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Integrated Application of Phosphogypsum and Nano-Silica on Enhancing Soil Properties and Crop Productivity in Saline-Sodic Clay Soils

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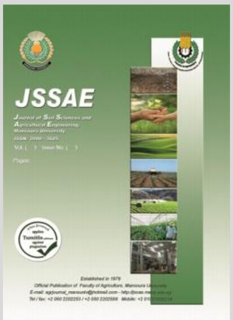

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ABSTRACT

Soil salinity and sodicity are among the primary constraints to agricultural productivity in Egypt. A study was conducted to evaluate the impact of phosphogypsum (PG; 4.13 tons/fed) and nano-silica foliar sprays (at concentrations of S_1:100 and S_2: 200 mg/L) on soil properties, nutrient dynamics, and the performance of wheat and maize grown in saline-sodic clay soils. The treatments included individual applications of PG and nano-silica (S_1 and S_2), as well as their combined use. The combination of PG and S_2 resulted in significant improvements: the exchangeable sodium percentage (ESP%) decreased by 12.6%, sodium adsorption ratio (SAR) fell by 14.3%, and soil electrical conductivity (EC) was reduced by up to 22.5% compared to untreated plots (control). Additionally, this treatment lowered bulk density (BD) by 2.9%, and increased total porosity (TP), indicating enhanced soil structure. Nutrient availability, particularly nitrogen, phosphorus, and potassium, was enhanced, supporting healthier plant growth. Yield outcomes were also promising, with grain production rising by 27.2% in wheat and 43.3% in maize, alongside significant gains in plant height, biomass, and 1000-grain weight. The K/Na ratio in both straw and grain improved, reducing sodium stress and increasing crop resilience. Overall, the combined application of PG and nano-silica proved more effective than their separate use, suggesting this integrated approach as a viable strategy for improving saline-sodic soils and supporting sustainable agriculture.

Keywords: Saline-Sodic Soil, Phosphogypsum, Nano-Silica, Foliar Spray, Wheat and maize yield

INTRODUCTION

Salinity and sodicity represent significant challenges to global agricultural productivity, particularly in arid and semi-arid regions, where they pose a serious threat to both crop yields and food security (Tarolli et al., 2024; Hosseini and Bailey, 2024; Outbakat et al., 2022). It is estimated that 20% of the world's cultivated land and 33% of irrigated areas are affected by salinity (Devkota et al., 2022). In Egypt, saline soils are a particular concern in critical agricultural regions, including the Nile Delta and newly reclaimed lands (Hagage et al., 2024; Aboelsoud et al., 2022). The issue is exacerbated in clay soils due to their high sodium (Na^+) retention capacity and low water permeability, which leads to ionic imbalances, osmotic stress, oxidative damage, and hindered nutrient absorption by plants (Vieira et al., 2024; Atta et al., 2023).

Wheat (*Triticum aestivum* L.) is not only a global dietary staple but also a vital crop in Egypt, where it plays a key role in national food security. However, it is particularly susceptible to salinity stress (Abdalla et al., 2022). Despite Egypt producing approximately 9 million metric tons of wheat in the 2021/22 season, a modest 1.1% increase over the previous year, demand continues to outpace supply, with domestic consumption reaching 21 million metric tons in the same period (USDA, 2021). Exposure to salt stress disrupts ionic balance and nutrient allocation in wheat, leading to reduced yields and poorer grain quality (Khalifa et al., 2023; Khedr et al., 2022; Nadeem et al., 2020).

Maize (*Zea mays* L.), which contributes about one-third of the world's total grain output (Maqbool and Beshir, 2019), also exhibits high sensitivity to saline conditions (Ali et al., 2022). Egypt's maize output stood at 7.1 million metric tons in 2023 (FAOSTAT, 2023), and the crop is crucial not only for food security but also for livestock feed and renewable energy production (Misbah et al., 2022). When subjected to salinity, maize tends to limit the movement of sodium ions (Na^+) to aerial parts of the plant in an effort to minimize biomass reduction (Hu et al., 2022).

The global phosphate fertilizer industry produces around 160 million tons of phosphogypsum (PG) annually, with only about 15% of it being utilized (Liu et al., 2019). In Egypt, the annual production of PG ranges from 11 to 14 million tons (El-Kammar et al., 2019; El Rafie et al., 2019). PG is known to improve soil physical properties, increase nutrient solubility, and promote root development without causing significant changes in soil pH (Elbagory et al., 2024; Khalifa et al., 2021; Bossolani et al., 2021; da Costa et al., 2018). When applied to saline clay soils, it has been found to enhance aggregate stability and soil fertility (Hasana et al., 2022; Mahmoud et al., 2021; Tao et al., 2021). However, excessive application (above 20%) can lead to metal toxicity and disrupt nutrient balance (Smaoui-Jardak et al., 2024).

In response to these issues, nano-fertilizers have emerged as a promising solution (Ahmad and Akhtar, 2019). Nano-silica (Nano-Si), known for its large surface area and slow-release characteristics (Fatima et al., 2021), has been shown to enhance the salt tolerance of crops like wheat and

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maize by reducing the accumulation of sodium ions (Na) and improving the K/Na ratio (Ismail et al., 2022). Additionally, it helps mitigate the physiological damage caused by NaCl stress (Abdel-Haliem et al., 2017) and promotes plant growth and productivity through a variety of physiological mechanisms (Rizwan et al., 2023; Mushtaq et al., 2017).

