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Effect of Phosphogypsum on Soil Physical Properties in Moroccan Salt-Affected Soils

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Abstract: Salinity is one of the most critical challenges for crop production and soil and water management in arid and semi-arid regions, such as a large area of Morocco. These regions are characterized by low rainfall with an erratic distribution, long drought periods, and high evaporation, resulting in salt accumulation in the superficial layer of the soil and soil and water degradation. Therefore, phosphogypsum (PG) could be a promising amendment to reduce the salinity effect and improve soil quality in salt-affected soils. In this context, the present study aimed to evaluate the effect of PG on the physical properties of Luvisols and Cambisols collected from salt-affected soils in four regions in Morocco: Chichaoua, Ras El Ain, Sidi Zouine, and Sed El Masjoune. The treatments consisted of different rates of PG (15, 30, and 45 t/ha), natural Gypsum (G) (15 t/ha), and control. Our findings revealed that PG application improved soil structure by promoting flocculant action provided by calcium. Linear regression indicated that Water Aggregate Stability (WAS) and PG doses were strongly correlated with a high coefficient of determination (R2 = 93.41%, p value < 0.05). Compared to the control, the overall efficiency of 45 t/ha of PG amendment reached 53%, 95%, and 36%, respectively, in Chichaoua, Ras El Ain, and Sed El Masjoune soils. PG application presented a positive effect on other soil physical properties (soil hydraulic properties, total porosity, and bulk density), especially for the soils of Chichaoua and Ras El Ain regions. The total porosity was increased by 8% with 45 t PG/ha in Ras El Ain soil, and in Chichaoua soil, the bulk density was 5% lower in the pot treated with 45 t PG/ha compared to the control. This study supports the use of PG as an amendment for reclaiming salt-affected soils through monitoring agronomic and environmental impacts.

Keywords: sustainability; soil salinity; sodicity; soil degradation; soil physical properties; circular economy

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1. Introduction

Soil is one of the most important natural resources that may be prone to different forms of degradation. Soil degradation results in its quality and health deterioration and the reduction of its capacity to provide ecosystem services, and to ensure its main functions as well [1,2]. By 2050, population and income growth are expected to require a 70% increase in food production worldwide and up to 100% in developing countries [3], while the agricultural land surface is increasingly degraded. In fact, 33% of the land surface is subject to at least one soil degradation type [4]. The soil is susceptible to different types of degradation: physical, chemical, biological, and ecological. Degradation processes can be natural, but it has limited effects when compared to anthropogenic degradation by different factors, called accelerated degradation with large scale-impacts [5].

Salinity is a type of soil chemical degradation. It is one of the most limiting factors for crop production in arid and semi-arid regions, which are characterized by low and irregular annual rainfall, long drought periods, and high levels of evaporation, resulting in salts accumulation in the superficial layer of the soil [1,6,7]. According to Mukhopadhyay et al. [8], climate change could have a direct effect on the rising sea level and unbalancing groundwater extraction and annual recharge, increasing groundwater salinity used in irrigation and soil salt accumulation as well. The total area impacted by salts is about 1 billion hectares, and the trend is significantly increasing [9]. However, 40–60% of these soils are also under threat from sodicity problems [10,11].

Salinity, a worldwide phenomenon, threatens food security by reducing arable land and impacting crop yields. Salt presence in the rhizosphere induces an osmotic effect which limits root water uptake [12,13]. Salinity decreases the chloroplast number in the leaf cells and damages roots and leaves anatomy [14]. On the other hand, salinity and sodicity negatively affect soil's physical attributes. Rengasamy et al. reported that the increase in Na, K, and Mg concentrations in soil cause soil swelling and clay dispersion, which affects soil aggregation, reduces soil porosity and water infiltration, and, hence, makes the soil more susceptible to different types of erosion [15]. Saidi et al. reported that high exchangeable sodium content limits soil water retention and increases soil dispersion, which destroys soil aggregate stability [16]. High Na and K content in the soil solution affects infiltration, structural stability, and hydraulic conductivity, which in turn has an impact on soil water storage and crop productivity [17]. Sodicity impacts soil electrochemistry; the adsorbed cations shield the negative charge of the soil, such as clay colloids, which leads to clogging the pores, surface crusting, and hardsetting [18]. Soil salinization reduces soil fertility, caused by an imbalance in the charge of the cations in soil solution, interfering with normal microbial activities, which reduces soil health [19].

Several strategies are used to decrease the effect of accumulated salts in the topsoil, such as engineering, reclamation, and agricultural techniques. Soil reclamation is the process of improving the productivity of degraded soil by the improvement of soil's chemical, physical, and biological properties as well as soil fertility. Phytoremediation is a sustainable strategy to mitigate the effects of salinity and sodicity. This technique consists of using salt-tolerant plants (halophytes) [20,21]. Soil leaching is also used to overcome salinity stress; this method consists of pushing salts below the root zone. However, this method requires appropriate drainage-sufficient amounts and good quality of water with low salt concentration to ensure good results [22]. On the other hand, the use of different amendments, such as organic amendments, gypsum (G), and phosphogypsum (PG), is a promising, useful, and low-cost strategy [23–25].

PG is a coproduct of the phosphate fertilizer industry. The digestion of rock phosphate with sulfuric acid results in the production of phosphoric acid and PG, according to the following reaction [26,27]:

$$Ca_{10}(PO_2)6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 6H_3PO_4 + 2HF + 10(CaSO_4{\cdot}.2H_2O) \quad (1)$$

Annual worldwide production of PG is about 300 Mt [28]. PG is recycled and reused in several sectors and applications [29], such as cement manufacturing, concrete, panels production [30,31], material for coastal protection [32], and, also, as daily landfill cover [32]. Diouri et al. reported that the use of phosphogypsum in the pavement structure showed promising results, good performance, and lower cost compared to other road construction materials [33]. PG has also been used in agriculture. It has shown positive effects on crop nutrition because it contains several nutrients (Ca, S, and P). Moreover, PG is used as an amendment for the reclamation of degraded soils: saline, sodic, acidic, and alkaline soils [26,34].

