Addressing Soil Fertility Challenges in Arid Agriculture: A Two-Year Evaluation of Combined Soil Organic Amendments Under Saline Irrigation

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Addressing Soil Fertility Challenges in Arid Agriculture: A Two-Year Evaluation of Combined Soil Organic Amendments Under Saline Irrigation

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Abstract: Background: Soil salinity poses a significant threat to agricultural lands by adversely affecting soil properties, crop productivity, and, consequently, global food security. This study evaluated the effects of date palm waste compost (C), applied alone or combined with biochar (BCC) or Ramial chipped wood (RCWC), on soil properties and barley yield under arid and saline conditions. Methods: A field experiment was performed in a completely random design with three replications. In addition to the unamended soil (control), treatments with compost (C), biochar + compost (BCC) and Ramial chipped wood + compost (RCWC) were tested. We monitored soil physico-chemical parameters, straw biomass, grain yield, and soluble sugar levels over two crop seasons. Results: All treatments enhanced soil fertility. However, the sodium adsorption ratio (SAR) and the cation ratio of soil structural stability (CROSS) increased in soils amended with compost alone in the second crop year. Barley (*Hordeum vulgare* L.) cultivated in soil amended with C and BCC produced 28% and 37% more dry biomass, respectively, in the second year, while no significant effects were observed in the first year. This may be attributed to the higher availability of nutrient content (N and P) in soils during the second year. In the first year, plants amended with BCC exhibited the highest accumulation of sucrose and fructose, with increases of up to 39% and 66%, respectively. Conclusions: Compost application did not affect barley yield during the first crop year, highlighting limited effects on soil fertility. However, C and BCC improved barley yield in the second year after application. No synergistic effect was observed between biochar, Ramial chipped wood, and compost. Future Perspective: Further studies should focus on the long-term effects of organic soil management, including salinity issues, to support sustainable agriculture in arid regions.

Keywords: date palm waste compost; biochar; Ramial chipped wood; salinity; arid regions

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1. Introduction

The sustainability of agricultural production is a major concern of humanity while agriculture in arid regions faces increasing threats. The Middle East and North Africa regions are highly vulnerable to the impacts of soil and water salinization, desertification, and climate change, adding new challenges for agriculture [1]. Maintaining soil fertility in arid regions presents a significant priority due to the scarcity of water and nutrient rich organic matter (OM).

Sandy soils occupy approximately 900 million ha of land worldwide, mainly in arid and semi-arid regions [2]. They are typically characterized by a lack of OM, generally $<10\ kgC{\cdot}m^{-2}$ in arid regions [3], a very low nutrient level, poor physical structure, and limited water holding capacity. In arid conditions of southern Tunisia, barley yields range between 30 and 34 q/ha with 120–180 kg of N applied per hectare under irrigation [4]. These characteristics convert these areas into stressful environments for plant growth. These soils are particularly prone to degradation processes, mainly due to OM depletion and aeolian erosion, which poses a major threat to agricultural productivity and sustainable development [5].

However, the use of high quantities of poor-quality irrigation water in arid environments may cause secondary soil salinization, with adverse effects on date palm cultivation [6]. Climate change and rapid population growth have contributed to a significant decrease in water resources available for agriculture in arid regions [7]. This forces farmers to partly use low-quality water for crop irrigation, which accelerates soil salinization.

Soil salinization is one of the most important environmental problems that adversely affects the physical, chemical, and soil microbiological processes and decreases ecosystem sustainability [8,9] and agricultural production in the world's arid regions [10]. The presence of excess salt (Na^+) can affect the soil physical properties by causing dispersion of soil particles and soil sodicity [11]. Sodic soils are characterized by a soil exchangeable sodium percentage (ESP) greater than 15% (or 5% according to Saidi et al. [11]) and a high SAR, which impacts the physical properties of the soils [12]. The deterioration of soil structure and fertility is subsequently accompanied by an increase in soil osmotic pressure, which limits nutrient and water uptake by plants and soil biochemical processes [13] that hinder plant growth and yield [14], water uptake, photosynthetic responses [15], and physiological processes causing severe abiotic stress for plants [16].

New environmentally friendly methods are needed to improve plant performance in nutrient-poor and saline soil that could maintain plant productivity under unfavorable conditions. Soil management practices such as organic amendments inputs would improve soil organic matter (SOM) stocks and, hence, help soil restoration in drylands [17]. Date palm waste compost and Ramial chipped wood have the potential to be used for the purpose of restoring such degraded soils and mitigating the drastic effects of salinity and sodicity stresses on crop [18].

Biochar is a carbon-rich product obtained from the pyrolysis of organic material under high temperature and low oxygen levels [19]. Biochar's persistence is high due to its high proportion of aromatic carbon and condensed aromatic structures [20]. It can be produced from a wide range of source materials such as organic waste and feedstock like wood chips, sewage sludge, microalgae biomass, animal manure, and crop residues [21,22]. The physical and chemical properties of biochar mainly depend on the feedstock composition and pyrolysis conditions, such as heating rate, temperature, and holding time [23]. Date palm biochar has the potential to improve soil water retention [24] and some studies have shown that biochar can mitigate the effects of sodium by releasing Ca^{2+} and Mg^{2+} into the soil solution, which can be exchanged on soil CEC [25]. Due to its mineral soluble content, directly after application, biochar increased salinity in amended horizons in field conditions [26]. However, the same authors conclude that after several irrigation-evaporation cycles, biochar has the potential to reduce salinity, promote salt leaching and reduce water demand. Wang et al. [27] observed a reduction in SAR measured in a soil–water suspension in a saline irrigated soil. In monocropped date palm groves, the annual production of residues is around ≈2.1 t/ha [28].

