Amendment with Nanoparticulate Gypsum Enhances Spinach Growth in Saline-Sodic Soil

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Abstract
The use of nano-gypsum in low doses can be an innovative method to mitigate salinity-sodicity effects and enhance spinach growth in saline-sodic soil. We evaluated nano-gypsum in four low doses of 960, 480, 240, and 120 kg ha⁻¹, in addition to the control and the recommended conventional gypsum dose (~ 30 t ha⁻¹), in a randomized complete pot experiment. The pots of soil were incubated in a laboratory for 2 months and leached 5 times for another 2 months. Then, spinach was grown in the soil for 60 days. The nano-gypsum dose of 240 kg ha⁻¹ with leaching was the best at improving the soil and spinach growth characteristics compared with the other doses and both control and conventional gypsum rate. Moreover, it was considered the critical nano-gypsum threshold rate. Compared to control after soil leaching, the critical rate increased the water-stable aggregate index and reduced bulk density by 57.39% and 16.30%, respectively; accordingly, the saturated hydraulic conductivity increased up to 2.34 times. Improved hydraulic conductivity led to a decrease in exchangeable Na ratio by 91% and reduced both soil salinity and pH by 83% and 1 unit, respectively. These great improvements in the soil properties favored the spinach growth indicators, which increased leaf area index, root hair index, and fresh yield by 2.20, 4.41, and 1.29 times, respectively, when compared to the recommended conventional gypsum rate. Accordingly, nano-gypsum in low doses is considered an innovative alternative to high doses of conventional gypsum to mitigate salinity-sodicity effects and enhance spinach growth in saline-sodic soil.

Keywords Calcium sulfate · Nanotechnology · Amelioration · Root hair index

1 Introduction
Saline-sodic soils account for more than 10–12% of the world’s irrigated land (Wang et al. 2021). Saline-sodic soils are rich in both soluble salts (ECₑ > 4 dS m⁻¹) and exchangeable Na⁺ (ESP > 15%) (Oad et al. 2002). However, the leaching of soluble salts usually indicates Na⁺ as a great problem that causes a pH rise to > 8.5 (Sparks 2003). Soils with high levels of exchangeable Na⁺ ratio (ESR) may negatively affect plant growth by dispersion of soil particles, i.e., destroying soil structures and clogging pores (Harper et al. 2021; Bello et al. 2021); nutrient deficiency or imbalances, i.e., excess Na⁺ competes with Ca²⁺, K⁺, and the other cations to reduce their availability (Neina 2019), and by resulting in specific toxicity to Na-sensitive plants (Wu 2018). Such problems can be addressed by providing a Ca²⁺ source to replace the abundance of Na⁺ in the cation exchange site (Kaledhonkar et al. 2019; Kim et al. 2018). Conventional gypsum (CG) is a universal source of soluble Ca²⁺ that can be used as an amendment in Na-rich soil (Günal 2021; Sundha et al. 2020). Although CG is used in large quantities as soil amendment, because of its low solubility (Cuervo-Alzate and Osorio 2020; Makoi and Verplancke 2010), the activity of CG is generally limited to its degree of homogeneity in the soil, which varies depending on the amount applied and the size of particles (Abate et al. 2021; Fontenele et al. 2014). Therefore, adding very fine or nano-gypsum particles to Na-rich soils can decrease salinity and sodicity more effectively than adding CG (Abdel-Fattah et al. 2015; Kumar and Thyiageshwari 2018). This can be attributed to the fact that nanomaterials is composed of very...
small particles (≤100 nm) with a high surface-to-volume ratio, which helps increase their reactivity and possible biochemical activity (Abd El-Halim and Omae 2019; Ahmed et al. 2021; Kumar and Thiyageshwari 2018).

Spinach is an important and popular nutritional vegetable crop, which grows in different soils of low salinity, and therefore it is considered a Na-sensitive crop (Grieve et al. 2012; Ors and Suarez 2017). Moreover, spinach requires slightly acid to slightly basic soil (pH 7 ± 0.5) for better growth and higher production (Parwada et al. 2020; Qiu and Liu 2020; Wyenandt et al. 2020). Thus, spinach has been selected as a test crop in the present study.

