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Combined Application of Compost, Zeolite and a Raised Bed Planting Method Alleviate Salinity Stress and Improve Cereal Crop Productivity in Arid Regions

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Abstract: Soil salinity and climate change have a negative impact on global food production and security, especially in arid regions with limited water resources. Despite the importance of planting methods, irrigation, and soil amendments in improving crop yield, their combined impact on saline soil properties and cereal crop yield is unknown. Therefore, the current study investigated the combined effect of soil amendments (i.e., compost, C and zeolite, Z) and planting methods such as raised bed (M1) and conventional (M2), and different fractions of leaching requirements from irrigation water, such as 5% (L1) and 10% (L2), on the soil physio-chemical properties and wheat and maize productivity in an arid region. The combined application of C + Z, L2, and M1 decreased soil salinity (EC) and sodicity (ESP) after wheat production by 37.4 and 28.0%, respectively, and significantly decreased by these factors by 41.0 and 43.0% after a maize growing season. Accordingly, wheat and maize yield increased by 16.0% and 35.0%, respectively under such a combination of treatments, when compared to crops grown on unamended soil, irrigated with lower leaching fraction and planted using conventional methods. This demonstrates the significance of using a combination of organic and inorganic amendments, appropriate leaching requirements and the raised bed planting method as an environmentally friendly approach to reclaiming saline soils and improving cereal crop production, which is required for global food security.

Keywords: saline soils; soil amendments; wheat; maize; leaching requirements; planting methods

1. Introduction

Water scarcity limited natural resources and rapid population growth have all had a negative impact on irrigated land in arid regions, increasing soil salinity and negatively impacting soil health and crop production [1,2]. Furthermore, climate change, as well as the associated rise in temperature and changes in precipitation variability, has accelerated land deterioration, reduced crop production and increased food insecurity and malnutrition [3,4]. As a result, salt-affected soils have increased globally to approximately 930 Mha [5], with saline-alkaline soils accounting for the majority of this area [6]. This problem has compelled the scientific community to seek significant solutions to remediate soil salinity and increase plant resistance to salinity and drought. Ploughing [6], gypsum [7], sulphuric acid [8], polyacrylamide [9], sugar crop waste [2], compost [10] and biochar application [2] are some of the technologies used to reclaim saline soils. Zeolites (Z) are alkaline-hydrated aluminosilicates that come in more than 50 distinct forms [11]. They are used as heat storage materials and solar refrigerators, molecular sieve agents, ion-exchange elements and catalysts in different chemical reactions [12]. Natural zeolites are good soil amendments because they have a high water and nutrient holding capacity, which improves infiltration rates, saturated hydraulic conductivity, cation exchange capacity, and prevents water loss through deep percolation [13–17]. They can also be used as chelating agents and fertilizer [18]. Nonetheless, the use of Z to reclaim salt-affected soils has received less attention thus far, particularly in arid regions. Furthermore, the combination of Z and other common amendments, such as compost, may improve the efficiency of saline soil remediation, though this effect is still unknown, necessitating extensive research.

The raised bed (RB) planting method has the potential to improve irrigation water distribution, reduce water use, and increase crop yield and water productivity compared to traditional planting methods [19,20]. Li., et al. [21] found that using the RB method increased wheat productivity and solar radiation use efficiency, and they interpreted this as a consequence of the vertical distribution of photosynthetically-active radiation. The effect of RB application on saline soils and crop productivity in arid regions is however still unknown. Moreover, the integrated effect of composting, zeolite application and raised bed growing has received less attention thus far. Despite the fact that cereal crops, particularly wheat and maize, are considered strategic crops for ensuring food security, most countries in arid regions rely heavily on imports due to land degradation, poor management of salt-affected soils, and climatic changes [22–25]. As a result, proper saline soil management is an urgent need for improving cereal crop production and closing the food gap in arid regions. In this regard, the current study aims to assess the effects of zeolite, compost, and planting methods on the physical and chemical soil properties of saline soil. Furthermore, additional research was conducted to investigate the impact of such treatments on wheat and maize yield grown in arid regions.