PG is an alternative to natural gypsum generally used to reduce salinity. Calcium sulfate can readily furnish soluble calcium to substitute exchangeable sodium [35]:

$$CaSO_4 + 2Na\text{-soil} \rightarrow Ca\text{-Soil} + Na_2SO_4 \quad (2)$$

The PG showed its desalinization and desodification efficiencies by reducing electrical conductivity (EC) and exchangeable sodium percentage (ESP) [36]. Under saline conditions [37] found that P, Ca, and Fe soil contents were boosted by PG application when compared to control soil and gypsum-amended soil. In addition, PG improved rice and wheat yields. Miller reported that PG application improves soil's physical properties by increasing water infiltration and pore stabilization, and consequently, decreases soil erosion [38]. PG has also been approved for its ability to reduce soil dispersion [39] and enhance soil stabilization and aggregation [40]. The application of PG increases ion concentration, which leads to enhanced soil permeability [41]. Nayak et al. concluded that PG application improved hydraulic conductivity better than gypsum amendment [37]. On the other hand, PG contains many heavy metals. This aspect must be deeply investigated in future research.

Morocco is dominated by large arid and semi-arid conditions, and the salt-affected soil area is estimated to be 1.148 Mha [42]. This country is among the major PG producers in the world. However, it is essential to promote the use of PG as an amendment for the farmers by testing and evaluating the effect of PG in different soil classes and different saline–sodic soils [43]. Although several pieces of research were devoted to the agricultural uses of PG [44], few studies are interested in the evaluation of the use of PG as an amendment for reclaiming saline–sodic soils in Morocco [25]. In addition, the evaluations of soil physical properties were seldom considered in this type of study. The evaluation of PG as an amendment could contribute to understanding its mechanism of action and to define the optimal rate that could be used in different situations, to reduce the PG stocks and increase its valorization.

The objective of this study was to evaluate the impact of different phosphogypsum rates on soil physical properties of different salt-affected soils. We hypothesized that the application of phosphogypsum, as a source of calcium and sulfur besides its acidity that can contribute to soil lime solubilization could improve soil physical properties by reducing the dispersive effect of sodium and increasing cementing agents in the soil, which could improve soil aggregation, soil porosity, and soil water retention capacity.

2. Materials and Methods

2.1. Soil Sampling

Soil samples from the 20 cm topsoil, were collected from four regions of Morocco: Chichaoua (31°32′57.6″ N 8°53′00.4″ W), Ras El Ain (32°00′56.0″ N 8°28′21.1″ W), Sidi Zouine (31°39′02.2″ N 8°22′04.9″ W), and Sed El Masjoune (32°07′44.7″ N 7°37′07.9″ W) as indicated in Figure 1.

Sed el Masjoune, an area affected by salinity [24], has a semiarid climate with an annual average rainfall of 200 mm, a minimum temperature of 3.6 °C in winter, and a maximum temperature of 48 °C in summer [45]. The Chichaoua region is a part of a large watershed basin called Tensift. It is a semi-arid area with an average annual rainfall of 180 mm and an average temperature of 15 to 20 °C [46]. Sidi Zouine area is part of the Marrakech region; the minimum and maximum temperatures are, respectively, around 4.9 °C and 38 °C, with an average of 18 °C. The annual rainfall is about 190 mm [47]. Ras El Ain is located in the Rehamna region, which is characterized by a semi-arid climate with high precipitation interannual variability and an annual average rainfall of 189 mm. The temperature ranges between −3.4 and 35 °C [48]

The soils were described and classified according to IUSS Working Group (2022) [49]. The soils were classified as Haplic Luvisol in Chichaoua and Ras El Ain regions, and as Haplic Cambisol in Sidi Zouine and Sed El Masjoune regions. According to different studies, the dominant clay mineral in these study regions is Montmorillonite [50,51].

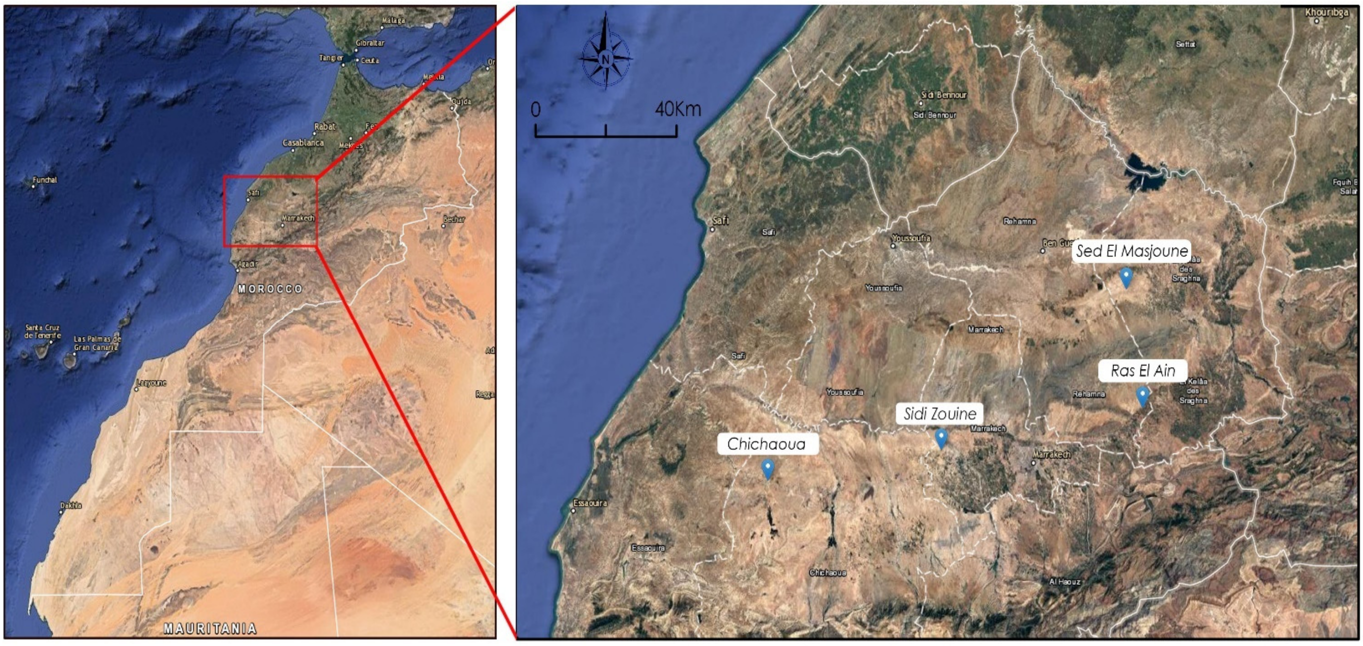

Figure 1. Location of studied salt-affected soils.