The two main limitations of using CG in the management of Na⁺ in Na-rich soils are its low solubility and its large quantities. As such, the main purpose for using nanogypsum (NG) in this study is to reduce the application rate and to increase solubility. Because of the high cost of using NG as a soil amendment, a new practical and cost-effective method, called low dose, is proposed in this study to reduce costs by ensuring sufficient gypsum requirement to reduce ESR and to enhance spinach growth in Na-rich soils. The new method involves applying a small amount of NG according to soil NG requirement, which can be estimated based on reducing soil reaction (soil pH), instead of soil CG requirement, which can be estimated based on reducing exchangeable sodium percentage.

### 2 Materials and Methods

#### 2.1 Study Soil

Saline-sodic soil was collected from a field located in Sakha, Kafr El-Sheikh province, Egypt, as a bulk sample (0–20 cm). Soil samples were transferred to the laboratory. Then, they were air-dried; sieved (2-mm sieve), and finally analyzed for hydro-physical and chemical properties (Table 1).

#### 2.2 Preparation of Nanoparticulate Gypsum (NG)

To prepare NG, we used pure hydrated gypsum (calcium sulfate, CaSO₄·2H₂O, purity 99.9%) with particles ≤74 µm. It was ground in a mill (MM 400, Retsch GmbH, Germany) at 1500 rpm for 10 min with 2 min in between each 5 min. In transmission electron microscopy, the particle average diameter was <100 nm (Fig. 1).

#### 2.3 Conventional Gypsum Requirement (CGR) of the Soil Studied

The CGR was calculated for the 15-cm soil depth according to Day et al. (2018):

\[
\text{CGR} \, \text{t ha}^{-1} = \left[ \frac{\text{CEC} \times (\text{ESP}_a - \text{ESP}_f)}{\text{gypsum purity}} \right] \times 1.72
\]

Table 1 Physical and chemical properties of the saline-sodic soil investigated (n = 3)

| Property                     | Unit   | Mean  |
|------------------------------|--------|-------|
| Sand                         | %      | 14.30 |
| Silt                         | %      | 32.30 |
| Clay                         | %      | 53.40 |
| Texture                      |        | Clay  |
| Bulk density                 | g cm⁻³ | 1.38  |
| Total porosity               | %      | 47.92 |
| Saturation percent           | %      | 60.85 |
| Field capacity               | %      | 41.04 |
| Wilting point                |       | 15.47 |
| Kₑ                          | cm h⁻¹ | 0.57  |
| Organic matter               | g kg⁻¹ | 15.80 |
| pH (saturated soil paste)    |        | 8.87  |

EC, saturated hydraulic conductivity; SAR, sodium adsorption ratio; CEC, cation exchange capacity; ESP, exchangeable sodium percentage.

Kₑ saturated hydraulic conductivity; SAR, sodium adsorption ratio; CEC, cation exchange capacity; ESP, exchangeable sodium percentage.
where CEC (cmolc kg\(^{-1}\) of soil) is the cation exchange capacity of the studied soil; ESP\(_a\) is the actual ESP of the investigated soil; ESP\(_i\) is the ESP that should be reached at the end of the experiment (stipulated 5%). Accordingly, the CGR is ~30 t ha\(^{-1}\), as indicated by the studied soil information available in Table 1.

### 2.4 Nano-gypsum Requirement (NGR) of the Soil Studied

The NGR was estimated from an initial study, which is based on the level of NG required to reduce soil pH to ≤7.5 in the 15-cm top surface layer. This was done by shaking the soil with varying levels of NG in distilled water (1:1 soil: water) intermittently for 72 h at 500 rpm (9 days, 8 h a day), and then measuring the pH. The varying levels of NG checked were 2% CGR (NG\(_2\), 600 kg ha\(^{-1}\)); 4% CGR (NG\(_3\), 1200 kg ha\(^{-1}\)); 8% CGR (NG\(_4\), 2400 kg ha\(^{-1}\)); 16% CGR (NG\(_5\), 4800 kg ha\(^{-1}\)); and 32% CGR (NG\(_6\), 9600 kg ha\(^{-1}\)), in addition to the reference treatment (NG\(_1\), control; 0 kg NG ha\(^{-1}\)). In general, the results indicated that the pH value decreased with increasing the dose of NG (Table 2). The results of the statistical analysis also showed that though the 9600 kg NG ha\(^{-1}\) decreased soil pH to the lowest value (Table 2), there was no significant difference after 2400 kg NG ha\(^{-1}\). Taking into consideration the cost of NG, which is more expensive than conventional gypsum (CG), in addition to the resource-poor farmers, the level of NG required to minimize soil pH (in the 15-cm top layer) was chosen to be 8% of the CGR, i.e., 2400 kg NG ha\(^{-1}\), which is referred to as the NG requirement (NGR) of the investigated soil.