2. Materials and Methods

2.1. Experimental Design and Agronomic Practices

A field experiment was conducted over two successive growing seasons (winter 2019/2020 and summer 2020) in the North Nile Delta, Egypt (31°05′31′′ N and 30°56′55′′ E). The experiment was conducted to explore the integrated effect of compost, zeolite, leaching requirements and planting methods on saline soil properties and productivity of wheat (*Triticum aestivum* L., cv Sakha171) and maize (*Zea mays*, cv Hybrid Cross Giza 168). Wheat grains were sown at a rate of 140 kg ha^{-1} on 27 November 2019. Meanwhile, maize grains were sown in five ridges at rate of two grains per hole with 20 cm spacing on June 10th, 2020. The experimental design was a split-plot design with four replicates. Irrigation treatments were installed in the main plots and included irrigation to field capacity (FC) with 5% leaching requirements (LR) and irrigation to FC with 10% LR. Two planting methods, traditional and raised bed, were assigned to the sub-main plots. The sub-sub main plots included soil amendments such as control, compost (C), zeolite (Z), and compost plus zeolite (CZ). The application rates of Z, and C were 680 kg ha^{-1}, and 12.0 t ha^{-1} respectively, while CZ was added at a 1:1 w/w ratio of C and Z. This equals 340 kg ha^{-1} of Z and 600 kg ha^{-1} of compost. Irrigation scheduling was determined by identifying the irrigation time using daily time domain reflectometery (TDR)measurements and irrigation water quantity was controlled using the cuthroat flume (20 cm × 70 cm). Raised bed treatments were structured with 15 cm high, flat tops about 70 and 100 cm width as well as 70 cm spacing, while the traditional planting treatment was flat for wheat and furrowed for maize. The analysis data for SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5 and loss on ignition (LOI) of the Z as reported by the National Research Centre, Egypt were 41.86, 0.64, 36.45, 0.75, 0.02, 0.04, 0.16, 0.09, 0.51, 0.18 and 10.26% as wt., respectively. The chemical composition of compost includes EC (3.2 dS m^{-1}), pH (7.7), OM (54.2%), C (18), N (1.75 g kg^{-1}), P (0.92 g kg^{-1}), K (1.25 g kg^{-1}), Fe (165 g kg^{-1}), Zn (71.0 g kg^{-1}), Mn (120 g kg^{-1}) and moisture content (27.8%). Fertilization and other agricultural practices for wheat and maize plants in the North Delta region were carried out in accordance with the Egyptian Ministry of Agriculture recommendations.

2.2. Initial Soil Analysis and Climatic Conditions

Soil samples were collected at three depths (0–20, 20–40 and 40–60 cm) before sowing of wheat for initial analysis of physical, chemical and nutritional properties (Table 1). The soil texture is clayey, characterized by high values of salinity and sodicity. For both seasons, daily weather data include maximum and minimum temperatures, solar radiation and rainfall were collected from a nearby eddy covariance station (Figure 1).

Table 1. Initial soil physio-chemical analysis of experiment before wheat sowing (2019/2020).

Soil Depth (cm)	pH	$CaCO_3$(%)	EC (dS m^{-1})	ESP	Available Macro Nutrients (mg kg^{-1})		
					N	P	K
0–20	8.27 ± 0.1	3.12 ± 0.2	6.13 ± 0.4	17.05 ± 0.7	31.95 ± 2.5	8.75 ± 0.2	265 ± 9.5
20–40	8.65 ± 0.1	2.56 ± 0.1	7.35 ± 0.5	18.87 ± 0.8	27.18 ± 2.8	8.26 ± 0.4	228 ± 8.7
40–60	8.75 ± 0.2	2.18 ± 0.3	9.85 ± 0.6	21.36 ± 1.1	23.36 ± 3.1	7.56 ± 0.1	196 ± 10
	OM (%)	CEC (C mol kg^{-1})	FC (%)	PWP (%)	BD (Mg m^{-3})	AI	MWD (mm)
0–20	1.36 ± 0.01	38.93 ± 0.2	43.81 ± 0.2	22.39 ± 0.1	1.32 ± 0.01	0.24 ± 0.01	0.32 ± 0.01
20–40	1.24 ± 0.02	37.28 ± 0.1	40.68 ± 0.1	20.65 ± 0.2	1.37 ± 0.03	0.28 ± 0.02	0.29 ± 0.01
40–60	1.09 ± 0.03	36.81 ± 0.3	38.98 ± 0.3	19.75 ± 0.3	1.43 ± 0.05	0.25 ± 0.01	0.25 ± 0.02
	Sand (%)	Silt (%)	Clay (%)	Texture class	PR (N cm^{-2})	HC (cm d^{-1})	
0–20	12.0 ± 0.2	33.9 ± 0.9	54.1 ± 1.1	Clay	275 ± 8.5	2.7 ± 0.2	
20–40	11.9 ± 0.3	34.4 ± 1.1	53.7 ± 1.3	Clay	282 ± 12.3	2.5 ± 0.1	
40–60	20.5 ± 0.1	34.3 ± 0.8	54.2 ± 1.2	Clay	289 ± 13.5	2.1 ± 0.1	

EC: electrical conductivity (salinity); OM: soil organic matter; CEC: soil cation exchange capacity; FC: field capacity; PWP: permanent wilting point; BD: soil bulk density; AI: soil aggregation index; MWD: mean weight diameter of soil particles; PR: soil penetration resistance; HC: soil hydraulic conductivity; Mean values ± Stdev, n = 4.