Compost is the stabilized end-product derived from the controlled biological decomposition of organic materials under aerobic conditions [29]. Compost serves as a valuable source of both nutrient and OM capable of enhancing soil properties [30]. When applied to salt-affected soils, compost rich in Ca and K elements accelerate sodium (Na) leaching, improves aggregate stability, water infiltration, water holding capacity, and cation exchange capacity, while simultaneously decreasing exchangeable sodium percentage [31]. Furthermore, compost's active sites and functional groups bind salty ions, decreasing their availability for plant uptake [32]. Date palm compost has emerged as a valuable soil amendment with promising application in arid environments [33,34].

In the same way, Ramial chipped wood (RCW) is an organic amendment that has received increasing attention in recent years. It is derived from the chipping of tree branches less than 7 cm in diameter and twigs, which have a richer composition than wood. RCW is a source of OM in degraded soils, and it improves soil porosity, reducing erosion, improving soil structure [35,36], and soil biological properties [37]. Hence, compost and RCW combination could improve crop productivity, reduce the need for chemical fertilizers, and promote sustainable agricultural practices. Further research is needed to optimize proportions and application methods of these amendments to maximize the benefits for soil and crop management.

In this context, this study sought to explore the potential of biochar + compost (BCC) and Ramial chipped wood + compost (RCWC) as soil amendments for the restoration of a degraded saline-alkaline soil using saline surface water table for irrigation under arid climate. The study aims to (i) assess the impacts of organic amendments on selected soil properties, (ii) examine whether the application of these amendments mitigates salt stress in plants, and (iii) to evaluate the efficacy of these combinations on barley yield under saline soil and arid field conditions.

2. Materials and Methods

2.1. Experimental Design

The field trial was carried out from 2021 to 2023 in the experimental farm of the Arid Region Institute of Medenine, located in southeastern Tunisia (33°.73′25″ N, 10°.66′72″ E). The region is characterized by an arid climate, characterized by hot, dry summers and mild winters [38]. The used sandy soil is classified as an Arenosol based on the FAO Classification System, with a sandy texture over a depth of more than 120 cm [39]. It is a slightly alkaline and saline soil with the EC of the saturated paste extract being >4 mS·cm^{-1}. It contains low organic carbon and low total nitrogen (Table 1).

The experimental design consisted of four soil treatments conducted in three replicates distributed in three randomized blocks. Each replicate had a surface area of 1 m^2 (1 m × 1 m) separated from other neighboring plots by a pathway of 1 m. Treatments were as follows: (1) unamended soil (Control); (2) date palm waste compost (C) applied at 40 t ha^{-1}; (3) 12 t ha^{-1} biochar+ 28 t ha^{-1} compost (BCC); and (4) 12 t ha^{-1} Ramial chipped wood + 28 t ha^{-1} compost (BCC) (Figure 1).

Table 1. Initial physico-chemical properties of the soil (0–20 cm).

Parameters	Soil
Sand (%)	89.6 ± 0.2
Clay (%)	2.3 ± 0.1
Silt (%)	7.7 ± 0.1
pH	7.2 ± 0.1
EC (mS·cm^{-1})	6.5 ± 0.1
Total C (%)	0.21 ± 0.02
Total N (%)	0.02 ± 0.003
Total $CaCO_3$ (%)	9.8 ± 0.4
Active $CaCO_3$ (%)	3.0 ± 0.5
Gypsum (%)	4.2 ± 0.6

Values are means ± SD (*n* = 3).

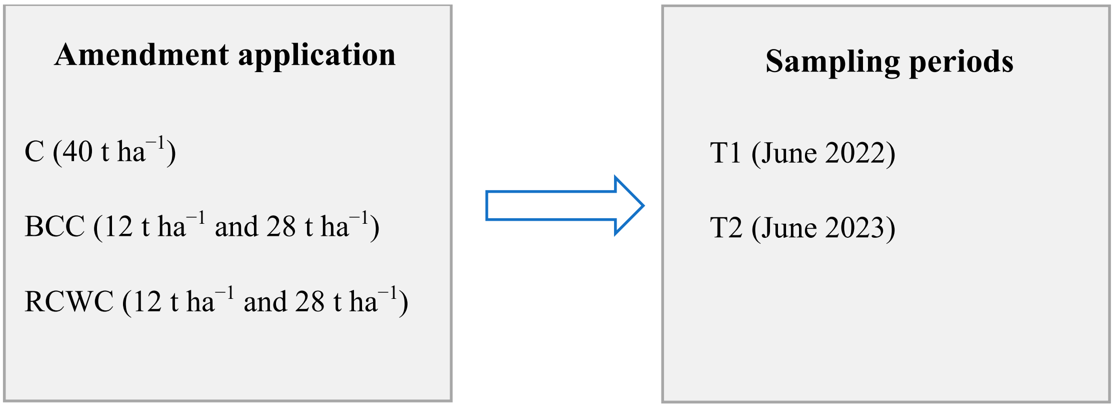

Figure 1. Flow diagram illustrating the experimental setup.

Soil amendments were applied once in November 2021 and incorporated manually into the topsoil layer (≈10 cm deep). No mineral fertilizers were applied. Soils were collected from each replicate plot (*n* = 3) at post-harvest stage in June 2022 and in June 2023 at the depth of 0–20 cm (Figure 1). Winter barley seeds (*Hordeum vulgare* L.) of the 'Ardhaoui' cultivar were first sown in November 2021, and the first harvest took place in June 2022. Seeds were sown again in November 2022 with the second harvest occurring in June 2023. The sowing density was 160 kg ha^{-1}. At harvest, barley plants were sampled from each plot to determine grain yield and straw biomass.

A drip irrigation system was employed using salty well-water with an EC of 8.5 mS·cm^{-1} (Table 2). The total amount of irrigation water applied was ≈425 mm/growing season. Total Ca^{2+}, K^{+}, Mg^{2+}, and Na^{+} in irrigation water were analyzed by inductively coupled plasma-optical emission spectroscopy (ICP-OES). Soluble anions (SO_4^{2-} and Cl^{-}) concentrations were determined using a Dionex ICS1000 ion chromatograph system with membrane suppression and conductivity detection.