2.2. Trials Setup

The experiment was conducted using pot trials under greenhouse conditions at Mohammed 6 Polytechnic University (UM6P) in Ben Guerir (Morocco). Each pot was filled with 10 kg of soil. Phosphogypsum (PG) was provided by the industrial complex of Jorf Lasfar, situated near El Jadida city. The second amendment consists of natural gypsum (G) for agricultural use. The experimental design consists of a completely randomized design (CRD) with three replicates. The treatments were: Control (0 t/ha), 15 t/ha of G, 15, 30, and 45 t/ha of PG. PG and G were mixed with the top 9 cm of the soil in the pot to ensure good homogenization.

2.3. Soil and Amendment Characterization

The soils were air-dried, crushed, and passed through a 2 mm sieve. pH was determined in 1:5 soil: water extract using a pH meter (InoLab pH 7310). The saturated paste was manually prepared and mixed [52], and electrical conductivity (ECe) was determined by an electrical conductivity meter (Mettler Toledo. SevenCompact). Determination of soil organic carbon was performed using sulfochromic oxidation of carbon in a mixture of potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) at 135 °C according to Walkley and Black [53]. Calcium carbonate was analyzed using chlorohydric acid [54]. The available phosphorus was carried out by spectroscopy using the Olsen method [55]. Soil texture was determined using the hydrometer method proposed by Bouyoucos [56]. Spectrophotometry (Agilent Technologies. Cary 60 UV-Vis) was used to determine Sulfate content. The sodium, potassium, calcium, and magnesium contents were extracted with ammonium acetate at pH = 7 and determined by atomic absorption spectroscopy (Agilent Technologies. 200 Series AA). Soil total nitrogen was determined by distillation after mineralization using the Kjeldahl method [57]. The exchangeable sodium percentage and sodium adsorption ratio were calculated as indicated in Equations (3) and (4):

$$ESP = \text{Exchangeable } \{(\text{Na})/(\text{Ca} + \text{Mg} + \text{K} + \text{Na})\} \times 100 \quad (3)$$

Na, Ca, Mg, and K expressed as mEq/100 g.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}\left(Ca^{2+} + Mg^{2+}\right)}} \quad (4)$$

Na, Ca, and Mg expressed as mEq/l.

Soils, PG, and G characterization was carried out at the Soil-Plant-Water Laboratory of the Agriculture Innovation Transfer Technology Center at the University Mohammed 6 Polytechnic at Ben Guerir (Morocco). Collected soils were classified for their salinity status following the classification proposed by Rengasamy [15]. The soil of Chichaoua is alkaline–saline soil (ECe > 4; SAR < 6; pH 8–9), while Ras Al Ain, Sidi Zouine, and Sed El Masjoune soils are very alkaline–saline–sodic soils (ECe > 4; SAR > 6; pH 8–9) (Table 1).

Table 1. Characterization of physical and chemical properties of studied soils.

Properties	Chichaoua	Ras El Ain	Sidi Zouine	Sed El Masjoune
ECe (mS/cm)	11.7	26.47	94.6	140.6
pH	8.1	8.3	8.1	8.1
OM (%)	1.86	1.28	1.62	1.61
$CaCO_3$ (%)	8.4	2.0	9.8	7.5
P_2O_5 (mg/kg)	67	40	43	43
Clay (%)	20	34	22	26
Silt (%)	28	42	34	28
Sand (%)	52	24	44	46
Class texture	Loam	Clay Loam	Loam	Loam
SO_4 (mg/kg)	3210	2145	2323	2728
Na_2O (mg/kg)	759	2873	11,027	26,628
K_2O (mg/kg)	308	351	817	697
CaO (mg/kg)	7984	7973	10,754	10,923
MgO (mg/kg)	1067	814	2157	2496
Total N (%)	0.12	0.1	0.11	0.08
ESP (%)	7%	22%	41%	62%
SAR(mEq/l)	1.9	9.9	29.7	69.6

pH and EC were measured in the 1:5 PG or G: water extracts. The amendments were analyzed using aqua regia extraction followed by two hours of digestion at 95 °C. Ca, S, P, K, Mg, and Al were determined by ICP-OES (Agilent Technologies. 5110 ICP-OES) (Table 2)

Table 2. Phosphogypsum and Gypsum properties.

Properties	PG	G
pH	5.8	8.1
EC (mS/cm)	2.4	2.3
Solubility (g/L)	2.5	2.03
Ca (%)	22.8	17.0
S (%)	23.7	13.1
K (mg/kg)	869	969
Mg (mg/kg)	259	7587
Al (mg/kg)	719	1328

2.4. Soil Physical Evaluation

Soil physical attributes were evaluated after the Faba bean (*Vicia faba* L.) harvest. The sowing was on 22 December 2020, and the harvest was on 20 May 2021. The crop received

287 mm of water irrigation. Then, 30 and 15 Kg/ha of nitrogen and potassium, respectively, were applied.

Undisturbed soil samples were collected to determine the bulk density using rings (21.62 cm^3) according to the method proposed by Blake and Hartge [58]. These undisturbed samples were saturated by capillarity with water up to two-thirds of the ring height and submitted after saturation to the matric potentials of suction using 33 kPa and 1500 kPa to determine field capacity (FC) and permanent wilting point (PWP) [59], respectively. Available water capacity for plants was calculated using the Equation (5):

$$\text{AWC} = \text{FC} - \text{PWP} \tag{5}$$

Total porosity (TP) was estimated using saturated volumetric soil water content (θs). Aggregate stability was performed using the wet sieving apparatus (Eijkelkamp Agrisearch Equipment) [60]. Four grams of sieved aggregates from 1 to 2 mm air-dried soil was transferred to a sieve with 0.25-mm. Soil samples were pre-moistened for ten minutes before being submerged in distilled water. The apparatus sieved mechanically the samples in cans by an up and down movement for three minutes (42 cycles/min) while placing sufficient distilled water into the cans to cover the soil. Unstable aggregates, passed through the 0.25-mm sieve, were separated from the stable aggregates, and sand and organic matter were retained on the 0.25-mm sieve. The cans having unstable aggregates were oven-dried at 105 °C for 24 h and weighed. Retained materials in a 0.25-mm sieve were immersed and sieved again for ten minutes in cans filled with a dispersing solution (containing 2 g sodium hexametaphosphate/L). The water stable aggregate (WSA) was calculated as the weight of soil obtained in the dispersing solution cans divided by the sum of the weights obtained in the dispersing solution cans and distilled water cans:

$$\text{Water aggregate stability } (\%) = \frac{(\text{A} - 0.2)}{(\text{A} - 0.2) + \text{B}} \times 100 \tag{6}$$

where: A − 0.2: is the oven-dried mass (g) of the water-stable aggregates (soil obtained in the dispersing solution cans) and B is the oven-dried mass (g) of water unstable aggregates.