Although both phosphogypsum (PG) and nano-silica (Nano-Si) have shown promise individually in alleviating salinity stress, their combined effects on wheat and maize grown in saline clay soils remain underexplored. This study aims to combine traditional soil amendments with nanotechnology to develop a sustainable approach for managing saline-affected agriculture. The objectives are to evaluate the role of PG in soil reclamation, examine the efficacy of Nano-Si foliar treatments in mitigating Na^+ toxicity and enhancing stress tolerance in wheat and maize, and identify the most effective combination of PG and Nano-Si to optimize crop yield, nutrient uptake, and soil health. By integrating conventional and nano-enhanced methods, this research intends to offer practical, scalable solutions for improving salt-affected agricultural systems.

MATERIALS AND METHODS

Experimental Design and Treatments

Two seasons field experiment spanning two growing seasons was carried out during the winter of 2022/2023 and the summer of 2023 at Sakha Agricultural Research Station farm (31° 5'42.25"N, 30°54'28.51"E), located in Kafr El-Sheikh Governorate, Egypt. The trials were conducted on saline-sodic heavy clay soil (refer to Table 1). A randomized complete block design (RCBD) with three replications was employed to structure the study. The experimental treatments included the following:

– Control (C): no PG or foliar spray
– S_1: foliar spray of 100 mg/L Nano-Si
– S_2: foliar spray of 200 mg/L Nano-Si
– PG: 4.13 ton/feddan
– PG + S_1,
– PG + S_2.

Table 1. Soil physicochemical properties at the experimental site.

Chemical characteristics	Value	Physical characteristics	Value
EC (paste extract) dS m^{-1}	7.83	Particle size distribution (%)	
pH (suspension 1:2.5 w:v)	8.69	Sand	17.96
Soluble ions mmol L^{-1}		Silt	25.34
Na^+	57.57	Clay	56.70
K^+	0.443	Texture	Clayey
Ca^{2+}	11.44	$CaCO_3$ (%)	2.38
Mg^{2+}	9.38	CEC ($cmol_c$ kg^{-1})	39.18
HCO_3^-	5.00	Bulk density ($g.cm^{-3}$)	1.38
Cl^-	41.3	Total porosity (%)	47.92
SO_4^{2-}	32.53	Available NPK (mg kg^{-1})	
Sodium adsorption ratio (SAR)	17.77	N	17.86
Exchangeable sodium percent (ESP%)	19.97	P	9.48
Organic matter ($g.kg^{-1}$)	11.40	K	302.5

*** SO_4^{2-} was calculated by the difference, based on the charge balance between the total measured soluble cations and anions.**

Field Management

Each experimental plot measured 3 × 3 meters, with the total study area covering 162 m^2. Phosphogypsum (PG) was applied at a rate of 4.13 tons/fed, following Tao et al. (2021). Phosphogypsum application estimated using the gypsum requirement method, which is based on the soil's cation exchange capacity (CEC) and the desired reduction in exchangeable sodium percentage (ESP). The following calculations outline the steps involved. The initial ESP of the soil is 19.97%, and the target ESP is 15%. Therefore, the ESP reduction required is: ESP to be reduced=19.97%−15%=4.97%

The amount of exchangeable sodium to be replaced is calculated by multiplying the ESP reduction by the soil CEC:

Exchangeable Na=0.0497×39.18=1.95 meq Na/100 g soil

Using the standard conversion factor of 1.7 tons of gypsum per 1 meq of sodium per 100 g soil per feddan, the gypsum requirement is:

Gypsum Requirement =1.95×1.7=3.32 tons per feddan

Since the phosphogypsum available has a purity of 80%, the actual amount required is adjusted as follows:

Phosphogypsum required=3.320.80=4.15 tons per feddan

Along with 150 kg/fed of calcium superphosphate (15.5% P_2O_5), both incorporated into the soil during seedbed preparation. Potassium sulfate (50 kg/fed, 50% K_2O) was added 30 days after sowing (DAS). Nitrogen was supplied in the form of urea in two equal applications at 30 and 60 DAS at rates of 70 kg N/fed for wheat and 120 kg N/fed for maize at 30 and 45 DAS.

Wheat cultivar Giza 171 was broadcast sown on 12 November 2022 at a seeding rate of 70 kg grain/fed, while maize hybrid 368 was ridge-planted on 15 May 2023 at 10 kg/fed. Seeds for both crops were obtained from the Field Crops Research Institute, Sakha Agricultural Research Station, Kafr El-Sheikh, Egypt.

Nano-silica (Nano-Si) was applied as a foliar spray at a rate of 200 liters/fed at both 15, 30 and 60 DAS. Irrigation was scheduled at 30-day intervals for wheat and 15 day for maize, and all additional field management practices adhered to the protocols established by the Egyptian Ministry of Agriculture.