Table 2. Chemical characteristics of water used for irrigation.

Sampling Date	pH	EC (mS·cm^{-1})	Ca^{2+} (mg·L^{-1})	K^{+} (mg·L^{-1})	Mg^{2+} (mg·L^{-1})	Na^{+} (mg·L^{-1})	Cl^{-} (mg·L^{-1})	SO_4^{2-} (mg·L^{-1})
28 February 2023	7.19	8.51	667.4 ± 5.8	31.5 ± 2.1	245.7 ± 7.9	1103 ± 32	2275	3452

Values are means ± SD (*n* = 3), except for pH, EC, and anions.

The soluble fractions of Na (1103 mg·L^{-1}), sulfates (3451.5 mg·L^{-1}), and chlorine (2274.9 mg·L^{-1}) were extremely high. NO_3^{-}, NO_2, and PO_4^{3-} were below the limit of quantification (<1 mg·L^{-1}). SAR index of the irrigation water was calculated with the following Equation (1):

$$\text{SAR}\ (\text{mmol}\cdot\text{L}^{-1}) = \frac{C_{Na}}{\sqrt{\frac{C_{Ca}+C_{Mg}}{2}}} \quad (1)$$

where C represents concentrations in mmol·L^{-1} of the cations in irrigation water. Results indicated a SAR value of 13.1 mmol·L^{-1} for irrigation water, indicating a high risk of salinization and sodization for soil.

2.2. Organic Amendments

Date palm waste compost was provided from the composting station of ASOC (Association for Saving Oasis of Cheneni-Gabes). The process involves collecting and drying date palm residues, previously crushed and ground into pieces of 5 mm in diameter. The ground materials were transferred to soaking basins for a 4–7 day period to initialize the composting process. Then, the raw materials were mixed in a proportion of 2/3 crushed date palm waste leaves and 1/3 cow manure (*v:v*). This mixture was co-composted in an open area using a windrow of 10 m length, 1.5 m wide base, and 1.3 m height. Aeration was achieved by mechanically rotating the materials within the windrow.

The biochar used in the experiment was obtained from the production unit Biofire (Tebourba, Tunisia). The biochar was produced according to the following steps: (1) grinding of residues from 3 to 5 cm (disk mill + hammer mill); (2) drying of ground product; (3) making briquettes with a briquette press; (4) pyrolyzing at a temperature of 420 °C in a carbonization furnace for 9h; (5) grinding of all the samples in a mill (particle size < 2 mm).

To obtain Ramial chipped wood, we chose small branches (*Citrus* sp., *Vitis vinifera* sp., *Ficus* sp.) <7 cm in diameter from the fruit tree of the Institute of Arid Regions. The branches were pruned with shears and crushed to obtain fibers between 0.5 and 1 cm in length, then dried and sieved with a 0.5 mm sieve to ensure the uniformity of fragments. The physico-chemical properties of the organic amendments are presented in Table 3. The compost had a slightly alkaline pH while the biochar had a very alkaline pH. The compost had a very high EC of 11.7 mS·cm^{-1}.

Table 3. Physico-chemical properties of the organic amendments.

Variables	Compost	Biochar	Ramial Chipped Wood
pH	7.5 ± 0.02	10.0 ± 0.1	6.0 ± 0.04
EC (mS·cm^{-1})	11.7 ± 0.4	0.9 ± 0.1	4.7 ± 0.03
Total C (%)	14.2 ± 0.1	50.18 ± 0.13	56.1 ± 0.3
Total N (%)	1.16 ± 0.26	0.53 ± 0.05	1.14 ± 0.01
Total K (mg kg^{-1})	1192.9 ± 2.1	126.2 ± 4.1	117.4 ± 3.1
Total Na (mg kg^{-1})	6271.3 ± 5.5	110.8 ± 2.0	984.7 ± 3.1
Total Ca (mg kg^{-1})	752.1 ± 5.7	692.1 ± 5.7	4417 ± 2.0
Total Mg (mg kg^{-1})	233.9 ± 3.0	38.1 ± 2.9	167.1 ± 1.5

Mean values ± SD (n = 3).

2.3. Physico-Chemical Analyses

The physico-chemical properties were determined using air-dried soil samples sieved through a 2 mm mesh, except for extractable mineral nitrogen, which was measured using fresh soil samples. The electrical conductivity (EC) and concentrations of soluble cations K^+, Na^+, Mg^{2+}, and Ca^{2+} were directly measured in saturated paste extracts (SPE). To this aim, deionized water was gradually added to 200 g of dry soil under continuous mixing until the soil paste became saturated. The saturated paste was left undisturbed for 24 h before undergoing a low-pressure filtration. Subsequently, the vacuum extracts were collected [40]. The EC was measured using a conductivity meter (InoLab, Weilheim, Germany). Soluble cations in saturated paste extracts were determined by atomic absorption spectrophotometry (Shimadzu AA-6200, Shimadzu, Duisburg, Germany). Soil pH was determined in deionized water using a 1:5 soil:solution ratio [41]. Soil texture was determined using the Robinson pipette method. Total organic carbon (TOC) was determined using dichromate oxidation and subsequent titration with ferrous ammonium sulfate [42].

Total nitrogen (TN) was carried out by the Kjeldahl method. Extractable mineral N was expressed as total mineral N because NH_4^+ concentrations in the soil were not detected. Moist soil (≈25 g) was weighed and immediately extracted with 100 mL KCl (1M) and shaken for 1 h [43]. After 30 min of decantation, the supernatant was filtered through a n°40 Whatman filter. The extracts were analyzed for soil inorganic N using steam distillation method [44]. In brief, a 20 mL aliquot of the filtrate was placed in a distillation flask containing 0.5 g of calcinated MgO. Immediately, 0.2 g Devarda alloy was added before connection to the flask of the distillation apparatus (UDK 132 Semi-Automatic Distillation Unit, VELP Scientifica, Usmate Velate, Italy). Distillation was carried out for 5 min, after which the released NH_3 was collected in 20 mL of 2% boric acid-indicator solution. The ammonia concentration was then determined by titration with 0.05 NH_2SO_4.

