-ZnO application as zinc plays a role in proteins and carbohydrate metabolism in plants and applied in sole addition has no vital relationship with organic matter content in the soil (Shaban et al. 2019). In the presence of faba bean plants with compost additions, the increase of soil organic matter after harvesting takes two ways to explain; the direct way includes the growth of different microbes in these byproducts, and the other way is indirect from its effect on plant growth and root zone coverages (Tejada and Gonzalez 2004).

Faba bean biomass

Foliar application of nano-ZnO seems to affect positively on plant biomass parameters (plant height, 100 seeds weight, total yield, and seed yield). These results are in agreement with Adhikari et al. (2015) and Mohasedat et al. (2018). Sturikova et al. (2018) demonstrated that foliar nutrition has more of a marginal effect on the plants and manifested that

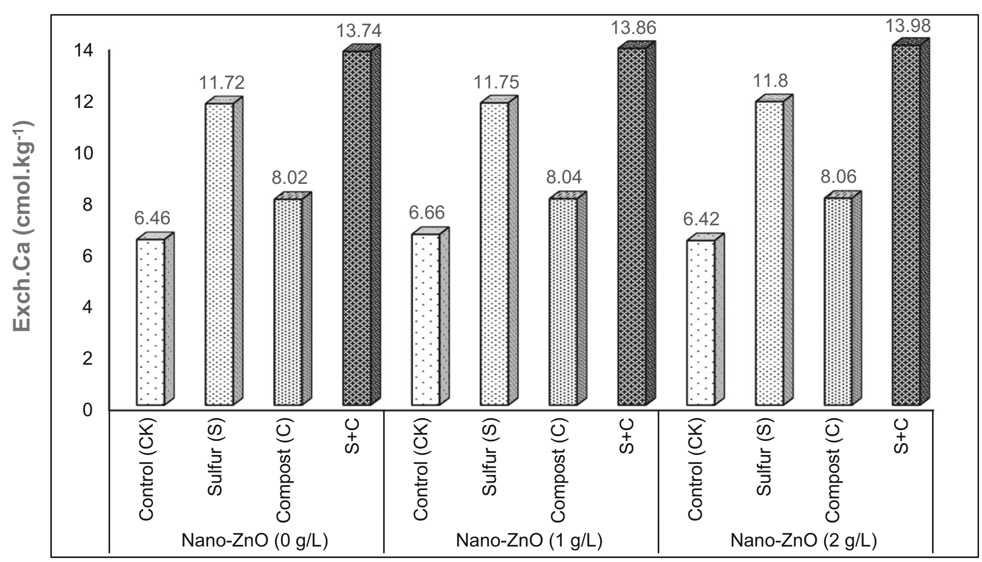

Fig. 5 Effect of sulfur (S), compost (C), and its combination under different nano-ZnO foliar concentrations on soil exchangeable calcium (cmol·kg −1) after faba bean harvesting

Table 6 Effect of foliar nano-ZnO incorporated with soil application of sulfur, compost, and its combination on faba bean seed component

Nano-Zn foliar app.	Soil amendment	N %	P	K	Zn mg kg^{-1}
0	Control (CK)	0.59 ± 0.03	0.15 ± 0.02	0.33 ± 0.03	7.70 ± 1.01
	Sulfur (S)	0.79 ± 0.03	0.21 ± 0.01	0.45 ± 0.02	9.56 ± 0.41
	Compost (C)	0.75 ± 0.06	0.21 ± 0.02	0.43 ± 0.04	9.13 ± 0.74
	S+C	1.05 ± 0.11	0.30 ± 0.03	0.60 ± 0.07	12.72 ± 1.30
1 g/l	Control (CK)	0.97 ± 0.07	0.26 ± 0.02	0.55 ± 0.04	11.70 ± 0.87
	Sulfur (S)	1.61 ± 0.07	0.44 ± 0.02	0.92 ± 0.04	19.47 ± 0.92
	Compost (C)	1.55 ± 0.20	0.42 ± 0.06	0.89 ± 0.11	18.77 ± 2.43
	S+C	1.83 ± 0.03	0.50 ± 0.01	1.05 ± 0.02	22.15 ± 0.41
2 g/l	Control (CK)	1.21 ± 0.04	0.33 ± 0.01	0.70 ± 0.02	14.62 ± 0.45
	Sulfur (S)	2.11 ± 0.09	0.57 ± 0.03	1.21 ± 0.05	25.52 ± 1.08
	Compost (C)	2.02 ± 0.20	0.55 ± 0.06	1.16 ± 0.11	24.40 ± 2.38
	S+C	2.17 ± 0.05	0.59 ± 0.02	1.25 ± 0.03	26.30 ± 0.56
Source of variation	Degrees of freedom				
Foliar nano-ZnO	2	3.591**	0.268**	1.201**	514.158**
Soil amendments	3	0.959**	0.075**	0.323**	134.99**
Foliar nano-ZnO and soil amendments	6	0.081**	0.006**	0.025**	13.569**
LSD (0.05)		0.0797	0.0221	0.0453	1.0292