Materials

1.Phospho-gypsum (PG)

Source: Fertilizer industry (Abu-Zaable, El-Sharkia, Egypt).
Properties:

– pH: 3.2 was measured in the 1:5 (PG: water extracts)
– Major components: CaO (35.9%), SO_3 (44.08%), SiO_2 (9.95%), P_2O_5 (1.08%)
– Trace elements: Fe_2O_3 (1.64%), Na_2O (0.24%), TiO_2 (0.15%), F (0.36%)

2.Nano-Silica (Nano-Si) Synthesis

Nano-silica (Nano-Si) was produced from rice husks following the procedure described by Wang et al. (2011). Initially, rice husks were boiled in a 10% hydrochloric acid solution for two hours, then thoroughly washed with deionized water and dried at 100°C for 24 hours. The dried material underwent calcination at 700°C for two hours in a muffle furnace. Characterization techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and transmission electron microscopy (TEM) confirmed that the synthesized nanoparticles ranged in size from 20 to 30 nm.

Measurements and Analysis

Soil Analysis

Surface soil samples collected from the 0–30 cm layer were air-dried, passed through a 2.0 mm sieve, and thoroughly mixed to ensure uniformity. Chemical and physical properties were analyzed using procedures outlined by Piper (1950), Page (1982), Campbell (1994), and Rengasamy and Churchman (1999). The methods used were as follows:

- **pH:** Measured using a pH meter (Jenway model 4320)
- **Electrical Conductivity (EC):** Measured using an EC meter (Jenway model 4320)
- **Soluble ions:** Measured using titration and using a flame photometer
- **Available Nitrogen:** Determined by the semi-micro Kjeldahl method
- **Available Phosphorus**: Measured using a spectrophotometer
- **Available Potassium:** Determined using a flame photometer
- **Organic Matter:** Estimated using the Walkley and Black method
- **Cation Exchange Capacity (CEC):** Measured by the ammonium saturation method
- **Calcium Carbonate ($CaCO_3$):** Determined using a calcimeter
- **Particle Size Distribution:** Determined by the pipette method
- **Bulk Density:** Measured using the core sampler method
- **Total Porosity:** Calculated using the formula: 1 - (Bd/Dp), where Bd is bulk density and Dp is particle density

Plant Analysis

At the time of harvest, several parameters were measured for both wheat and maize, including plant height (cm), thousand-grain weight (gm), grain yield, and straw yield (ton/fed). Nutrient content specifically nitrogen (N), phosphorus (P), potassium (K), and sodium (Na) was analyzed in both grain and straw samples following the procedures described by Page (1982). Additionally, K/Na ratios were calculated.

Statistical Analysis

Statistical analysis was performed using analysis of variance (ANOVA) with Minitab version 21, followed by Tukey's post hoc test to determine significant differences at the 0.05 significance level according to (Bower, 2000)

RESULTS & DISCUSSIONS

Results

Soil Characteristics

Table 2 illustrates that the application of phosphogypsum (PG), particularly in combination with nano-silica (PG+S_2), significantly improved soil properties during both the wheat and maize growing seasons.

Salinity and Sodicity:

Under the PG+S_2 treatment, electrical conductivity (EC) decreased by 19.5% following wheat cultivation (from 7.54 to 6.07 dS/m) and by 22.5% after maize (from 6.31 to 4.89 dS/m). Similarly, the sodium adsorption ratio (SAR) was reduced by 3.8% in wheat and 14.3% in maize compared to the control treatments. The exchangeable sodium percentage (ESP) also showed a decline, with a 3.2% reduction following wheat and a 12.6% reduction following maize, from 19.04% to 16.64%. These results demonstrate the effectiveness of PG-based treatments in ameliorating saline-sodic soils. The calcium ions (Ca^{2+}) provided by PG replace the sodium ions (Na^{+}) adsorbed onto soil colloids, facilitating their leaching from the soil. Additionally, spraying nano-silica enhance plant growth which led to more root growth and distribution this may be affect soil organic matter and increase root channels, further promoting the displacement of sodium. These findings are consistent with the work of Elbagory et al. (2024), Khalifa et al. (2021), Bossolani et al. (2021), and da Costa et al. (2018).

Table 2. Soil properties under PG and nano-silica treatments.

Treatment	EC(dS/m)	SAR	ESP(%)	BD(g/cm³)	TP(%)	N(mg/kg)	P(mg/kg)	K(mg/kg)
				Wheat 2023				
C	7.54a	17.02a	19.25a	1.37a	48.43b	17.84b	10.35b	328.93b
S_1	7.53a	17.01a	19.24a	1.37a	48.43b	17.82b	10.69b	328.96b
S_2	7.53a	17.00a	19.24a	1.36a	48.76b	17.76b	10.59b	329.35b
PG	6.07b	16.39b	18.64b	1.34b	49.56a	25.64a	11.77a	359.61a
PG+S_1	6.07b	16.38b	18.64b	1.34b	49.56a	25.77a	11.89a	359.70a
PG+S_2	6.07b	16.38b	18.64b	1.33b	49.69a	26.06a	11.93a	359.77a
				Maize 2023				
C	6.31a	16.80a	19.04a	1.36a	48.55b	18.02b	9.78d	315.59b
S_1	6.30a	16.79a	19.03a	1.36a	48.68b	18.04b	10.13c	315.88b
S_2	6.29a	16.78a	19.02a	1.36a	48.68b	18.14b	10.12c	316.09b
PG	4.95b	14.46b	16.71b	1.32b	50.19a	28.37a	12.14b	393.30a
PG+S_1	4.93b	14.40b	16.65b	1.32b	50.08a	28.55a	12.41ab	394.23a
PG+S_2	4.89b	14.39b	16.64b	1.32b	50.06a	28.82b	13.02a	394.63a