The soil available phosphorus (P) was determined by UV-vis spectrophotometer after extraction according to the Olsen method. Gypsum was measured with amended $BaSO_4$ method [45]. Total soil carbonate ($CaCO_3$) was measured by the method of calcimetry [46], while the active carbonate was determined following the Drouineau method [47]. The parameter SAR is a measure of the proportion of Na^+ relative to Ca^{2+} and Mg^{2+} in the water extract from saturated paste extract. CROSS indicates the dispersive effects of Na and K on clay dispersion, and Ca and Mg on flocculation. SAR (Equation (1)) and CROSS (Equation (2)) were calculated based on Na^+, K^+, Ca^{2+}, and Mg^{2+} content in SPE expressed in mmol·L^{-1} as follows:

$$\text{CROSS} = (\text{Na} + 0.56\text{K}) / \sqrt{(\text{Ca} + 0.6\text{Mg})/2} \tag{2}$$

Cation exchange capacity (CEC) was determined using the modified procedures because of Ca solubility in calcareous and gypsiferous soils [45]. A soil sample (4 g) was first placed in a centrifuge tube, mixed with 33 mL of 1M sodium acetate, and pH adjusted to 8.2. The soil suspension was agitated for 5 min and then centrifuged until the supernatant liquid was clear. The supernatant was then completely discarded. This extraction process was repeated a total of four times. The excess salt of sodium acetate was washed four times by adding 33 mL 95% ethanol to the tube. The adsorbed sodium was replaced by three extractions using 33 mL of 1 M ammonium acetate; it was shaken, centrifuged, and the supernatant liquid was collected in a 100 mL volumetric flask. Finally, the sodium concentration was measured using a flame photometer.

All organic materials were dried, grounded, and sieved with a mesh size of 2 mm before analysis. Ramial chipped wood, compost pH, and electrical conductivity (EC) were measured at a ratio of 10 g of solid material to 50 mL of deionized water [48]. Biochar pH and EC were determined at a ratio of 5 g of biochar to 50 mL of deionized water [49]. The total K^+, Na^+, Ca^{2+}, and Mg^{2+} in organic amendments were analyzed by atomic absorption spectrophotometry (Shimadzu AA-6200, Shimadzu, Duisburg, Germany) after mineralization with concentrated nitric acid and filtering < 0.45 µm.

2.4. Soil Humic Substances Investigations

Humic acids were extracted from the soil samples according to the method described by Schnitzer [50] and modified by Fourti et al. [51]. Briefly, 10 g of soil were shaken overnight with 100 mL of NaOH (0.1 N) until the calcium-containing humic compounds were depleted. We separated the solution via centrifugation at 4000 rpm for 20 min, followed by the addition of 2N sulphuric acid (pH = 1) to the supernatant. After 24 h and another centrifugation of 4000 rpm for 20 min, humic acids (HA) were isolated from the supernatant containing fulvic acid (FA). The quality of soil OM was assessed using a colorimetric method outlined by Chen et al. [52]. Before the final extraction of FA and HA, absorbance of the mixture (pH 7–8) was measured at two wavelengths (E4 = 465 nm; E6 = 665 nm). The ratio of E4/E6, known as the Welt ratio, serves as an indicator of OM quality, representing the humification index [52].

2.5. Plant Analyses

Grain yield was assessed at the harvest stage. Whole plots (1 m^2) were manually harvested. Subsequently, the grain was separated from the straw using a manual threshing process. The grains were weighed using a precision balance to determine the grain yield, expressed in quintal per hectare. The straw biomass of each plot was also determined.

At maturity, sugars in grains were extracted and analyzed using the method of Booij et al. [53]. Approximately 10 g of powdered grains were extracted in 10 mL water–ethanol (80/20, *v*/*v*) for 3 h. The extract was filtered over a Whatman filter paper. Under reduced pressure, the remaining filtrate evaporated till dryness. Then, each sample was diluted and adjusted with ultrapure water to 50 mL. The obtained solutions were subjected to a centrifugation at 6000 rpm for 20 min and were filtered through 0.45 µm membrane. Sample filtrates were used for the determination of the sugar contents using high performance liquid chromatography (HPLC). The mobile phases used were acetonitrile and ultrapure water (80/20, *v*/*v*). The flow rate and the injection volume during the experiment were 2 mL/min and 1 mL, respectively.

2.6. Statistical Analyses

Analyses of variance (ANOVA) were carried out using SPSS Software (version 25) to test the effects of the organic amendments on soil properties and plant response with field replicates of 3. All parameters were expressed as the mean value ± SD (standard deviation) of 3 replicate samples. The treatments were compared to the control (unamended) soil. Tukey's honest significant difference test (p = 0.05) was applied to separate the means.

3. Results

3.1. Monitoring of Soil Physico-Chemical Properties Changes

According to Figure 2, the application of date palm waste compost (C), biochar mixed with date palm waste compost (BCC), and Ramial chipped wood mixed with compost (RCWC) for one year significantly influenced the soil physico-chemical properties. A significant reduction in pH was observed for treatments C and BCC in the first season (Figure 2a). None of the treatments induced significant changes in soil pH after two cropping seasons. In 2022, no significant changes in soil electrical conductivity were found between the control and all amended plots (Figure 2b). In 2023, the highest value of EC was observed in soil amended with C and BCC compared to the control, despite the lowest value being observed in soil amended with RCWC. The soil EC was significantly lower in the second season than in the first season for all treatments, except in C amended soil. In fact, EC decreased in all treatments in comparison between both years by 17%, 8%, 18%, and 33% in treatments control, C, BCC, and RCWC, respectively.