Overall efficiency (%) of the soil amendment was used to evaluate the effect of the rate of the amendment on the water stable aggregate, using Equation (7) [23].

$$\text{Overall efficiency } (\%) = \frac{(\text{WASt} - \text{WASc})}{\text{WASc}} \times 100 \tag{7}$$

WASt is the water aggregate stability in soil treated by amendment, and WASc is water aggregate stability in the control treatment.

2.5. Statistical Analysis

The different soil physical properties were used to evaluate the effects of phosphogypsum rates using analysis of variance (ANOVA). When ANOVA indicates a significant difference between treatments, post-hoc pair-wise comparisons were performed to investigate differences between treatment means using the Tukey test. All statistical analyses were performed using the R 3.4.1 software [61].

3. Results

3.1. Water Aggregate Stability

The region and the amendment have a significant effect on the water aggregate stability (WAS) (Figure 2). Region effect differs from one soil to another, and the highest value of WAS was observed in the soil of Chichaoua region. Overall, PG application increases WAS, except for soil collected from the region of Sidi Zouine. The impact of PG on the improvement of soil structure was more remarkable in the soil of Chichaoua, and the overall efficiency of 45 t/ha of PG amendment reached 53% compared to the control. In soil from the Ras El Ain region, PG improved soil aggregation by 12% using 30 t PG/ha, and 95% using 45 t PG/ha. Concerning Sed El Masjoune soil, the PG improved the soil structure using a rate greater than 30t/ha, and the overall efficiency of PG was 36% and 64% for 45 t PG/ha and 30 t PG/ha, respectively (Table 3).

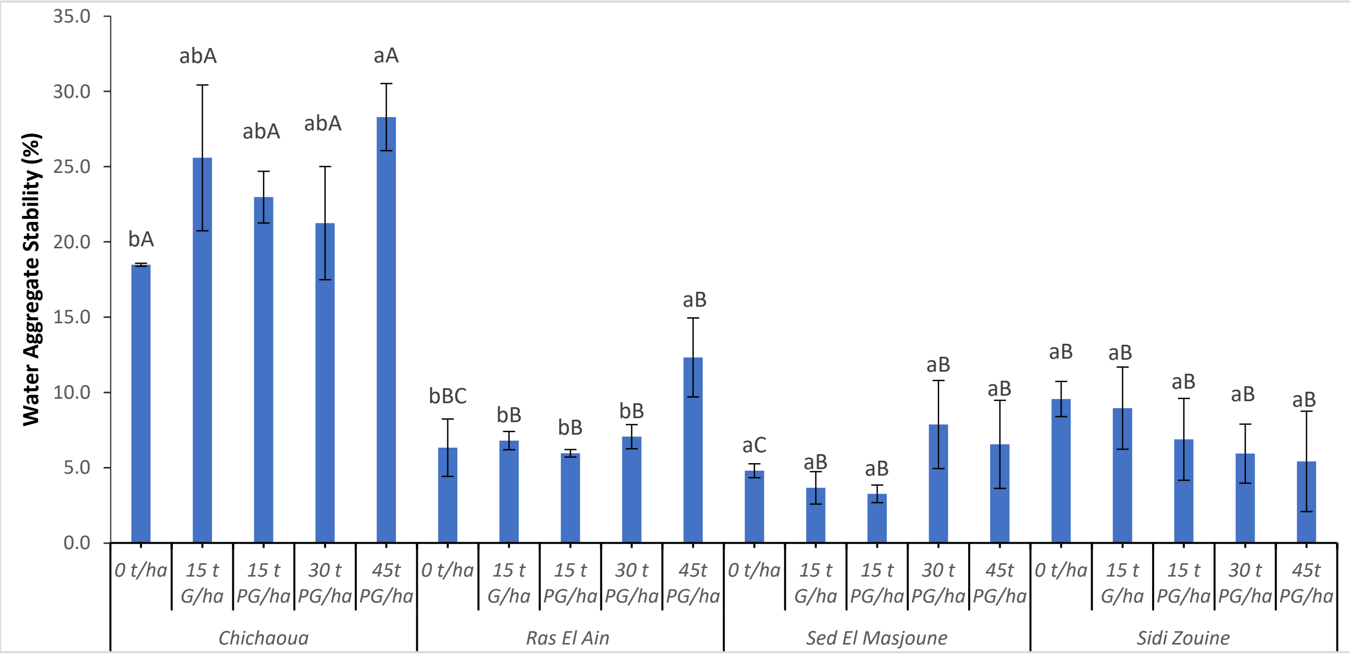

Figure 2. Effects of phosphogypsum rates on Water Aggregate Stability. The values represent the mean (n = 3) and the vertical bars represent the standard error. Lower-case letters compare the different treatments in the same region and upper-case letters compare the same treatment in different region using the Tukey test ($p < 0.05$).

Table 3. Overall efficiency (%) of the amendment to improve Water Aggregate stability.

	Soil Amendment Dose	Overall Efficiency (%)
Chichaoua	15 t G/ha	−38%
	15 t PG/ha	24%
	30 t PG/ha	15%
	45t PG/ha	53%
Ras El Ain	15 t G/ha	8%
	15 t PG/ha	−6%
	30 t PG/ha	12%
	45t PG/ha	95%
Sed El Masjoune	15 t G/ha	−24%
	15 t PG/ha	−32%
	30 t PG/ha	64%
	45t PG/ha	36%
Sidi Zouine	15 t G/ha	−6%
	15 t PG/ha	−28%
	30 t PG/ha	−38%
	45t PG/ha	−43%

There is a linear relationship between the PG application rate and WAS (Table 4 and Figure 3). This relationship in different soils showed two types of correlation. The first group presented a positive correlation in soil from the regions of Chichaoua, Ras El Ain, and Sad El Masjoune. The second group presented a negative correlation in soil from the region of Sidi Zouine. Figure 3 represents the linear regression between the PG application rate and WAS for all regions. PG rates effect on Water Aggregate stability showed a high coefficient of determination (R^2 = 93.41%, p value < 0.05).