*** Notes: C: control; S1: Spray with 100 Nano-Si L^{-1};**
S2: Spray with 100 Nano-Si L^{-1}; PG: 4.2 ton phosphogypsum fed^{-1}

Soil Physical Properties

The application of PG+S_2 also resulted in improvements to the soil's physical structure. Bulk density (BD) decreased by 2.9% (from 1.37 to 1.33 g/cm³), while total porosity (TP) increased by 2.6% for wheat and 3.2% for maize. These modifications indicate enhanced soil aeration and reduced compaction, likely due to the flocculation of clay particles induced by PG (Nayak et al., 2013). Spraying with nano silica can increase soil permeability by improving root growth, which leads to penetration into the soil and decomposing root remains, increasing organic matter and as a result, decreasing bulk density.

Nutrient Availability

The combination of PG+S_2 notably enhanced nutrient availability. Nitrogen levels increased by 46.1% in wheat and 59.9% in maize compared to the control. Phosphorus content rose by 15.3% in wheat and 33.1% in maize, while potassium (K) saw an increase of 9.4% in wheat and 25.0% in maize. These improvements are likely due to reduced interference from Na^{+} in nutrient uptake, along with enhanced microbial mineralization facilitated. Furthermore, S_2 may enhance plant growth plant growth and increase acidic secretions in the root leading to increase the solubility of PG, thereby increasing the availability of calcium ions (Ca). Overall, the PG+S_2 combination consistently outperformed the individual treatments, suggesting a synergistic effect where PG improves soil chemical properties, while S_2 enhances nutrient efficiency and promotes soil biological activity (Bossolani et al., 2022; Hasana et al., 2022; Mahmoud et al., 2021; Tao et al., 2021).

Crop Growth and Yield

Wheat (2023)

The PG+S_2 treatment resulted in the highest grain yield of 3.65 t/fed, marking a 27.2% increase compared to the control (2.87 t/fed). Both, PG+S_2 and PG alone boosted yields by 23.0% and 13.6%, respectively (Table 3). Additionally, biomass yield improved by 14.2% under PG+S_2. The 1000-grain weight increased to 57.6 g, representing a 12.3% gain over the control, while plant height grew by 29.9%, reaching 116.1 cm compared to 89.4 cm in the control (Table 3).

Table 3. Crop growth and yield parameters under PG and nano-silica treatments.

Treatment	Grain Yield (ton/fed)	Straw Yield (ton/fed)	1000-Grain Weight (g)	Plant Height (cm)
		Wheat 2023		
C	2.87d	3.51c	51.3e	89.4f
S1	3.08c	3.79b	53.8c	98.4e
S2	3.16bc	3.77b	54.6b	103.0d
PG	3.26ab	3.79ab	54.9a	106.5d
PG+S1	3.53a	3.99a	57.6a	114.4b
PG+S2	3.65a	4.01a	57.6a	116.1a
		Maize 2023		
C	1.64 e	5.11f	384.07d	118.33d
S1	1.93 d	6.26 e	412.80c	136.80c
S2	2.24 c	5.59 d	423.20bc	163.33 c
PG	2.39 b	6.74 c	434.20b	171.67d
PG+S1	2.48ab	7.80 b	436.33ab	173.33ab
PG+S2	2.57 a	8.95a	449.33a	176.67a

*** Notes: C0: control; S1: Spray with 100 Nano-Si L^{-1}; S2: Spray with 100 Nano-Si L^{-1}; PG: 4.2 ton phosphogypsum fed^{-1}** ***Maize (2023)***

The PG+S_2 treatment significantly boosted maize grain yield by 56.7%, from 1.64 to 2.57 t/fed. Biomass yield increased by 75.2%, from 5.11 to 8.95 t/fed, and the 1000-grain weight rose by 17.0%, from 384.07 to 449.33 g. Plant height also increased by 49.3%, reaching 176.67 cm.

These findings suggest that PG+S_2 substantially enhanced growth parameters by improving nutrient uptake, mitigating Na^+ toxicity, and enhancing stress tolerance. PG supported root development and nutrient movement, while S_2 improved the K/Na ratio and facilitated osmotic adjustment. The performance of treatments across both crops followed this ranking: PG+S_2 > PG+S1 > PG > S_2 > S1 > Control.

This ranking highlights that while PG alone is effective, nano-silica further amplifies its impact. In saline-affected areas, the combination of PG+S_2 provides the greatest benefit, PG alone offers a cost-efficient solution, and S_2 can be a useful alternative where PG is not readily available. These results align with earlier studies. For instance, Grechishkina et al. (2024) noted a gradual increase in PG's effectiveness over time, and Ayman et al. (2020) reported enhanced NPK and silicon uptake with similar treatments.