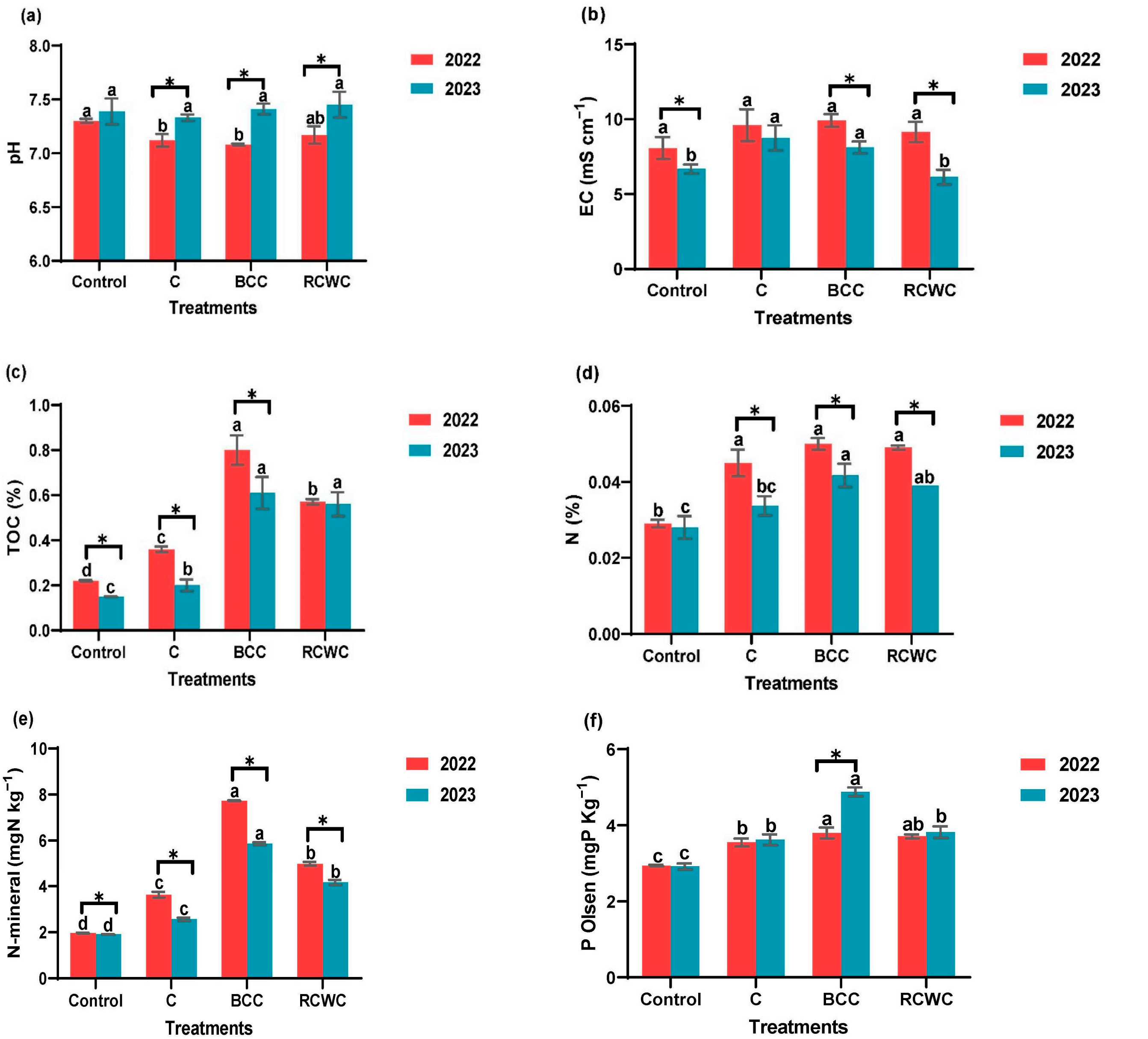

Figure 2. Variation in soil physico-chemical parameters after a one application of C, BCC, and RCWC. (**a**) pH; (**b**) electrical conductivity; (**c**) total organic carbon; (**d**) total nitrogen; (**e**) extractable mineral nitrogen, and (**f**) available P. Lower case letters indicate significant differences between treatments within the same sampling time. Asterisks (*) indicate a significant difference between sampling times within each treatment over time ($p < 0.05$).

Additionally, total carbon content was also substantially improved by the applied amendments. In 2022, the soil organic carbon (SOC) content was 1.6, 2.6, and 3.7 times higher in the soils amended with C, RCWC, and BCC, respectively, (Figure 2c). In 2023, the SOC content had decreased in all treatments, although it was generally still significantly higher than in the control soil (3.7 and 4-fold increase for RCWC and BCC), respectively.

On the other hand, total nitrogen significantly increased in the first year for all of the treatments (up to 36, 40, and 42% in soils amended with, respectively, C, RCWC, and BCC) and significantly decreased in the second year (Figure 2d). The total soil extractable mineral N values were quite low overall. Although the variations were significant, the variations were relatively low. In 2022, the total extractable soil mineral N content of all amended soils increased compared to the control (Figure 2e) by (46%, 74%, and 60%), respectively, in treatments (C, BCC, and RCWC). In 2023, the total extractable soil mineral N was lower in all treatments, although it was still higher than in the control soil (up to 54% for treatment RCWC and 67% for treatment BCC).

The application of C, BCC, and RCWC to the soil increased available phosphorus (P) ($p < 0.05$) (Figure 2f). In 2022, the highest increase in available P was found in the soils amended with BCC (23%) followed by RCWC (21%), and the lowest value was the application of C (17%) in comparison with the unamended soil. In 2023, our observations were similar to those observed in the first year (Figure 2f).