Table 4. Relationship between PG amendment rate and Water Aggregate stability.

Region	Regression Model	R^2	RMSE	p Value
Chichaoua	WSA = 17.81 + 0.17 × PG	0.95	0.64	<0.05
Ras El Ain	WSA = 5.05 + 0.12 × PG	0.69	1.44	0.17
Sad El Masjoune	WSA = 4.14 + 0.06 × PG	0.40	1.35	0.36
Sidi Zouine	WSA = 8.95 − 0.09 × PG	0.88	0.55	0.06

RMSE: Root Mean Square Error.

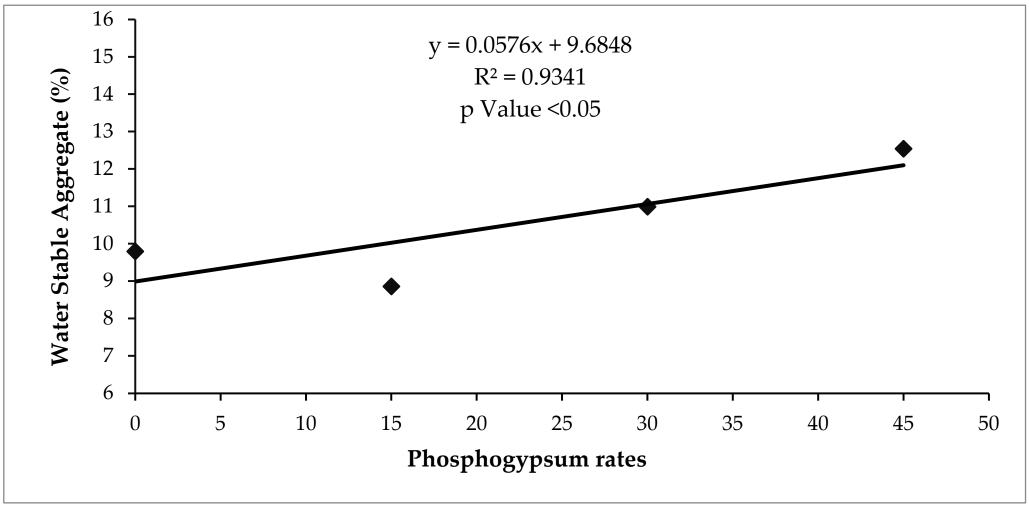

Figure 3. The relationship between phosphogypsum rates and Water Aggregate Stability.

3.2. Water Retention Characteristics

Table 5 summarizes the phosphogypsum effect on soil hydraulic properties. Soils had significantly different field-capacity moisture (FC) (p value< 0.05). Values of FC in the soils from Chichaoua and Ras El Ain were significantly different from the others. For each soil, field capacity (FC), permanent wilting point (PWP), and available water capacity for plants (AWC) were generally lower in the control treatment compared to treated pots. However, the FC was not significantly affected by the applied PG rate. Regarding the AWC in the soil of Chichaoua, the effect of PG was significantly different from the treatment that received G and the amendment rate of 15 t/ha improved AWC by 16% compared to the control. In the same soil, treatment with 45 t/ha of PG presented unexcepted results with AWC lower than the control. Concerning Ras El Ain soil, the soil amendments (PG and G) used did not present a significant effect on the hydrological properties. However, the AWC was increased by 69% with 45 t/ha of PG compared to the control. Regarding the soils from the Sed El Masjoune and Sidi Zouine regions, there was no significant difference among the amendment rates.

Table 5. Phosphogypsum effect on soil hydraulic properties in Moroccan saline–sodic soils.

Soil	Amendment Rate	FC	PWP	AWC
			$g.g^{-1}$ (%)	
Chichaoua	0 t/ha	26.95 aB ± 0.58	17.05 bC ± 1.38	9.91 aA ± 0.95
	15 t G/ha	27.14 aB ± 1.63	23.59 aAB ± 2.35	3.54 bAB ± 1.57
	15 t PG/ha	27.30 aB ± 0.57	15.80 bC ± 0.98	11.50 aA ± 1.08
	30 t PG/ha	27.54 aB ± 1.20	17.16 bC ± 3.57	10.38 aA ± 3.04
	45 t PG/ha	29.42 aB ± 2.06	24.29 aA ± 2.19	6.17 bA ± 1.85
Ras El Ain	0 t/ha	24.64 aB ± 0.68	22.84 aB ± 0.57	1.80 aC ± 0.12
	15 t G/ha	25.05 aB ± 0.49	22.82 aB ± 1.21	2.23 aB ± 0.94
	15 t PG/ha	25.64 aB ± 1.77	22.89 aB ± 2.33	2.75 aC ± 1.19
	30 t PG/ha	24.84 aC ± 0.51	23.12 aB ± 0.58	1.72 aB ± 0.43
	45 t PG/ha	26.59 aB ± 1.80	24.76 aA ± 3.35	3.03 aA ± 0.80
Sed El Masjoune	0 t/ha	20.25 aC ± 0.69	13.68 aD ± 0.23	6.57 aAB ± 0.71
	15 t G/ha	20.29 aC ± 1.79	15.99 abC ± 2.49	4.30 abAB ± 1.24
	15 t PG/ha	22.59 aC ± 2.72	17.36 abC ± 1.98	5.23 abB ± 1.28
	30 t PG/ha	23.60 aC ± 1.77	19.36 aC ± 2.20	4.24 abB ± 0.98
	45 t PG/ha	22.87 aC ± 3.22	19.14 aB ± 3.33	3.73 bA ± 0.97
Sidi Zouine	0 t/ha	32.35 abA ± 2.90	28.20 aA ± 0.08	4.15 aBC ±2.82
	15 t G/ha	31.21 bA ± 1.48	26.61 aA ± 2.16	4.60 aA ± 1.58
	15 t PG/ha	33.36 abA ± 1.31	29.61 aA ± 2.53	3.74 aBC ± 1.44
	30 t PG/ha	33.28 abA ± 0.91	29.35 aA ± 1.16	3.93 aB ± 1.01
	45 t PG/ha	33.50 aA ± 0.83	28.07 aA ± 3.08	5.43 aA ± 2.57

The values represent the mean (n = 3) ± the standard error. Lower-case letters compare the different treatments in same region and upper-case letters compare the same treatment in different region using the Tukey test ($p < 0.05$).