2.3. Soil Measurements

Soil samples were collected from all plots prior to the experiment, as well as after the first and second seasons, at three consecutive depths of 0–20, 20–40, and 40–60 cm to monitor some physical and chemical properties (i.e., salinity, sodium adsorption ratio and exchangeable sodium according to [26]. Soil bulk density and total porosity were measured as described by [27]. Infiltration rate was determined using a double cylinder infiltrometer as described by [28]. Field capacity and wilting point were determined by using the pressure plate extractor with regulated air pressure [29]. Organic matter content was determined according to the Walkley and Black method [30]. Calcium carbonate ($CaCO_3$) was determined using a calcimeter method as described by Senlikci et al. [31]. Soil available N was determined using K_2SO_4 (1%) according to Matsumoto et al. [32], and available P and K were extracted by ammonium bicarbonate- DTPA and determined according to Tian et al. [33].

2.4. Crop Growth and Yield Measurements

After air drying, the seeds of each plant bundle were manually threshed and weighed separately to obtain 1000 grain weight of wheat, and 100 grain of maize from each experimental plot. Five plants were chosen at random from each plot to measure the plant heights and spike lengths. The total yield of wheat and maize for each plot was harvested, weighed, and converted to tons ha^{-1} for each treatment.

2.5. Statistical Analysis

Data from this study were statistically analyzed using the analysis of variance method, as described by Snedecor and Cochran [34], and the treatments were compared by Duncan's multiple range test. Boxplots, principal component analysis (PCA), and pair plots were visualized using the plotly function in Python language.

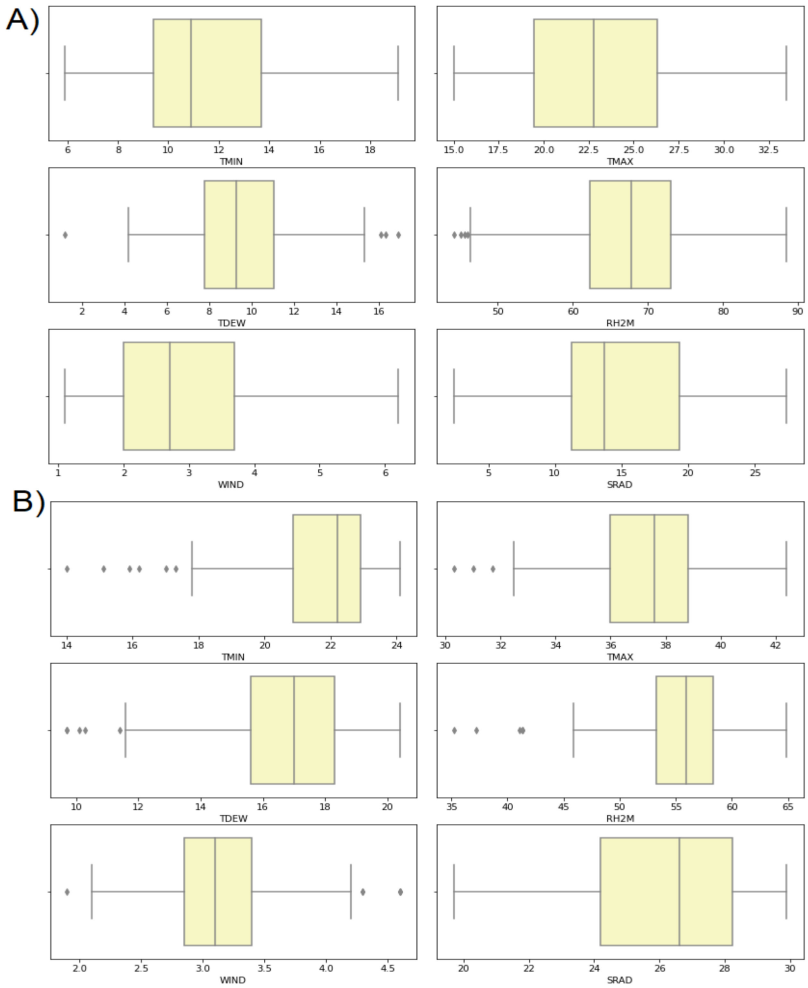

Figure 1. Boxplots of weather data over wheat growing season (**A**) and summer maize growing season (**B**). Parameters include minimum temperature (TMIN), maximum temperature, °C (TMAX), dew point temperature (TDEW), relative humidity, % (RH2M), wind speed, m/s (WIND), and solar radiation, MJ/m^2/day (SRAD).