According to Table 4, a significant increase in the content of water-soluble ions (Ca^{2+}, K^+, Mg^{2+}, and Na^+) was observed with the addition of both RCWC and BCC in the first year. In 2023, the increase in these ions relative to the control soil was maintained in all treated soils. All organic amendments enhanced the cation exchange capacity (CEC) of the soil during the first two years, even though a decrease was observed in 2023 (Table 4).

Table 4. Changes in soluble soil Ca^{2+}, K^+, Mg^{2+}, and Na^+ concentrations, CEC, SAR, and CROSS after a single application of C, BCC, and RCWC treatments during two growing seasons.

	2022				2023			
	Control	**C**	**BCC**	**RCWC**	**Control**	**C**	**BCC**	**RCWC**
Ca^{2+} ($mmol \cdot L^{-1}$)	$23.9 \pm 0.8^{b*}$	$22.7 \pm 0.8^{b**}$	28.2 ± 0.9^{a}	27.6 ± 0.9^{a}	$25.5 \pm 0.1^{b*}$	$27.4 \pm 1.3^{a**}$	27.6 ± 0.4^{a}	26.3 ± 0.1^{ab}
K^+ ($mmol \cdot L^{-1}$)	$2.8 \pm 0.05^{b***}$	$1.9 \pm 0.2^{c***}$	$2.5 \pm 0.1^{b**}$	3.9 ± 0.3^{a}	$3.7 \pm 0.1^{b***}$	$4.3 \pm 0.03^{a***}$	$3.6 \pm 0.3^{b**}$	3.7 ± 0.2^{b}
Mg^{2+} ($mmol \cdot L^{-1}$)	$6.9 \pm 0.3^{c*}$	8.8 ± 0.2^{b}	$9.0 \pm 0.1^{b**}$	$9.7 \pm 0.3^{a**}$	$8.0 \pm 0.4^{c*}$	8.9 ± 0.3^{b}	$9.8 \pm 0.2^{a**}$	$7.8 \pm 0.4^{c**}$
Na^+ ($mmol \cdot L^{-1}$)	38.3 ± 0.4^{b}	$38.8 \pm 0.1^{b**}$	42.4 ± 0.8^{a}	42.6 ± 1.3^{a}	39.0 ± 0.5^{b}	$51.6 \pm 4.2^{a**}$	49.3 ± 5.6^{a}	38.2 ± 2.7^{b}
CEC ($cmol \cdot kg^{-1}$)	$0.8 \pm 0.05^{c***}$	$9.5 \pm 0.4^{a***}$	$9.3 \pm 0.5^{a***}$	$5.1 \pm 0.3^{b**}$	$1.7 \pm 0.1^{c***}$	$6.3 \pm 0.03^{a***}$	$6.1 \pm 0.05^{a***}$	$2.0 \pm 0.1^{b**}$
SAR ($mmol \cdot L^{-1}$)	9.8 ± 0.2^{a}	$9.8 \pm 0.1^{a**}$	9.8 ± 0.3^{a}	9.9 ± 0.2^{a}	9.5 ± 0.2^{bc}	$12.1 \pm 0.8^{a**}$	11.4 ± 1.3^{ab}	9.2 ± 0.7^{c}
CROSS	10.7 ± 0.3^{a}	$10.7 \pm 0.1^{a**}$	10.7 ± 0.3^{a}	11.0 ± 0.2^{a}	10.6 ± 0.2^{bc}	$13.3 \pm 0.8^{a**}$	12.6 ± 1.3^{ab}	10.2 ± 0.7^{c}

Lower case letters indicate significant differences between treatments within the same sampling time. An asterisk indicates a significant difference between sampling times within each treatment over time. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Mean values ± SD ($n = 3$). The data were analyzed comparatively for the years 2022 and 2023.

Soil sodicity indices, including SAR and CROSS, are presented in Tables 4 and 5. Regarding SAR, in the first year, no significant differences were observed between amended and unamended plots. However, in the second year (2023), soil SAR significantly increased in C (21%) and BCC (16%) treatments compared to the control treatment. No change in SAR value was observed in the control between 2022 and 2023. As shown in Tables 4 and 5, in 2022, CROSS index was not affected by all the treatments, but in 2023, BCC and C led to a significant increase in soil CROSS. In fact, soil CROSS reached 12.6 and 13.3 in BCC and C treatments, respectively, while it was 10.6 in control soil.

Table 5. Significance of the effects of treatments on soil parameters and yield across two growing seasons.

Parameters	**Significance**	
	2022	**2023**
pH	NS	NS
EC ($mS \cdot cm^{-1}$)	NS	***
TOC (%)	**	***
N (%)	***	***
N-mineral ($mgN \cdot kg^{-1}$)	***	***
Olsen P ($mgP \cdot kg^{-1}$)	***	***
CEC ($cmol \cdot kg^{-1}$)	***	***
SAR ($mmol \cdot L^{-1}$)	NS	**
CROSS	NS	**
E4/E6	NS	**
Grain yield ($q \cdot ha^{-1}$)	NS	*

Significant at * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. NS: non-significant.

As shown in Figure 3, no significant differences in E4/E6 ratio were observed between amended and unamended plots in 2022. Contrarily in 2023, all treatments induced a significant ($p < 0.05$) increase in E4/E6 ratio compared with the control soil. RCWC and BCC treatments significantly increased the E4/E6 ratio by 10 and 25%, respectively. In all the treated soils, the E4/E6 ratios were higher in 2023 compared with 2022.