3.3. Porosity and Bulk Density

Figure 4 shows the effects of phosphogypsum rates on the Total Porosity (TP). Soil region and amendment rate of PG presented a significant effect on TP (p value < 0.05). In general, the phosphogypsum increased TP. In Chichaoua Soil, TP was 6 and 8% greater in the 15 t PG/ha and 30 t PG/ha treatments than in the control treatment. In Ras El Ain soil, the increase in TP was proportional to the increase in phosphogypsum rates, and 45 t PG/ha resulted in an 8% increase in TP when compared to the control treatment. Regarding the Bulk density (BD), soil region and amendment rate of PG presented a significant effect on this soil property (p value < 0.05) (Figure 5). A slight effect was observed of BD in Chichaoua Soil, and BD was 5% lower in the pot treated with 45 t PG/ha compared to the control. However, the soil of Sidi Zouine and Sed El Masjoune showed similar values of BD for the different phosphogypsum rates.

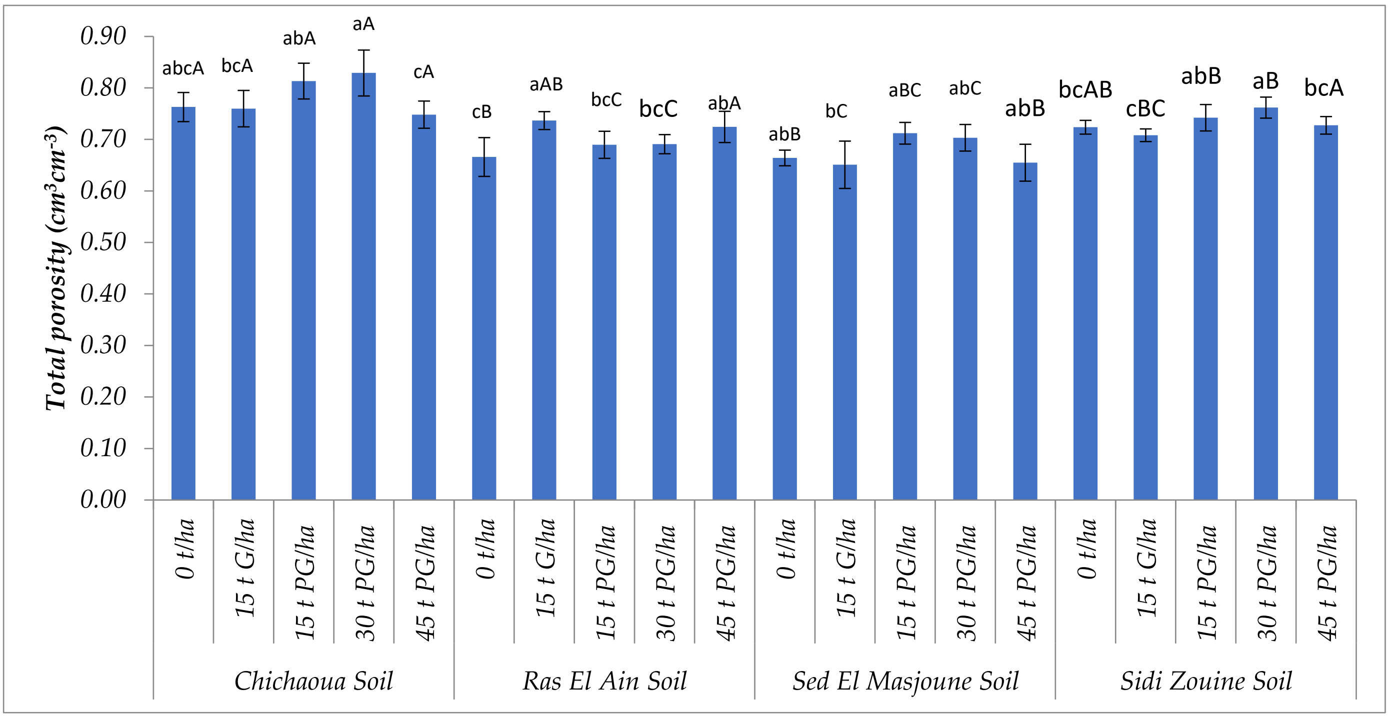

Figure 4. Effects of phosphogypsum rates on the Total porosity. The values represent the mean (n = 3) and the vertical bars represent the standard error. Lower-case letters compare the different treatments in same region and upper-case letters compare the same treatment in different region using the Tukey test ($p < 0.05$).