3. Results and Discussion

3.1. Soil Physio-Chemical Properties

During the wheat and maize growing seasons, all treatments had lower soil EC, SAR, and ESP (Figure 2A–C). During the wheat season, the EC, SAR, and ESP decreased by 20.08%, 21.95%, and 19.59%, respectively, under irrigation to FC + 5% LR (L1); by 26.89%, 25.40%, and 22.83%, respectively, under irrigation to FC + 10% LR (L2). In addition, such parameters were reduced by 23.52%, 23.69%, and 21.22% under irrigation to FC + 5% LR (I1), respectively, and by 29.88%, 32.71%, and 29.95% under irrigation to FC + 10% LR (I2), respectively, compared to initial values in the following maize season. This supports the importance of leaching fractions in reducing soil salinity and sodicity. These findings are similar with those obtained by [35,36]. Over the course of the study, the salinity and sodicity of the soil in the raised beds' 60 cm soil (M1) were higher than in the other two treatments. During the wheat season, the flat (M2) had EC, SAR, and ESP levels of 5.85 dSm^{-1}, 12.78, and 14.96 at harvest, respectively, while such parameters were decreased by 3.49%, 1.67%, and 1.53% in the flat than in the raised beds. On the contrary, during the maize season, the EC, SAR, and ESP levels in the furrow (M2) were 5.57 dSm^{-1}, 11.86, and 13.94 at harvest, respectively, while decreased in the raised beds by 4.66%, 4.28%, and 4.06%, respectively. Soil amendments (C and Z) reduced soil salinity and sodicity significantly. Adding zeolite and/or compost decreased EC, SAR, and ESP during the wheat season, while the combination (S + C) recorded the lowest EC, SAR, and ESP with values of 5.37 dS m^{-1}, 12.25, and 14.39, respectively. During the maize season, the same treatments gave values of 5.11dS m^{-1}, 11.17, and 13.18, respectively. As a result, the changes in EC, SAR, and ESP after different treatments application in comparison to the initial ECe indicate that L2 + M1 + C+Z treatment has the better effect in decreasing the EC, SAR, and ESP by 37.40%, 30.91%, and 28.09% after wheat harvesting and by 41.00%, 45.94%, and 43.19% after maize harvesting. Baghbani-Arani et al. [37] found that combination of zeolite and vermicompost decreased soil salinity and sodicity significantly. Natural zeolites are good soil ameliorating substances because they have a high water and nutrient holding capacity (WHC); they improve infiltration rate, saturation hydraulic conductivity, cation exchange capacity, and limit water loss through deep percolation [13,17]. Organic amendments, on the other hand, such as compost and/or vermicompost, could improve the efficiency of water treatment residuals in improving soil physical properties, and could be considered as an ameliorating material for the reclamation of salt-affected soils [1,2,8,38]. However, the current study included not only organic amendments with zeolite, but also leaching fractions and planting methods. This combination significantly reduced soil salinity and sodicity, confirming the importance of current research in reducing soil salinity in arid regions.