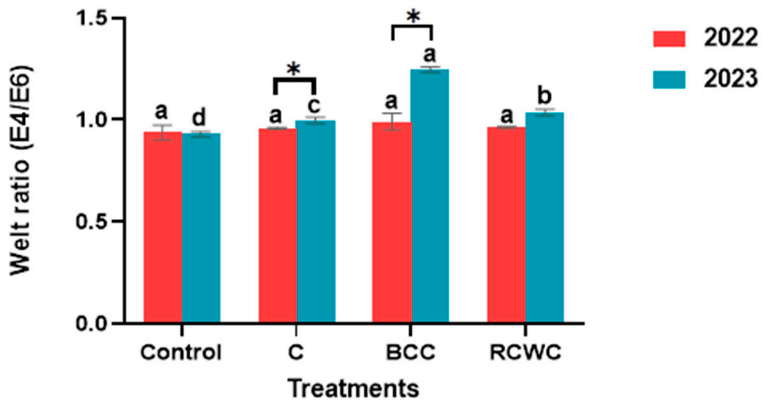

Figure 3. Variation in the Welt ratio (E4/E6) after one application of C, BCC, and RCWC. Lower case letters indicate significant differences between treatments within the same sampling time. Asterisks (*) indicate a significant difference between sampling times within each treatment over time ($p < 0.05$).

3.2. Monitoring Agronomic Performance of Barley

In 2022, the yields obtained in the soils amended with compost, either alone or in combination with biochar or Ramial chipped wood, did not significantly differ from those of the control soil ($p < 0.05$, Figure 4). In all the treatments, including the control, the grain yield was lower in the second growing season. But in C and BCC, barley yields were higher in the amended soils than in the control soil (+27% and 28%, respectively).

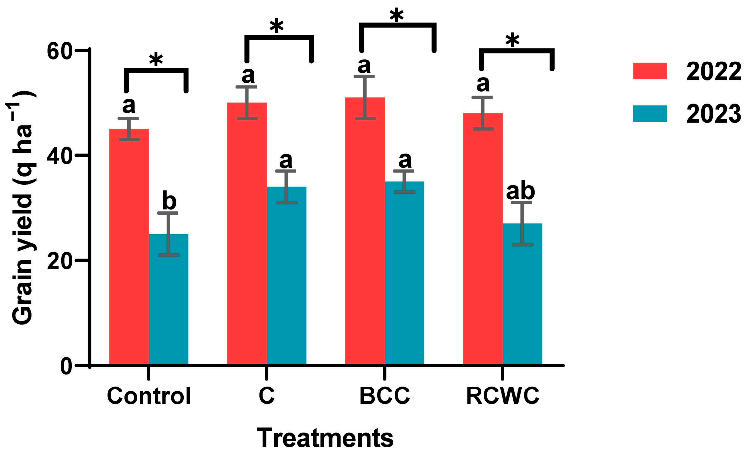

Figure 4. Effect of the soil amendment with C, BCC, and RCWC on the barley grain yield. Lower case letters indicate significant differences between treatments within the same sampling time. Asterisks indicate a significant difference between sampling times within each treatment over time (* $p < 0.05$).

Barley plants receiving C, BCC, and RCWC produced more straw biomass compared to that of the control, in the two seasons (Figure 5). Plants amended with RCWC, C, and BCC produced 25%, 37%, and 47% higher dry biomass, respectively, in 2022, compared to the no amended plants. In 2023, the dry biomass had decreased in all treated soils, although it was generally still significantly higher than in the control soil. It significantly increased by 28 and 37%, respectively, after C and BCC amendments, among which the BCC treatment induced the highest increase.

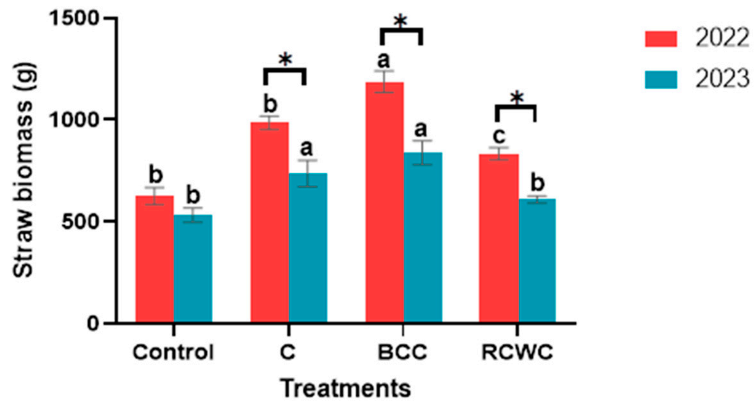

Figure 5. Effect of the soil amendment with C, BCC, and RCWC on straw biomass. Lower case letters indicate significant differences between treatments within the same sampling time. Asterisks indicate a significant difference between sampling times within each treatment over time (* $p < 0.05$).

3.3. Soluble Sugars Concentrations

The concentration of fructose and sucrose in amended and unamended plants under irrigation with saline water during the first season (2022) and the second season (2023) are presented in Table 6. In 2022, the concentration of fructose in the grains of barley increased by 60% and 66%, respectively, in plots treated with RCWC and in plots treated with BCC. Surprisingly, the concentration of fructose was much higher in 2023. There was a more pronounced fructose accumulation and a maximum (97% of the initial level in 2022) was reached in plants grown in unamended soil. In 2022, the highest accumulation of sucrose (up to 39%) was observed in plants amended with BCC. The concentrations of sucrose were much higher in 2023. The maximum concentration of sucrose was obtained with plants grown in unamended soil.

Table 6. Changes in fructose and sucrose concentrations in barley plants grown in soils non- amended and amended with C, BCC, and RCWC.