### 2.5 Experimental Design and Treatments

The experimental design was a completely randomized design (CRD) with six treatments as follows: four cost-effective levels of NG at a rate of 40% NGR (NG\(_{10%}\)), 20% NGR (NG\(_{20%}\)), 10% NGR (NG\(_{10%}\)), and 5% NGR (NG\(_{5%}\)). These levels equate to 960-, 480-, 240-, and 120-kg NG ha\(^{-1}\), respectively. In addition, there were also a control treatment (soil only, 0% NG, CT) and a recommended conventional gypsum treatment (~30 t ha\(^{-1}\) pure gypsum with purity of 99.9% and maximum particle diameter of ≤0.5 mm; 100% GR, CG\(_{100%}\)). This gives the total of six treatments \(\times\) nine replications = 54 pots.

### 2.6 Incubation of the Pots

The soil was first crushed and sieved (≤2 mm). Portions of the soil (3 kg dry weight of each) were weighed, mixed with a certain amount of NG, and then packed in a plastic pot (height 20 cm and inner diameter 15 cm) with a drain hole at the bottom. The potted soil was compressed to reach the same bulk density (\(\rho\), 1.38 g cm\(^{-3}\)) as mentioned in Table 1. The pots were incubated for 2 months at a laboratory temperature of 29 ± 2 °C and a relative humidity of 65 ± 5%. The pots were regularly watered with distilled water at field capacity (FC, 41% w/w) according to their weight.

### 2.7 Leaching of the Pots

After the incubation period, three replicates of each treatment were irrigated with a known volume of distilled water until leachate appeared. This indicates that the soil has been completely saturated. After that, the three volumes of water were averaged, which is defined as pore volume of the soil (PV; 1 PV = 1600 cm\(^3\) of water pot\(^{-1}\)). After saturation, distilled water (0.5 PV = 800 cm\(^3\) pot\(^{-1}\)) was added after incubation, and then every 10 or 12 days. Accordingly, each pot was leached five times for 2 months, and hence the PV was exchanged 2.5 times during the leaching period. Leach experiments were carried out under saturation conditions and laboratory temperature.

### 2.8 Spinach Cultivation and Agronomic Management

Seeds of spinach (Spinacia oleracea L.) were directly sown in the middle of six leached pots at four seeds per pot during the period from 15 Nov 2020 to 15 Jan 2021. Seedlings were thinned to keep the healthiest ones. After that, in an open filed, the pots were stacked next to each other so that the distance between each plant and other was about

| Table 2 | Mean values of soil reaction (pH) observed with the initial study that used to determine nano-gypsum requirement of the soil studied (\(n = 36\)) |
|---------|----------------------------------------------------------------------------------|
| Treat   | CT                                  | NG\(_1\) | NG\(_2\) | NG\(_3\) | NG\(_4\) | NG\(_5\) | P-value | SEM   | HSD   |
| pH\(_{12\text{a}}\) | 7.87\(^a\)                               | 7.70\(^b\) | 7.67\(^b\) | 7.48\(^c\) | 7.35\(^d\) | 7.28\(^d\) | <0.001 | 0.036 | 0.169 |

CT is the control treatment, 0 gypsum requirement (GR); NG\(_1\), NG\(_2\), NG\(_3\), NG\(_4\), and NG\(_5\) are the nano-gypsum (NG) treatments at 2% GR (600 kg ha\(^{-1}\)), 4% GR (1200 kg ha\(^{-1}\)), 8% GR (2400 kg ha\(^{-1}\)), 16% GR (4800 kg ha\(^{-1}\)), and 32% GR (9600 kg ha\(^{-1}\)). Means of column under each subheading followed by different uppercase letters (a–d) are significantly different at Tukey’s HSD test (\(p \leq 0.05\); otherwise statistically at par); SEM is the standard error of the mean; \(p < 0.001\) means strongly significant.
20 cm, i.e., 25 plants m$^{-2}$, to simulate the cultivation in furrows. During the daytime of the spinach growth months, the mean air temperature was around 16 °C, rainfall was about 50 mm, and the relative humidity was about 68%. Irrigation was applied with tap water (pH 7.4 ± 0.1; conductivity 0.46 ± 0.1 dS m$^{-1}$) twice a week to maintain soil moisture near the FC by weight. All pots received 0.42 g urea (equivalent to 100 kg N ha$^{-1}$) and 0.41 g KH$_2$PO$_4$ (equivalent to 78 kg K ha$^{-1}$ and 62 kg P ha$^{-1}$) in two doses, the 1st dose at 21 days after sowing and the 2nd was after 2 weeks from the first. Spinach was harvested at 60 days after sowing, as it reached the commercial maturity stage.