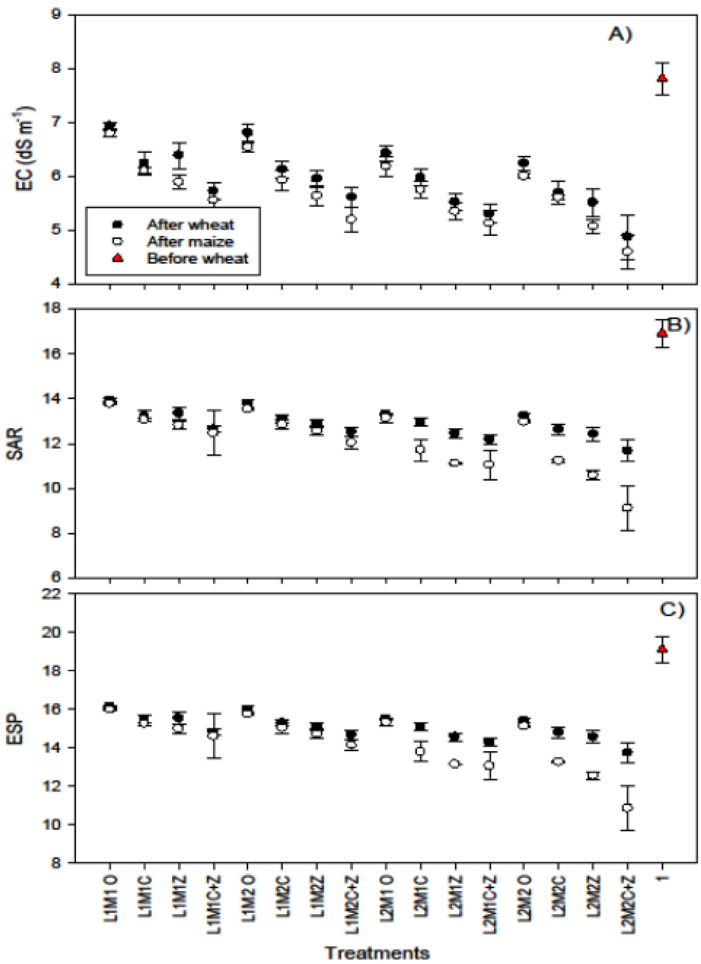

Figure 2. Soil EC, SAR and ESP following wheat (closed scatter) and maize (open scatter) subjected to different treatments of irrigation with various leaching requirements as 5% (L1) and 10% (L2), planting methods raised bed (M1) and conventional (M2), as well as conditioners application such as control, compost (C), zeolite (Z) and mixture of compost and zeolite (C + Z) compared to initial values (red triangle). The symbols are means and error bars are standard deviations.

Irrigation with different leaching requirements, planting method, and soil amendments improved soil physical properties, particularly bulk density and total porosity, and this effect was significant for maize crops (Figure 3). Over the first growing season, the lowest value of bulk density (1.23 Mg m^{-3}) and consequently the higher value of total porosity (53.5%) were achieved with treatments of irrigation quota plus 10% leaching requirements (LR), raised bed planting method, and adding mixture of compost and zeolite as soil amendment. Meanwhile, the highest value of bulk density (1.35 Mg m^{-3}) and the lowest value of total porosity (48.5%) were noted in first irrigation treatment (5% LR), using conventional planting method and without amendments application. This demonstrates the significance of raised bed sowing, higher LR irrigation, and the application of Z and C to improve soil physical properties. The effect of such treatments was greater in the second growing season than in the first, which may be due to the residual effect of soil amendments in improving soil organic matter and fertility content. Likewise, soil infiltration rate (IR) and cumulative infiltration (CUM) improved significantly with raised bed sowing method and application of compost and zeolite (). The highest values of IR (1.3 cm h^{-1}) and CUM (16 cm) were recorded with raised bed sowing method and application of compost and zeolite. The IR and CUM values, on the other hand, were lower with the conventional sowing method and without the use of soil amendments. Similar studies reported the importance of compost in improving saline soil properties in arid regions [2,10,39].

3.2. Wheat and Maize Productivity

Tables 2 and 3 show that L2 (FC + 10%) leaching requirements significantly increased 1000-GW, straw, grain, and biological yield of wheat and maize when compared to L1 (FC + 5% LR). Further, the raised bed method increased such features significantly and recorded the highest values compared with the conventional planting method. Application of amendments increased the yield of both crops, and the highest values were recorded with the mixture of C and Z. The results showed that the interaction between L×M, L×A, and M×A resulted in a significant increase in wheat and maize yield. Wheat and maize yields were recorded at their highest levels due to the interaction of L×M×A (L2 + M1 + C+Z). Recent studies have explored the interactive effect of soil amendments and fertility under salinity stress [40], interactive between amendments and soil biotic and abiotic stresses [41], mitigating degraded soils using biochar and compost [42], and combination of gypsum and straw pellets to alleviate soil sodality [43].

Table 2. Effect of different studied treatments on wheat yield and yield attributes.

Treatments	1000-GW (g)	Straw Yield (Mg/ha)	Grain Yield (Mg/ha)	Biological Yield (Mg/ha)	Harvest Index
		Leaching Requirements (I)			
L1	59.19 b	3.450 b	5.129 b	8.756 b	58.67 a
L2	63.95 a	3.928 a	5.407 a	9.336 a	58.04 b
F-test	**	**	**	**	**
LSD0.05	0.184	0.0013	0.002	0.005	0.004
LSD0.01	0.426	0.0032	0.007	0.009	0.009
		Planting methods (M)			
M1	63.63 a	4.115 a	5.430 a	9.547 a	56.91 b
M2	59.51 b	3.440 b	5.106 b	8.547 b	59.79 a
F-test	**	**	**	**	**
LSD0.05	0.076	0.0012	0.002	0.005	0.014
LSD0.01	0.126	0.0018	0.004	0.007	0.023
		Amendments (A)			
CK	56.94 d	3.261 d	4.666 d	7.928 d	57.79 d
C	60.58 c	3.590 c	5.062 c	8.652 c	58.10 c
Z	62.87 b	3.974 b	5.416 b	9.390 b	58.57 b
C + Z	65.89 a	4.287 a	5.929 a	10.22 a	58.96 a
F-test	**	**	**	**	**
LSD0.05	0.043	0.013	0.002	0.0032	0.013
LSD0.01	0.058	0.018	0.005	0.0043	0.018