Nutrient Composition

The application of PG+S_2 significantly increased nutrient concentrations in both grain and straw for wheat and maize (Table 4).

Nitrogen levels in grain rose by 16.4-17.2% and by 77.5-87.0% in straw, phosphorus content increased by 53.1-56.8% in grain and by 134.6-163.6% in straw and potassium concentrations nearly doubled in grain and increased by 58.5-132.1% in straw.

Table 4.Crop growth and yield parameters under PG and nano-silica treatments.

	Grain					Straw				
Treatment	N% G	P% G	K% G	Na% G	K/Na G Ratio	N% S	P% S	K% S	Na% S	K/Na S Ratio
					Wheat 2023					
C	1.16e	0.463g	0.668f	2.69a	0.248e	0.244e	0.022e	0.381d	4.33a	0.088d
S1	1.24de	0.521e	0.795e	2.22bc	0.358e	0.298de	0.032d	0.456cd	4.14ab	0.110cd
S2	1.26cd	0.530e	0.827de	2.10c	0.394d	0.325d	0.042c	0.477c	4.08b	0.117cd
PG	1.27cd	0.569d	0.869d	1.94c	0.448cd	0.365cd	0.031d	0.488c	4.05b	0.120 cd
PG+S1	1.33b	0.592b	0.933d	1.70d	0.559d	0.406b	0.055b	0.562b	3.86cd	0.146b
PG+S2	1.36a	0.606a	0.966a	1.54e	0.627a	0.433a	0.058a	0.604a	3.75d	0.161a
					Maize 2023					
C	1.22e	0.484g	0.587f	2.99a	0.196e	0.237e	0.026e	0.284e	4.59a	0.062e
S1	1.30de	0.512e	0.708e	2.54c	0.279de	0.291de	0.035d	0.346cd	4.17b	0.083d
S2	1.30de	0.539e	0.767e	2.42c	0.317d	0.307d	0.043cd	0.454c	4.05b	0.112cd
PG	1.33cd	0.554d	0.782d	2.31d	0.339cd	0.318cd	0.047c	0.488c	3.95b	0.124d
PG+S1	1.37b	0.599b	0.890b	1.94e	0.459b	0.359b	0.050b	0.526b	3.68c	0.143b
PG+S2	1.42a	0.620a	0.869a	1.86f	0.468a	0.386a	0.061a	0.543a	3.64c	0.149a

*** Notes: C: control; S1: Spray with 100 Nano-Si L^{-1}; S2: Spray with 100 Nano-Si L^{-1}; PG: 4.2 ton phosphogypsum fed^{-1}**

The combination of PG+S_2 significantly reduced Na accumulation in grain by 69-70.2% and in straw by 13.4–20.7%. The K/Na ratio was improved by 29.7-482% in grain and 82.9-187.1% in straw, which is a crucial indicator of enhanced salt stress tolerance. The superior performance of PG+S_2 is attributed to the synergistic effects of each treatment. PG provides calcium and sulfur, improving soil chemistry, facilitating clay flocculation, and enhancing nutrient movement (Michalovicz et al., 2019). Meanwhile, nano-silica boosts physiological resilience, regulates ions, enhances photosynthesis, and helps maintain osmotic balance. This combined action results in healthier plants, improved yields, better nutrient status, and increased salt tolerance, making PG+S_2 an effective strategy for sustainable agriculture in salt-affected soils. The nano-silica likely facilitated ion transport and promoted growth-enhancing mechanisms. These results are consistent with the findings of Coskun et al. (2019), who reported that nano-silica limits Na^+ translocation through endodermal barriers. Additionally, Shoukat et al. (2024) and Rizwan et al. (2023) emphasized that nano-Si enhances phosphorus and potassium uptake under saline-sodic conditions.

CONCLUSION

The combined application of 4.13 tons of phosphogypsum per fed and 200 mg/L nano-silica (S_2) foliar spray effectively alleviated salinity stress in wheat and maize grown on clay soils. This treatment improved soil health by lowering salinity (EC), sodicity (SAR, ESP), and bulk density, while enhancing porosity and nutrient availability (N, P, K).

PG+S_2 consistently produced the highest yields, better grain quality, and increased stress resilience, as indicated by improved K/Na ratios and reduced sodium accumulation in plant tissues. While PG alone also provided significant benefits and proved to be a cost-effective option, S_2 can be used in regions where PG is not available.

Future research should investigate the optimal application rates for different soil types, long-term effects on soil biology and organic matter, and the economic feasibility of adopting this approach on a larger scale.

REFERENCES

Abdalla, A., Stellmacher, T. and Becker, M., 2022. Trends and prospects of change in wheat self-sufficiency in Egypt. Agriculture, 13(1), p.7.

Abdel-Haliem, M.E., Hegazy, H.S., Hassan, N.S.and Naguib, D.M. 2017. Effect of silica ions and nano silica on rice plants under salinity stress. Ecological Engineering, 99, pp.282-289.

Aboelsoud, H.M., AbdelRahman, M.A., Kheir, A.M., Eid, M.S., Ammar, K.A., Khalifa, T.H. and Scopa, A., 2022. Quantitative estimation of saline-soil amelioration using remote-sensing indices in arid land for better management. Land, 11(7), p.1041.