### 2.9 Soil Hydro-physical and Chemical Properties

After soil leaching and spinach harvest, intact soil core samples (volume about 100 cm$^3$ from a depth of 5 to 10 cm) and disturbed soil samples were taken from three pots to determine soil hydro-physical and chemical properties. Soil bulk density ($\rho$, g cm$^{-3}$), saturated hydraulic conductivity ($K_s$, cm h$^{-1}$), particle-size analysis using the pipette method, water stable aggregate index (WSAI), soil reaction in soil paste extract (pH), electrical conductivity in soil paste extract (EC), cation exchange capacity (CEC, cmol$_c$ kg$^{-1}$) using the sodium acetate method, and exchangeable cations (Na$^+$, Mg$^{2+}$, and Ca$^{2+}$) using the ammonium acetate method were all determined according to the methods outlined in Estefan et al. (2013). The exchangeable sodium percentage (ESP) was calculated as the percentage of Na$^+$ exchanged in the total CEC. The exchangeable sodium ratio (ESR) was calculated using the following equation (Sundha et al. 2020):

$$\text{ESR} = \frac{\text{Na}_{\text{exch}}}{(\text{Ca}_{\text{exch}} + \text{Mg}_{\text{exch}})}$$

where $\text{Na}_{\text{exch}}$ is the ratio of the exchangeable Na$^+$ (cmol$_c$ kg$^{-1}$), and $\text{Ca}_{\text{exch}} + \text{Mg}_{\text{exch}}$ is the sum of exchangeable Ca$^{2+}$ and Mg$^{2+}$ (cmol$_c$ kg$^{-1}$).

### 2.10 Spinach Growth Indicators

To assess the impact of NG on yield, the spinach shoot was harvested at a commercial maturity stage and weighed to obtain the fresh yield (FY, kg ha$^{-1}$). The leaf surface area (LSA) and root hairs surface area (RHSA) were estimated by the analysis of leaves and roots in ImageJ software (Aboukarima et al. 2017; Chaudhary et al. 2012; Method S1). Then, the leaf area index (LAI, cm$^2$ m$^{-2}$) was calculated as LSA (cm$^2$) multiplied by plant leaves number (PLN) and divided by the soil surface area covered by plant (400 cm$^2$). Also, the root hair index (RHI, cm$^3$ cm$^{-2}$) was calculated as RHSA (cm$^2$) multiplied by root length (RL, cm) and divided by the soil volume in the pot (cm$^3$). The RL was measured by a ruler with an error of ± 1 mm. The soil volume was calculated by dividing the soil dry weight by the soil bulk density after harvesting. The spinach relative yield ($Y_{rs}$, %) as a function of soil salinity (EC, dS m$^{-1}$) was estimated with the following equation (Grieve et al. 2012):

$$Y_{rs} = 100 - b(\text{EC} - a)$$

where $a$ is the salinity threshold expressed in dS m$^{-1}$ (2 dS m$^{-1}$); $b$ is the yield loss per unit increase in salinity (7.6% per dS m$^{-1}$), and EC is the mean salinity of the soil saturated extract in dS m$^{-1}$.

### 2.11 Statistical Analyses

The differences between the means were tested by one-way analysis of variance (ANOVA), followed by the Tukey honestly significant difference (HSD) test when a significant difference was detected as ($P < 0.05$). Linear stepwise regression analysis was also done by means of the statistical program SPSS v. 13.0 for Windows (Inc. Chicago, IL, USA) to study the effect of soil properties after leaching (WSAI, $\rho$, $K_s$, pH, EC, and ESR) on spinach growth indicators (FY, LAI, and RHI) after harvesting. In stepwise regression, a variable was introduced when $F < 0.05$ and removed when $F > 0.10$.