Table 2. *Cont.*

Treatments	1000-GW (g)	Straw Yield (Mg/ha)	Grain Yield (Mg/ha)	Biological Yield (Mg/ha)	Harvest Index
			Interaction		
L*M	ns	**	**	**	**
L*A	**	**	**	**	**
M*A	**	**	**	**	**
L*M*A	**	**	**	**	**

L1: leaching requirements by 5%, L2: leaching requirements by 10%, M1: raised bed planting method, M2: conventional planting method, CK: control (without amendments), C: compost, Z: zeolite. Small letters similar have no significant differences, while different letters show significant differences between them. *: is significant at 5 %, while **: is highly significant at 1%. ns: refers to non-significant.

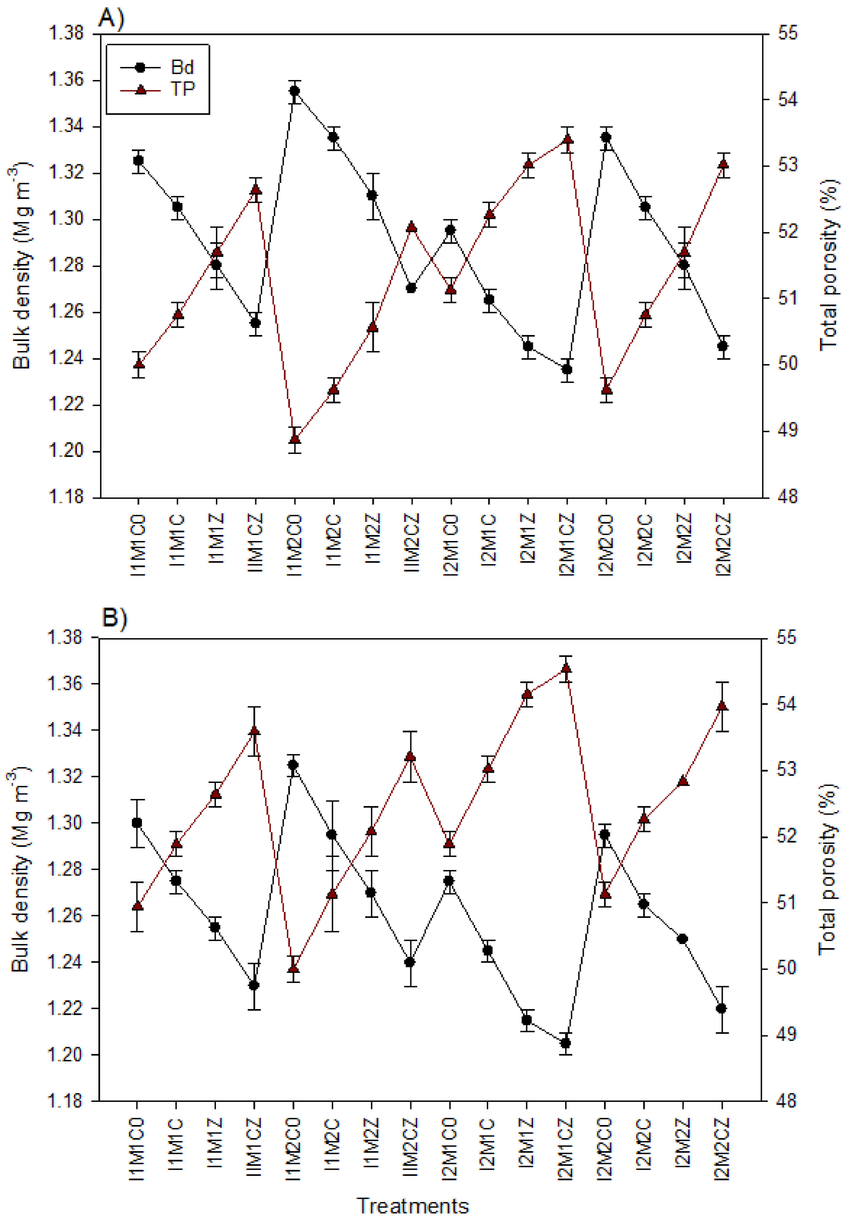

Figure 3. Soil bulk density and total porosity following wheat (**A**) and maize (**B**) subjected to different treatments of irrigation with various leaching requirements as 5% (I1) and 10% (I2), planting methods raised bed (M1) and conventional (M2), as well as conditioners application such as control, compost (C), zeolite (z) and mixture of compost and zeolite (C + Z). The symbols are means and error bars are standard deviations. The initial values of bulk density and total porosity before wheat crop were 1.37 Mg m^{-3} and 48.3%, respectively.