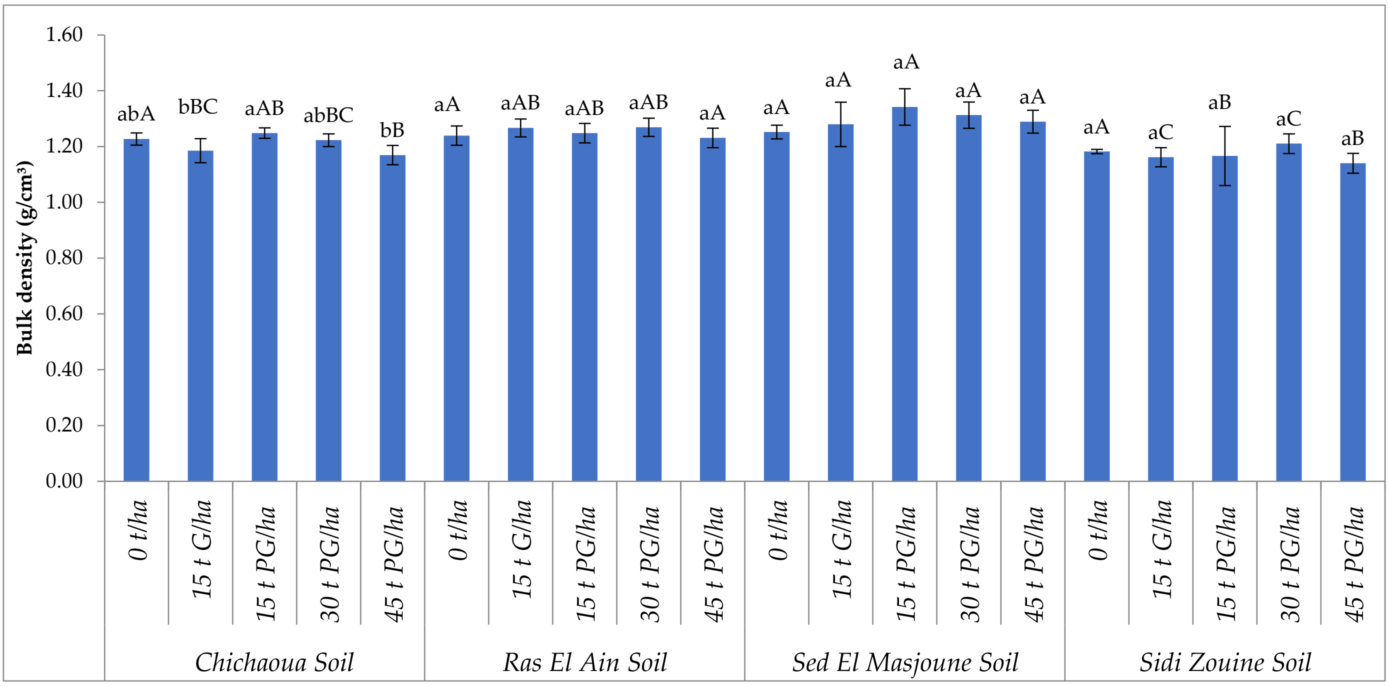

Figure 5. Effects of phosphogypsum rates on the bulk density. The values represent the mean (n = 3) and the vertical bars represent the standard error. Lower-case letters compare the different treatment in same region and upper-case letters compare the same treatment in different region using the Tukey test ($p < 0.05$).

4. Discussion

4.1. Effect of Amendment by Phosphogypsum/Gypsum on Soil-Aggregate Stability

In general, soil structure is affected by soil salinization and sodification [62], which was supported by the results of this study, when comparing soil aggregation in different soils with different levels of salinization and sodification. The action of phosphogypsum on soil aggregation can occur by ensuring cation and electrolyte concentration balance and altering the soil susceptibility to dispersion, by affecting the balance between attractive and repulsive forces [38]. In addition, phosphogypsum application prevents soil structure deterioration during leaching and reduces sodium concentration and its dispersant effect on soil aggregation [63]. Phosphogypsum acted by bringing divalent cations (Calcium and Magnesium) in the soil solution to replace the monovalent cations (Sodium and Potassium) with Ca^{2+} and Mg^{2+} and contributes to the formation of aggregates and macro-pores. Therefore, improving soil structure and soil water retention.

According to Farahani et al. [64], the monovalent cation caused clay dispersion and reduced soil aggregation. In this study, we evaluated the effect of phosphogypsum rates on water aggregate stability (WAS). The results indicate that the application of PG explained 93% of WAS variation (coefficient of determination, $R^2 = 0.93$), as indicated in Figure 3 and Tables 3 and 4. This relationship was more pronounced in saline soils with a low level of salinity (SAR < 6), principally in the soil of Chichaoua and Ras El Ain (SAR = 9.9). Similar results were obtained by Farahani et al. and Levy et al. [64,65], who observed an effect of sodium on reducing aggregate stability and the amount of macro-aggregates. The response to amendment rate (gypsum or phosphogypsum) in different soils was different, as well as the reaction between sodium concentration and aggregate stability. This response can be explained by salinity and by the effect of other cement agents (soil organic matter and divalent cations) on soil aggregations. However, Armstrong and Tanton found that an application of 10 T/ha of gypsum did not have an effect on aggregate stability in saline-sodic clay soils [66].

Concerning the comparison between PG and G, chemical analysis revealed that PG has a lower pH (Table 2). Ennaciri et al. attributed the acidity of the PG to the presence of residual acids like H_3PO_4, H_2SO_4, and HF [67]. PG has a higher calcium and sulfur content than natural gypsum. However, the latter is richer in Mg, K, and Al. Calcium and sulfur are the major constituents of PG and G. However, other elements present in low concentrations include magnesium, phosphorus, potassium, and aluminum [68,69]. Our finding confirmed that PG is more soluble than G (Table 2); as reported by Ennaciri et al. [67], due to the low pH of PG [70].

The ratio Ca: Mg and Ca: K are very low in the studied amendments. Indeed, K and Mg contents could not affect the amendment application. On the other hand, several authors reported that G and PG applications increased K and Mg leaching from the soil [71,72]. He et al. reported that Ca: Mg ratios did not influence clay dispersion of montmorillonite and kaolinite [73].

4.2. Effect of Amendment by Phosphogypsum/Gypsum on Soil Hydraulic Properties

The response to the application of phosphogypsum regarding hydraulic soil properties was observed in soil with a low-salinity level, principally in Chichaoua and Ras El Ain regions. According to Farahani et al., the presence of sodium in the soil increases clay dispersion, decreases soil aggregation, and reduces the macro-porosity in the soil, hence, reducing the soil water holding capacity [64]. Chawla et al. reported that soil water holding capacity is less for samples with higher salinity than those with lower soil salinity [74]. Overall, PG improved soil hydraulic properties compared to G and control, which could be explained by the effect of calcium and sulfate. PG promoted a greater concentration of calcium and sulfate compared to G (Table 2). PG has a favorable effect in increasing Ca^{2+} and reducing the pH and increasing the efficiency of reducing Na concentration in the soil. Furthermore, acidifying effect of PG contributed to the solubilization of soil calcium carbonates and enhanced Ca^{2+} in the soil [71,75].

Melo et al. attributed the increase in soil water dynamic to the substitution of the sodium for the calcium contained in the gypsum amendment [76]. Soil hydraulic properties were considered by different studies to be invariant to variations of salt concentration in the soil [77]. Previous research by Ağar showed that PG improved water infiltration over the 90 cm depth of a sodic soil and to leach 180 cm of water, and it took 1546 h in control without PG application, but only 368 and 225 h, respectively, for 7.5 and 15 t/ha of applied PG [78].

Cambisol and Luvisol, assessed in the presented study, are constituted by Montmorillonite. Montmorillonite is a 2:1 clay mineral characterized by a large specific surface area, high-cation-exchange capacity, and high ability to hold cations (Na^+, Mg^{2+}, K^+) [79]. In saline–sodic soils, the expandable interlayer space of Montmorillonite is occupied by sodium, causing soil swelling and clay dispersion. Sodium in the soil constituted a double layer due to low charge density [71], which reduces water flow in the soil, principally in soils with Montmorillonite [80]. However, the application of PG or G brings high content of calcium. Sodium is easily replaced by calcium due to valence, great hydrated ionic radius, and low adsorption selectivity (lyotropic series). Lyotropic series presented the relative strength of ion adsorption onto clay fraction. Lyotropic series for the principal cations in the soil is: $Ca^{2+} > Mg^{2+} > K^+ \approx NH4^+ > Na^+$. Sodium ranked in the last position in this sequence, which means low electrical charges with clay fraction, which promotes its replacement [81], reducing the sodic effect in the soil (Figure 6).