### 3 Results

#### 3.1 Soil Properties

Applying NG or CG, in addition to the use of leaching, changed the physical and chemical composition of saline-sodic soil significantly ($P < 0.001$) compared to the CT (0 kg NG ha$^{-1}$, leaching only) (Table 3 and Table 4). Leaching alone was not sufficient to improve the properties of saline-sodic soil. The significant difference (HSD) among the arithmetic mean of all the investigated properties indicates that the results of applying NG at 10% of NGR (NG$_{10\%}$, 240 kg ha$^{-1}$), in addition to the use of leaching, were better than the results obtained from the other studied treatments (Table 3 and Table 4). This indicates the superior treatment was NG$_{10\%}$ with leaching. The value of $\rho$ has noticeably decreased in the superior treatment in comparison to its value in the other treatments, as it decreased by 16.30% and 16.54% compared to CT after soil leaching and spinach harvesting, respectively (Table 3). In addition to the decreased value of $\rho$, a more stable soil structure expressed in terms of the WSAI has been also observed. This directly affected the $K_s$, which increased up to 2.34 and 2.43 times compared to CT after soil leaching and spinach harvesting, respectively (Table 3). Moreover, it is also observed that the increase of $K_s$ is accompanied by
a decrease of ESR, pH, and EC (Table 4). In addition, after spinach harvesting, the treatments of NG20% and NG40% with the use of leaching gave almost identical results with regard to the improvement of $\rho$, WSAI, and $K_s$. Moreover, the superior treatment (NG10%) indicates the best improvements in all the investigated soil chemical properties (i.e., the ERS has decreased by about 91% and 94%; the pH has improved to 7.59 and 7.5, and the EC has been reduced by about 83% and 81%, compared to CT after soil leaching and spinach harvesting, respectively (Table 4). A close inspection of the values obtained for the treatments of NG40% and CG100% after soil leaching and spinach harvesting showed that these values were comparable to most of the soil chemical properties studied (Table 4). Similarly, the same trend was found between the treatments of NG5% and CG100%; and also between the treatments of NG20% and NG40% (Table 4). This indicates that small amounts of NG (applied as a % of NGR) can be an effective alternative to the large amounts of CG (applied as a
total of CGR) in improving the chemical properties of saline-sodic soils. However, the NG doses less or more than 10% of the NGR showed less effectiveness in improving the chemical properties of saline-sodic soils. This indicates that the NG critical threshold rate that should be applied as a percentage of NGR to ameliorate the hydro-physical and chemical properties of saline-sodic soils is 10% (240 kg ha$^{-1}$ = 0.8% of CGR).

Most noticeable is that all the chemical and the hydro-physical properties of the soil show a much better improvement after spinach harvesting than after soil leaching, which the positive effect of root activities in increasing NG solubility. Compared to the values obtained after soil leaching, the values of all soil hydro-physical properties after spinach harvesting were noticeably improved due to the use of the superior NG treatment (NG10%), as it increased both the WSAI and the $K_s$ by about 5% and 5.23%, respectively, and reduced the $\rho$ by about 1.8% (Table 3). Similarly, the use of the superior NG treatment (NG10%) has also improved the values of all soil chemical properties, which helped reduce the ESR, the pH, and the EC by about 29.41%, 0.08 units, and 10%, respectively, when compared to the values obtained after soil leaching (Table 4).

The results, obviously, show that the NG critical threshold rate that should be applied as a percentage of NGR to ameliorate the hydro-physical and chemical properties of saline-sodic soils is 10% (240 kg NG ha$^{-1}$ = 0.8% of CGR).