Ahmad, I. and Akhtar, M.S., 2019. Use of nanoparticles in alleviating salt stress. Salt Stress, Microbes, and Plant Interactions: Causes and Solution: 1, pp.199-215.

Ali, Y., Nawaz, T., Ahmed, N., Junaid, M., Kanwal, M., Hameed, F., Ahmed, S., Ullah, R., Shahab, M. and Subhan, F., 2022. Maize (Zea mays) response to abiotic stress. In Maize genetic resources-breeding strategies and recent advances. IntechOpen. Available at: http://dx.doi.org/10.5772/intechopen.102892.

Atta, K., Mondal, S., Gorai, S., Singh, A.P., Kumari, A., Ghosh, T., Roy, A., Hembram, S., Gaikwad, D.J., Mondal, S. and Bhattacharya, S., 2023. Impacts of salinity stress on crop plants: Improving salt tolerance through genetic and molecular dissection. Frontiers in Plant Science, 14, p.1241736.

Ayman, M., Metwally, S., Mancy, M. and Abd Alhafez, A., 2020. Influence of nano–silica on wheat plants grown in salt–affected soil. Journal of Productivity and Development, 25(3), pp.279-296.

Bossolani, J.W., Crusciol, C.A.C., Garcia, A., Moretti, L.G., Portugal, J.R., Rodrigues, V.A., Fonseca, M.D.C.D., Calonego, J.C., Caires, E.F., Amado, T.J.C. and Reis, A.R.D., 2021. Long-term lime and phosphogypsum amended-soils alleviates the field drought effects on carbon and antioxidative metabolism of maize by improving soil fertility and root growth. Frontiers in Plant Science, 12, p.650296.

Bossolani, J.W., Crusciol, C.A.C., Moretti, L.G., Garcia, A., Portugal, J.R., Bernart, L., Vilela, R.G., Caires, E.F., Amado, T.J.C., Calonego, J.C. and dos Reis, A.R., 2022. Improving soil fertility with lime and phosphogypsum enhances soybean yield and physiological characteristics. Agronomy for Sustainable Development, 42(2), p.26.

Bower, K.M., 2000. Analysis of variance (ANOVA) using MINITAB. Scientific Computing & Instrumentation, 17, pp.64-65.

Campbell, D.J. 1994. Determination and use of bulk density in relation to soil compaction. In Soane and Ouwerk (Ed.). Soil Compaction in Crop Production. Elsevere, London, Amsterdam.

da Costa, C.H., Carmeis Filho, A.C., Crusciol, C.A., Soratto, R.P. and Guimarães, T.M., 2018. Intensive annual crop production and root development in a tropical acid soil under long-term no-till and soil-amendment management. Crop and Pasture Science, 69(5), pp.488-505.

Devkota, K.P., Devkota, M., Rezaei, M. and Oosterbaan, R., 2022. Managing salinity for sustainable agricultural production in salt-affected soils of irrigated drylands. Agricultural Systems, 198, p.103390.

El Rafie, S.H., El Ghetany, H., Abuel Aila, R.R. and GABER, M.H., 2019. Treatment and purification of phosphogypsum. Egyptian Journal of Chemistry, 62 (1), pp.243-250.

Elbagory, M., Shaker, E.M., El-Nahrawy, S., Omara, A.E.D. and Khalifa, T.H., 2024. The concurrent application of phosphogypsum and modified biochar as soil amendments influence sandy soil quality and wheat productivity. Plants, 13(11), p.1492.

El-Kammar, A., Surour, A., El-Sharkawi, M., Khozyem, H., El-Kammar, A., Surour, A., El-Sharkawi, M. and Khozyem, H., 2019. Mineral Resources in Egypt (II): non-metallic ore deposits. The Geology of Egypt, pp.589-634.

FAOSTAT, 2023. Food and Agriculture Data (https://www.fao.org/faostat/en/#home)

Fatima, F., Hashim, A. and Anees, S., 2021. Efficacy of nanoparticles as nanofertilizer production: a review. Environmental Science and Pollution Research, 28(2), pp.1292-1303.

Grechishkina, Y.I., Egorov, V.P. and Matvienko, A.V., 2024. The Effect of Neutralized Phosphogypsum on the Productivity and Safety of Winter Wheat Grain. In International Conference on Innovations in Sustainable Agricultural Systems (pp. 177-185). Cham: Springer Nature Switzerland.

Hagage, M., Abdulaziz, A.M., Elbeih, S.F. and Hewaidy, A.G.A., 2024. Monitoring soil salinization and waterlogging in the northeastern Nile Delta linked to shallow saline groundwater and irrigation water quality. Scientific Reports, 14(1), p.27838.

Hasana, H., Beyene, S., Kifilu, A. and Kidanu, S., 2022. Effect of phosphogypsum amendment on chemical properties of sodic soils at different incubation periods. Applied and Environmental Soil Science, 2022(1), p.9097994.