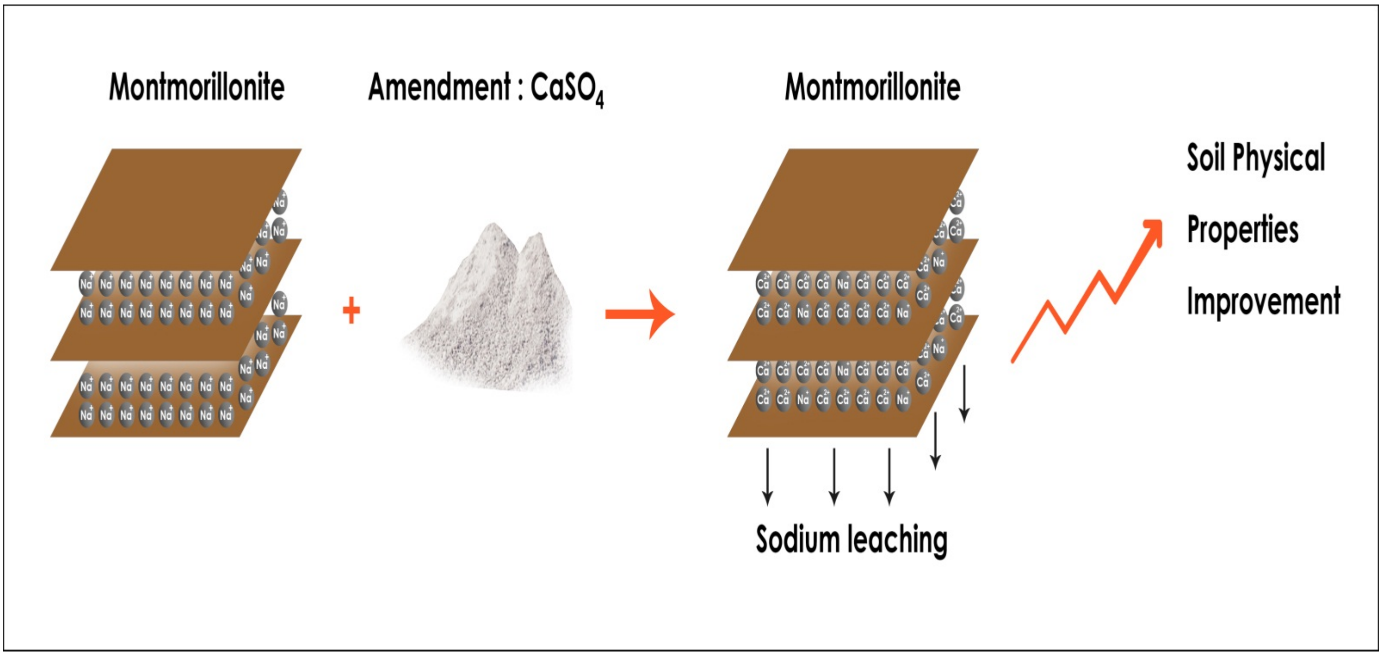

Figure 6. Effect of amendment (Ca SO_4) on Montmorillonite.

4.3. Effect of Amendment by Phosphogypsum/Gypsum on Total Porosity and Bulk Density

In the soil of Chichaoua, 45 t/ha of PG and 15 t/ha of G decreased Bulk density by 5% and 3%, respectively. A similar finding was reported by Müller et al., who indicated that the use of 12 t/ha of gypsum resulted in a 4% decrease in soil density compared to the control in Oxisols under no-till system [82]. The effect was clearer with the long-term application of gypsum (17 years) combined with green manure, limestone, and pasture. This strategy resulted in a 13.95% decrease in soil bulk density [83]. In this study, there is no effect of the amendment on the bulk density of the soils of Ras El Ain, Sidi Zouine, and Sed El Masjoune. This result can be explained by the short time of contact and reaction with the soil, the high-salinity level of those soils which probably require higher quantities of amendments. In fact, according to Gharaibeh et al., the positive effect of PG on saline-sodic soils was correlated with rising PG rates and time of contact and reaction with the soil [84].

PG application improved the total porosity. This can be explained by the improvement of soil aggregation promoted by PG due to the flocculant action provided by calcium [76]. In line with our results, studies conducted by Nayak et al., comparing different soil treated with gypsum, showed that gypsum-treated soils had higher porosity and soil aggregate stability [37]. Müller et al. demonstrated an increase in total porosity of 2.71% for 12 t/ha of gypsum and 2.38% for 4 t/ha [82].. This increase was mostly due to the increase in the total macropores.

The present study evaluated the effect of PG/G on the physical properties of Luvisols and Cambisols collected from salt-affected soils in four regions in Morocco. Overall, there is a clear difference between the soil of Chichaoua and the other soils, which could be explained by the low content of sodium in this soil (Soil no sodic: ESP = 7%). Overall efficiency is higher in Chichaoua soil by the fact that the calcium provided by the amendments (PG/G) was sufficient to replace the sodium in the clay fraction. Therefore, the reduction of the dispersive effect of sodium on clay and improvement of soil physical properties (aggregation, water retention, porosity, and bulk density).

5. Conclusions

This work presents the effect of phosphogypsum application as an amendment on some physical properties of Moroccan salt-affected soils. The overall efficiencies of phosphogypsum in different soils open the possibility of using phosphogypsum as an amendment in the reclamation process of marginated soils to improve soil structure, mitigate water stress, and reduce soil degradation processes and effects. Water stable aggregates improved with increasing phosphogypsum rate with a positive relationship and a high coefficient of determination (R^2 = 93.41%, p value < 0.05). Phosphogypsum application generally improved soil physical properties, principally for soils of Chichaoua and Ras El Ain regions. Phosphogypsum, a coproduct from the processing of phosphate rock, represents a promising solution for improving soil quality. The improvement of the soil's physical attributes enhances the root, vegetative and fructification development of the plants, which will positively affect agricultural yields, especially in arid and semiarid areas.

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