### 3.2 Spinach Growth Indicators

Regarding the CT treatment, leaching alone was not sufficient to improve the properties of saline-sodic soil, because it causes non-germination of spinach seeds. Accordingly, the treatments of NG applied as a percentage of NGR were compared to the recommended rate of CG applied as a total of CGR. NG significantly altered LAI, RHI, and FY ($P < 0.001$, Table 5). The treatment of NG10% with leaching was much better than the other treatments because it helps the increase of all the parameters of spinach growth, indicating that the NG rate of 240 kg ha$^{-1}$ is considered the critical threshold that should be applied as a percentage of NGR to enhance the spinach growth in saline-sodic soils. The superior treatment (NG10%) increased LAI, RHI, and FY by 2.20, 4.41, and 1.29 times, respectively, when compared to the treatment of CG100% with leaching (Table 5). Interestingly, the $Y_{rs}$ was higher in the superior treatment than in the other studied treatments. This indicates the ability of this treatment to reduce the soil’s EC near the critical threshold. Moreover, the treatments of NG40% and NG20% with leaching showed almost identical results for FY and $Y_{rs}$ (Table 5). A similar tendency was also observed for the treatments of NG5% and CG100% with leaching, as they also showed almost identical results for FY and $Y_{rs}$ (Table 5). This indicates that the effect of applying NG in low doses, as a percentage of NGR, is very similar to the effect of applying CG in high doses, as a total of CGR, on decreasing salinity and enhancing the spinach growth in saline-sodic soils.

### 3.3 Relationship Between Soil Properties and Plant Growth Indicators

A stepwise linear regression analysis revealed that the soil properties of EC, ESR, $\rho$, and WSAI were not significantly correlated with FY. In contrast, the $K_s$ alone explained 99.2% of the variance, and the $K_s$ and pH together explained 99.6% of the variance (Table 6). Also, neither the WSAI nor the $K_s$ was significantly correlated with LAI. However, four models can be proposed to explain the variance of LAI. First, the $\rho$ alone explained 91.1% of the variance; second, the $\rho$ and pH together explained 97.5% of the variance; third, $\rho$, pH, and ESR explained 98.6% of the variance; and fourth, the $\rho$, pH, ESR, and EC explained 99.0% of the variance. For RHI, the $\rho$ alone explained 85.3% of the variance (Table 6).

### 4 Discussion

#### 4.1 Impact of NG on Soil Properties and Plant Growth Indicators

The results indicated that the critical NG threshold rate, which improved all soil and plant characteristics to their
highest values, is 240 kg ha\(^{-1}\) (10\% of NGR = 0.8\% of CGR). These great improvement in the soil hydro-physical and chemical properties at the critical NG threshold rate favored the plant growth indicators (Xu and Mou 2016). The increase in spinach FY can be attributed to the effect of NG, which changed soil \(\rho\). This results in improving the soil structure, as expressed in terms of the WSAI, and in terms of NG, which changed soil \(\rho\) and soil reaction. 

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Enhanced spinach growth and root development would be expected if Na toxicity were alleviated by raising the Ca/Na ratio in soil solution (Al-Khateeb 2006; Rahman et al. 2016; Bello et al. 2021), and by lowering soil pH (Zhang et al. 2016). However, the NG rates above or below the critical NG threshold rate were insufficient to displace Na to high extent levels. Therefore, spinach growth decreased by the reduced LAI and RHI (Table 5). This can be attributed to the fact that NG rates below the critical threshold were not enough to increase soil aggregation to such an extent that drainable pores can increase the Ks to high levels. Conversely, with NG rates above the critical threshold rate, the excess of nano-particles can lead to a partial clogging of the drainable pores (Abd El-Halim and Omale 2019), thereby reducing Ks, which is the most effective factor to displace Na\(^+\) and reduce the EC (Klopp and Daigh 2020).

### 4.2 Relationship Between Soil Properties and Plant Growth Indicators

Increased Ks was the major limiting factor for increasing spinach FY (Table 6), whereas reduced \(\rho\) was the major limiting factor for the development of spinach root growth that is expressed as RHI (Table 6). This indicates that root development is more generally affected by the improvement in soil hydro-physical properties (\(\rho\) and Ks) than by the improvement in soil solution properties (pH and EC). This finding confirms the previous ones of Pivetta et al. (2019) on the cotton crop who indicated that the root growth is better related to soil properties than to soil solution properties. Currently, EC effects on root architecture/morphology currently are poorly understood (Maggio et al. 2011). However, root biomass has been reported to be generally less affected by excess EC than by aboveground organs (Munns and Tester 2008). This result is also confirmed with the increase of \(Y_{rs}\) in all NG treatments than in CG treatment. However, the \(Y_{rs}\) obtained with the NG5% treatment was very similar to that obtained with the recommended CG treatment (Table 5). This suggests that the NG in low doses had the potential to reduce EC more than the CG in high doses (Table 4). This proves that the small amounts of NG (applied as a % of NGR) can be an effective alternative to the large amounts of CG (applied as a total of CGR). Accordingly, the obtained results show that spinach