Hosseini, P. and Bailey, R.T., 2024. Mutual impact of salinity and climate change on crop production water footprint in a semi-arid agricultural watershed: Application of SWAT-MODFLOW-Salt. Science of The Total Environment, 955, p.176973.

Hu, D., Li, R., Dong, S., Zhang, J., Zhao, B., Ren, B., Ren, H., Yao, H., Wang, Z. and Liu, P., 2022. Maize (*Zea mays* L.) responses to salt stress in terms of root anatomy, respiration and antioxidative enzyme activity. BMC plant biology, 22(1), p.602.

Ismail, L.M., Soliman, M.I., Abd El-Aziz, M.H. and Abdel-Aziz, H.M., 2022. Impact of silica ions and nano silica on growth and productivity of pea plants under salinity stress. Plants, 11(4), p.494.

Khalifa, S.H., El-Seady, E.S.H. and Mohamed, E.N., 2023. Effect of salinity stress on yield and its components as affected by some antioxidants foliar application of two wheat cultivars. Journal of Sustainable Agricultural and Environmental Sciences, 2(4), pp.1-10.

Khalifa, T., Elbagory, M. and Omara, A.E.D., 2021. Salt stress amelioration in maize plants through phosphogypsum application and bacterial inoculation. Plants, 10(10), p.2024.

Khedr, R.A., Sorour, S.G.R., Aboukhadrah, S.H., El Shafey, N.M., Abd Elsalam, H.E., El-Sharnouby, M.E., El-Tahan, A.M., 2022. Alleviation of salinity stress effects on agro-physiological traits of wheat by auxin, glycine betaine, and soil additives. Saudi Journal of Biological Sciences, 29(1), pp. 534-540.

Liu, Y., Zhang, Q., Chen, Q., Qi, C., Su, Z. and Huang, Z., 2019. Utilisation of water-washing pre-treated phosphogypsum for cemented paste backfill. Minerals, 9(3), p.175.

Mahmoud, E., Ghoneim, A., El Baroudy, A., Abd El-Kader, N., Aldhumri, S.A., Othman, S. and El Khamisy, R., 2021. Effects of phosphogypsum and water treatment residual application on key chemical and biological properties of clay soil and maize yield. Soil Use and Management, 37(3), pp.494-503.

Maqbool, M.A. and Beshir, A., 2019. Zinc biofortification of maize (*Zea mays* L.): Status and challenges. Plant breeding, 138(1), pp.1-28.

Michalovicz, L., Müller, M.M.L., Tormena, C.A., Dick, W.A., Vicensi, M. and Meert, L., 2019. Soil chemical attributes, nutrient uptake and yield of no-till crops as affected by phosphogypsum doses and parceling in southern Brazil. Archives of agronomy and soil science, 65(3), pp.385-399.

Misbah, N.A.Z., Akram, I. and Saleem, M.A., 2022. Influences induced by salinity stress on germination, growth and proline contents of maize (*Zea mays* L.). Journal of Agriculture, Food, Environment and Animal Sciences, 3(1), pp.15-26.

Mushtaq, A., Jamil, N., Riaz, M., Hornyak, G.L., Ahmed, N., Ahmed, S.S., Shahwani, M.N. and Malghani, M.N.K., 2017. Synthesis of silica nanoparticles and their effect on priming of wheat (*Triticum aestivum* L.) under salinity stress. In Biol. Forum (Vol. 9, pp. 150-157).

Nadeem, M., Tariq, M.N., Amjad, M., Sajjad, M., Akram, M., Imran, M., Shariati, M.A., Gondal, T.A., Kenijz, N. and Kulikov, D., 2020. Salinity-induced changes in the nutritional quality of bread wheat (Triticum aestivum L.) genotypes. AGRIVITA Journal of Agricultural Science, 42(1), pp. 1-12.

Nayak, A.K., Mishra, V.K., Sharma, D.K., Jha, S.K., Singh, C.S., Shahabuddin, M. and Shahid, M., 2013. Efficiency of phosphogypsum and mined gypsum in reclamation and productivity of rice–wheat cropping system in sodic soil. Communications in soil science and plant analysis, 44(5), pp.909-921.

Outbakat, M.B., Choukr-Allah, R., EL Gharous, M., EL Omari, K., Soulaimani, A. and EL Mejahed, K., 2022. Does phosphogypsum application affect salts, nutrients, and trace elements displacement from saline soils?. Frontiers in Environmental Science, 10, p.964698.

Page A. L. (ed.), 1982. Methods of Soil Analysis, part 2: Chemical and Microbiological properties, (2nd ed.) American Society at Agronomy, Inc. Soil.Sci Soc. Of Am. Inc., Madison.Wisconsin, U S A.

Piper, C.S.,1950. Soil and Plant Analysis. Inter science Publication. New York.

Rengasamy P. and Churchman G. J., 1999. Cation Exchange Capacity, Exchangeable Cations and Sodicity. In Soil Analysis an InterpretationManual. (Eds KI Peve rill, LA Sparrow and DJ Reuter). CSIRO: Melbourne.

Rizwan, A., Zia-ur-Rehman, M., Rizwan, M., Usman, M., Anayatullah, S., Alharby, H.F., Bamagoos, A.A., Alharbi, B.M. and Ali, S., 2023. Effects of silicon nanoparticles and conventional Si amendments on growth and nutrient accumulation by maize (*Zea mays* L.) grown in saline-sodic soil. Environmental Research, 227, p.115740.