Table 3. Effect of different studied treatments on Maize yield and yield attributes.

Treatments	100-GW (g)	SY (Mg/ha)	GY (Mg/ha)	BY (Mg/ha)	Harvest Index
		Leaching Requirements (I)			
L1	34.31 b	7.222 b	6.734 b	13.956 b	48.18 a
L2	35.08 a	7.698 a	7.183 a	14.883 a	48.24 a
F-test	**	**	**	**	ns
LSD0.05	0.047	0.005	0.050	0.025	0.35
LSD0.01	0.011	0.012	0.117	0.057	0.80
		Planting methods (M)			
M1	34.88 a	7.629 a	7.084 a	14.713 a	48.29 a
M2	39.51 b	7.291 b	6.831 b	14.124 b	48.12 b
F-test	**	**	**	**	**
LSD0.05	0.037	0.032	0.009	0.034	0.09
LSD0.01	0.06	0.055	0.016	0.059	0.15
		Amendments (A)			
CK	33.57 d	5.382 d	4.940 d	10.322 d	47.85 c
C	35.09 b	7.100 c	6.509 c	13.611 c	47.86 c
Z	34.18 c	8.420 b	7.987 b	16.410 b	48.45 b
C + Z	36.03 a	8.937 a	8.395 a	17.335 a	48.68 a
F-test	**	**	**	**	**
LSD0.05	0.038	0.027	0.013	0.029	0.105
LSD0.01	0.05	0.039	0.018	0.041	0.143
			Interaction		
L*M	**	ns	*	**	*
L*A	**	**	**	**	**
M*A	**	**	**	**	**
L*M*A	**	**	**	**	**

SY: straw yield, GY: grain yield, BY: biological yield, L1: leaching requirements by 5%, L2: leaching requirements by 10%, M1: raised bed planting method, M2: conventional planting method, CK: control (without amendments), C: compost, Z: zeolite. Small letters similar have no significant differences, while different letters show significant differences between them. *: is significant at 5 %, while **: is highly significant at 1%, ns: refers to non-significant.

The PCA was used to investigate the relationships between crop yield and attributes, as well as between such features and treatments (Figure 4). For wheat crop (Figure 4A), there was a strong positive correlation between grain yield, anthesis, biological yield, harvest index (HI), straw yield and grain weight. Meanwhile, there was negative correlation between such features and maturity. This indicates that, factors responsible for accelerating the maturity, will definitely decrease yield and yield components and vice versa. Respecting the corresponding treatments, there was positive correlation between I2 (15% LR), raised bed sowing method (M1), and application of compost and zeolite (C + Z). Furthermore, there was positive correlation between such treatments with yield and anthesis and negative correlation with maturity (Figure 4A). For maize crop, there was positive correlation between grain yield, straw yield, biological yield which positively correlated also with treatments of M1, I2, and C + Z (Figure 4B). This demonstrates the value of such treatments in increasing cereal crop productivity in saline soils. Supplementary Figures S2 and S3 show the detailed correlations over all treatments and crop features for both wheat and maize crops.