*Significant at P < 0.05. **Significant at P < 0.01

foliar spray of nano-ZnO to peanuts resulted in boosting of germination and saplings, augmented the total volume of chlorophyll in the leaves, and encouraged the plants to blossom which, in turn, increased the plant height. The conjunction of organic-like substances with mineral conditioners enhances plant growth in different ways, through improvements in water holding capacity, as well as reducing soil consistency which reverses nutrient uptake as a result of modification of soil pH and microbial activity (Bashir et al. 2020). Fattah et al. (2020) reviewed that sulfur has positive impacts on shoot/root growth system in plants and positively influences nodulation in legume crops particularly. Moreover, López-Bucio et al. (2003) illustrated that the application of sulfur fertilizer fostered the growth of lateral roots which resort to absorb nutrients and water in the soil. Day et al. (2019) hypothesized that the combination between compost and chemical conditioners improves the performance of chemical amendments by mobilizing surface sodium which in turn causes enhancement of soil physical and chemical properties, and it will reflect in plant production, besides the nutrition availability regarding the decomposition of compost materials (Murtaza et al. 2013).

The S+C treatment that received foliar nano-ZnO at the rate of 2 g·L^{-1} recorded the highest plant biomass via total yield (8.46 Mg ha^{-1}), 100 seeds weight (65.74 g), and seed yield (6.15 M g^{-1}). In this respect, several studies interpreted the action of the conjunction of sulfur with organic additives on plant productivity, while the degradation of organic matter increases nutrient availability in soil (Bustamante et al. 2016), besides the nutrient content of compost like high nitrogen content (note the low C/N ratio of 11.14%). Additionally, compost increases soil macroporosity and reduces soil compaction (Shaheen et al. 2019), while sulfur had been recognized for its ability to alter the distributions of elements especially the mobile phase, i.e., Na and Cl (Shaheen et al. 2017). Hussein and Abou-Baker (2018) and Sadak and Bakry (2020) revealed that foliar application of nano-ZnO tended to increase the plant root system. The incorporation addition of nano-ZnO with compost was reported to have a prompt impact on plant growth and yield properties as described by Gheith et al. (2018) and Atteya et al. (2018). In this concern, Prasad et al. (2012) stated that zinc oxide has the prospect to elevate the yield and growth of some crops. Naderi and Abedi (2012) explained that as a result of the basic role of Zn in maintaining and protecting structural constancy of cell membranes under saline conditions. Application of nano-ZnO presented a significant boost of plant biomass, root and shoot lengths, chlorophyll and protein contents, and phosphatase enzyme activity in several plants including *Gossypium hirsutum*, cluster bean, *Cucumis sativus*, *Cicer arietinum*, *Brassica napus*, *Raphanus sativus*, and *Vigna radiata* (Mahajan and Nanda 2011; Raliya and Tarafdar 2013; Priyanka and Venkatachalam, 2016; Venkatachalam et al. 2017; Priyanka et al. 2019)

Chemical components of faba bean seeds

Applying sulfur to sodic soil tends to be oxidized by microorganisms and turned into sulfate and hydrogen ion and decreasing soil pH (Adib et al. 2020); on par with solubilizing phosphorus and microelements in the soil, it could increase plant nutrient content. The effect of sulfur and nano-ZnO can alter the lipid and nutrient content levels in bean and corn tissue (Patra et al. 2013). Priyanka et al. (2019) reported that nano-ZnO improves roots' cation exchange capacity, which is reflected in enhancing absorption of other basic nutrients (N, P, K, and particularly Zn). It has been reported that sulfur supply to the plant has a decisive effect on the growth, performance and fitness, and the resistance of plants to biotic and abiotic stresses. Furthermore, sulfur strongly affects the food quality of crop plants (Zhao et al. 2008); it is responsible for the synthesis of cysteine, methionine, chlorophyll, vitamins, metabolism of carbohydrates, oil, and protein contents (Sutar et al. 2017). Jankowski et al. (2015) demonstrated that application of sulfur fertilizers to rapeseed plants resulted in increasing plant element contents (N, P, K, Ca and Zn) as well as reduction of pH as a forthright result of sulfur and increment of soil microbe's activity caused a release of different nutrients.

Conclusion

It could be concluded that using nano-ZnO application has positive impacts on both soil physicochemical properties and faba bean (*Vicia faba* L.) plants grown under saline-sodic conditions. The results demonstrated that soil amendments with both sulfur and compost incorporated with foliar application of nano-ZnO is a good way to alleviate soil salinity, promote soil sodicity, and augment faba bean plant yields and quality.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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