Shoukat, A., Pitann, B., Hossain, M.S., Saqib, Z.A., Nawaz, A. and Mühling, K.H., 2024. Zinc and silicon fertilizers in conventional and nano-forms: Mitigating salinity effects in maize (*Zea mays* L.). Journal of Plant Nutrition and Soil Science, 187(5), pp.678-689.

Smaoui-Jardak, M., Turki, M., Zouari, M., Kallel, M., Ben Abdallah, F. and Elloumi, N., 2024. Effect of phosphogypsum amendment on saline soil and on growth, productivity, and antioxidant enzyme activities of pepper (*Capsicum annuum* L.). Euro-Mediterranean Journal for Environmental Integration, 9(1), pp.393-403.

Tao, T.I.A.N., Zhang, C.L., Feng, Z.H.U., Yuan, S.X., Ying, G.U.O. and Xue, S.G., 2021. Effect of phosphogypsum on saline-alkalinity and aggregate stability of bauxite residue. Transactions of Nonferrous Metals Society of China, 31(5), pp.1484-1495.

Tarolli, P., Luo, J., Park, E., Barcaccia, G. and Masin, R., 2024. Soil salinization in agriculture: Mitigation and adaptation strategies combining nature-based solutions and bioengineering. Iscience, 27(2), p. 108830.

USDA, 2021. Grain and Feed Update; Despite the COVID Pandemic, Egypt's Grains Supplies Hold Steady. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Grain%20and%20Feed%20Update_Cairo_Egypt_09-16-2021.pdf.

Vieira, C.B., Silva, G.H.M.C., Almeida, B.G.D., Pessoa, L.G.M., Freire, F.J., de Souza Junior, V.S., Melo, H.F.D., Lima, L.G.G.D., Paiva, R.F.D.N., Ferreira, J.F.D.S. and Freire, M.B.G.D.S., 2024. Saturated Hydraulic Conductivity of Nine Soils According to Water Quality, Soil Texture, and Clay Mineralogy. Agronomy, 15(4), p.864.

Wang, W., Martin, J.C., Zhang, N., Ma, C., Han, A. and Sun, L., 2011. Harvesting silica nanoparticles from rice husks. Journal of Nanoparticle Research, 13, pp.6981-6990.

التطبيق المتكامل للفوسفوجبسيم والنانو سيليكا فى تحسين خصائص التربة و انتاجية المحاصيل فى الاراضى الطينية الملحية الصودية

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الملخص

تُعد ملوحة التربة و الصودية من أهم المعوقات التي تُؤثر على الإنتاجية الزراعية في مصر. أُجريت دراسة لتقييم تأثير اضافة الفوسفوجيبسيم بمعدل ٤,١٣ طن/فدان والرش الورقى بالنانو سيليكا (بتركيز ١٠٠ و ٢٠٠ ملليجرام/لتر) على خصائص التربة، وتوافر العناصر الغذائية، وأداء القمح والذرة المنزرعين في تربة طينية ملحية صودية. شملت المعاملات استخدام الفوسفوجيبسوم والنانو سيليكا (S1 وS2) بشكل فردي، بالإضافة إلى الاستخدام المشترك لهما. وقد أدى الجمع بين الفوسفوجيبسيم والرش الورقى بالنانو سيليكا بمعدل ٢٠٠ ملليجرام / لتر إلى تحسينات ملحوظة: انخفضت نسبة الصوديوم المتبادل (ESP) بنسبة ١٢,٦٪، ونسبة ادمصاص الصوديوم (SAR) بنسبة ١٤,٣٪، والتوصيل الكهربائي للتربة (EC) بنسبة تصل إلى ٢٢,٥٪ مقارنةً بالكنترول. بالإضافة إلى ذلك، خفّضت هذه المعاملة انخفاض الكثافة الظاهرية (BD) بنسبة ٢,٩٪ وزادت المسامية الكلية (TP)، مما يشير إلى تحسن في بنية التربة. وتحسّن توافر العناصر الغذائية، وخاصة النيتروجين والفوسفور والبوتاسيوم، مما دعم نموًا صحيًا للنبات. وكانت نتائج الغلة واعدة أيضًا، حيث ارتفع إنتاج الحبوب بنسبة ٢٧,٢٪ في القمح و٥٦,٧٪ في الذرة، إلى جانب زيادات ملحوظة في طول النبات والكتلة الحيوية ووزن الألف حبة. وتحسّنت نسبة البوتاسيوم إلى الصوديوم في كل من القش والحبوب، مما قلل من إجهاد الصوديوم وزاد من تحمل المحاصيل. وبشكل عام، أثبت الاستخدام المشترك للفوسفوجيبسيم والرش الورقى بالنانو سيليكا بمعدل ٢٠٠ ملليجرام / لتر فعالية أكبر من استخدامهما بشكل منفصل، مما يشير إلى أن هذا النهج المتكامل يُعدّ استراتيجية فعّالة لتحسين التربة الملحية-الصودية ودعم الزراعة المستدامة.