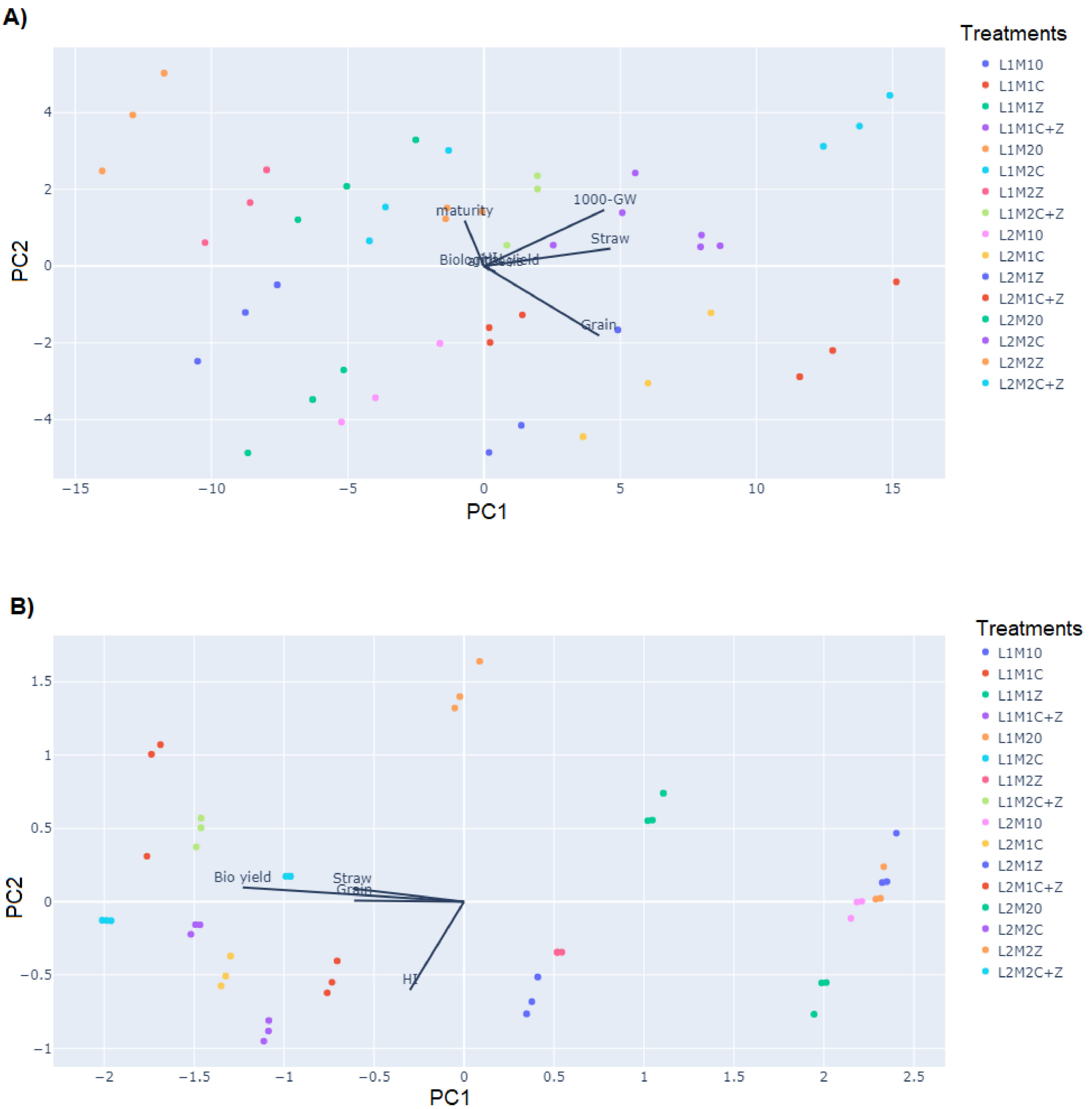

Figure 4. Principal component analysis (PCA) to better understand the variability of wheat (**A**) and maize (**B**) yield with their components (loadings), and corresponding treatments (scores). The loadings of wheat include wheat grain yield, straw yield, biological yield, grain weight, harvest index (HI), anthesis date and maturity date. Meanwhile, the loadings of maize consisted of grain yield, straw yield, biological yield, and harvest index. The treatments (scores) included combination of irrigation with different leaching fractions as 5% (L1) and 10% (L2), planting methods as raised bed (M1) and conventional (M2), as well as different soil amendments as control (C0), compost (C), zeolite (Z), and mixture of compost and zeolite (C + Z).

4. Conclusions

Higher rate leaching requirements, use of raised bed planting methods and the use of compost and zeolite reduced soil salinity and sodicity while increasing cereal crop productivity in arid regions. Leaching requirements of 10% from actual applied irrigation water, raised bed method, and mixture of compost and zeolite showed superiority to lower rate of leaching fraction, traditional planting method and adding individual amendments. Soil EC and ESP decreased significantly, while wheat and maize yield increased, confirming the importance of integrating irrigation, amendments, and planting methods in reclaiming saline soils and increasing crop production in marginal areas. Finally, it could be recommended that combining compost and zeolite, as well as using the raised bed planting method, is a cost-effective way for farmers to improve saline soils and cereal crop productivity.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11122495/s1, Figure S1: Infiltration rate and cumulative infiltration of soil following the corresponding treatments, Figure S2: Pair plot of wheat yield and yield components, Figure S3: Pair plot of maize yield and yield components.

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