### Table 6 Soil properties after leaching explaining the variance of spinach growth indicators

| Plant growth attributes | Variables entered | Adj. \(R^2\) | SEE | \(P\) |
|-------------------------|------------------|---------|-----|------|
| FY                      | \(K_r\)          | 0.992   | 0.474| <0.001|
| FY                      | \(K_{r-pH}\)     | 0.996   | 0.320| <0.001|
| LAI                     | \(\rho\)          | 0.911   | 0.186| <0.001|
| LAI                     | \(\rho-pH\)      | 0.975   | 0.098| <0.001|
| LAI                     | \(\rho-pH, ESR\) | 0.986   | 0.074| <0.001|
| RHI                     | \(\rho\)          | 0.990   | 0.062| <0.001|
| RHI                     | \(\rho\)          | 0.853   | 0.122| <0.001|

FY, fresh yield (t ha\(^{-1}\)); LAI, leaf area index (cm\(^2\) cm\(^{-2}\)); RHI, root hair index (cm\(^3\) cm\(^{-2}\)); \(\rho\), soil bulk density (g cm\(^{-3}\)); \(K_r\), saturated water hydraulic conductivity; ESR, exchangeable sodium ratio; EC, electrical conductivity (dS m\(^{-1}\)); pH, soil reaction; Adj. \(R^2\), adjusted \(R^2\); SEE, standard error of the estimate (\(n=18\)); \(P<0.001\), means strongly significant.
conductivity \( \rho \) results in the added benefit of improved physical properties (Ruganzu, 2013; Pivetta et al. 2019; Qadir et al. 2005). This leading to decrease bulk density and increase saturated hydraulic coalescence of micro-aggregates and preventing clay dispersion of soil particles and form very stable soil structural units by the types of saline-sodic soils.

investigate the effects of NG in field trials in a wide range of the presence of spinach plants. However, future work should being enhanced. Hence, soil properties were enhanced more in this study was 10% (240 kg \( \mu \text{m}^{-1} \)) within the root zone, enhancing the hydraulic conductivity \( (K_s) \) and allowing the leaching of \( Na^+ \) below the effective rooting depth (Akhter et al. 2004).

5 Conclusion

The results of this study show that the application of nano-gypsum in low doses (as a % of soil nano-gypsum requirement) was more effective in enhancing spinach growth and improving saline-sodic soil hydro-physical and chemical properties than the application of conventional gypsum in high doses (as a total of soil conventional gypsum requirement). Also, the nano-gypsum critical threshold rate that should be applied to fulfill these results was 10% (240 kg ha\(^{-1}\) = 0.8% of soil conventional gypsum requirement). These improvements were most probably related to the large surface area of NG, which improves the retention and release of exchangeable cations \( (Ca^{2+}, Mg^{2+}, \text{and } K^+) \) for an extended period. Hence, these cations can attract soil particles and form very stable soil structural units by the coalescence of micro-aggregates and preventing clay dispersion leading to decrease bulk density and increase saturated hydraulic conductivity. This results in faster leaching of \( Na^+ \). In turn, this also results in reduced exchangeable sodium ratio of the soil, and hence reduced the effects of Na toxicity, as well as soil salinity, on spinach growth. This resulted in spinach growth indicators being enhanced. Hence, soil properties were enhanced more in the presence of spinach plants. However, future work should investigate the effects of NG in field trials in a wide range of types of saline-sodic soils.

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4.3 Impact of Spinach Growth on Soil Properties

Most noticeable is that WSAI, \( \rho \), \( K_s \), pH, EC, and ESR of the soil were enhanced more in the presence of spinach plants. One possible explanation is that NG had a long-lasting effect for 180 days and spinach plants had the potential to enhance the dissolution rate of NG through root activities. The ability of plant roots in increasing the dissolution rate of gypsum, through processes at the soil-root interface, results in enhanced levels of \( Ca^{2+} \) in the soil solution to replace \( Na^+ \) from the cation exchange complex (Ndewumuremyi and Ruganzu, 2013; Pivetta et al. 2019; Qadir et al 2005). This results in the added benefit of improved physical properties (WSAI and \( \rho \)) within the root zone, enhancing the hydraulic conductivity \( (K_s) \) and allowing the leaching of \( Na^+ \) below the effective rooting depth (Akhter et al. 2004).

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Declarations

Conflict of Interest The authors declare no competing interests.

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