	2022				2023			
	Control	**C**	**BCC**	**RCWC**	**Control**	**C**	**BCC**	**RCWC**
Fructose (mg g^{-1})	0.0005 ± 0.002 ^{b**}	0.0007 ± 0.0001 ^{b***}	0.0015 ± 0.0003 ^{a***}	0.0013 ± 0.0002 ^{a***}	0.0192 ± 0.004 ^{a***}	0.0090 ± 0.002 ^{b***}	0.0095 ± 0.0008 ^{b***}	0.0077 ± 0.0003 ^{b***}
Sucrose (mg g^{-1})	0.0039 ± 0.003 ^{b***}	0.0041 ± 0.0004 ^{b***}	0.0063 ± 0.001 ^{a}	0.0036 ± 0.001 ^{b***}	0.0345 ± 0.002 ^{a***}	0.0093 ± 0.0002 ^{c***}	0.0075 ± 0.001 ^{c}	0.0174 ± 0.002 ^{b***}

Lower case letters indicate significant differences between treatments within the same sampling time. An asterisk indicates a significant difference between sampling times within each treatment over time. ** $p < 0.01$, *** $p < 0.001$. Mean values ± SD ($n = 3$).

4. Discussion

This study focused on the effects of date palm waste compost and its combination with biochar and Ramial chipped wood as soil amendments for improving the soil fertility of a degraded saline-alkali soil. It also explores soil–plant interactions to combat the effects of saline irrigation in arid conditions. While previous studies have reported an increase in soil pH following biochar and/or compost application [54], our results showed no significant effect of organic amendments on soil pH after two growing seasons. The decrease in soil pH may be attributed to irrigation, which facilitates the leaching of soluble elements provided by organic amendments.

Electrical conductivity (EC) is currently recognized in the scientific literature as an indicator of soil salinity [55]. A significant increase in EC was observed in the second year of soil amended with C and BCC. In this study, all amended plots showed that EC values exceeded 4 mS cm^{-1}, which is the limit for saline soils [55]. Moreover, the increase in soil EC might be explained by the high EC of the compost (EC = 11.7 mS cm^{-1}), which exceeded the threshold (i.e., EC > 5 mS·cm^{-1}) suggested by Gondek et al. [31] for composts. Since EC decreased in the 2nd year for the treatment RCWC, an explanation could be the lowest compost dose associated with the increase in water infiltration rate with Ramial fragmented wood particles.

As expected, one application of compost and its combination with biochar and Ramial chipped wood increased the total organic carbon content of the soils. The significant enrichment in the organic carbon content of amended soils can be attributed to the chemical composition of the used organic materials. Ramial chipped wood had the highest C (56.1%, Table 3), followed by biochar (50.2%), whereas compost had a significantly lower C content (14.2%). Since compost generally contains more labile carbon compared to biochar, which is more recalcitrant, their combination holds the potential to provide an effective supply of organic carbon over both short and long-term periods [56]. BCC increased the total organic carbon four-fold compared to the control, which can significantly improve soil structural stability and may contribute to combating land degradation and desertification.

On the other hand, all three organic amendments increased soil mineral nitrogen concentrations in the first year. Indeed, the highest soil mineral nitrogen concentrations were observed in soil amended with BCC at both years. This could be explained by the complementary effects of these two materials. Compost supplies a release of nitrogen through decomposition.

Additionally, all three organic amendments raised the available phosphorus (P) concentrations in the first year. This result was probably linked to the P input from the amendments. But the effect on soil available P was very limited, in agreement with [57] for date palm residues. Also, in the calcareous soil tested, phosphorus can be bound by the calcium forming unavailable chemical forms for plants such as Ca-P forms [58]. The effects of BCC and C treatments were very similar. They also improved the available phosphorus and mineral nitrogen in the second year.

Compared to the control treatment, the application of these amendments increased the water-soluble ions Ca^{2+}, K^+, Mg^{2+}, Na^+ in soils in both years. The soluble ions Ca and Na were considerably higher than those of K and Mg in all amended soils. Compared to the value of control soil, soluble Na was increased by 21% and 24% in BBC and C, respectively, in the second year. These results were consistent with those of Izilan et al. [59] who found that the addition of 20 t ha^{-1} biochar-compost significantly enhanced K, Ca, Na, and Mg levels in sandy-loam soils. This might be attributed to the biochar nutrients components [60] and also compost mineralization [61]. Moreover, date palm residues are an abundant resource available in the Middle East and North Africa, making their composting a sustainable approach to promoting agroecological practices under arid conditions.

SAR represents soil sodicity, which reflects the state of flocculation or dispersion of clay aggregates in a given soil [11]. All SAR values were lower < 13, the threshold for sodic soils [55], but soils amended with compost showed high values indicating a risk of soil sodisation. Our results showed that soil amended with compost alone caused a significant increase in SAR between the two years. Compost decomposition releases various organic acids that can affect the solubility and availability of ions in sandy soil. The decomposition process of the compost continued in the second year, which explains the distribution and concentration of sodium and other cations, leading to an increased SAR. However, two years after compost application, the soil pH remained similar between the control and the compost treatment (C). This suggests that the compost did not induce the soil acidification required to solubilize Ca^{2+} from $CaCO_3$ As a result, the release of Ca^{2+} into the soil and the subsequent displacement of Na_+ were likely insufficient, which may explain the absence of a significant reduction in SAR observed in this study. These results diverge from findings by Sarwar et al. [62], who demonstrated that application of compost notably reduced SAR. They attributed the reduction in SAR of the soil to release of Ca^{2+} from soil $CaCo_3$ or leaching of Na^+ from soil. In our case, despite the lower compost dose in the BCC mixture (28 t ha^{-1}), biochar did not mitigate the increase in SAR associated with compost application. This can be attributed to the high sodium content in the compost (Table 3), which releases Na^+ ions into the soil solution, thereby raising SAR levels. While biochar is considered effective at improving soil structure and retaining nutrients, it lacks the capacity to adsorb or neutralize sodium ions, which are responsible for the SAR increase [63]. Also, in sandy soils with low cation retention capacity, sodium accumulation is exacerbated due to poor ion buffering and leaching of divalent cations such as Ca^{2+} and Mg^{2+}. A previous study has shown that biochar's ability to reduce SAR depends largely on its chemical composition, particularly its content of exchangeable Ca^{2+} and Mg^{2+} [64]. In our case, the biochar used had relatively low levels of Ca^{2+} and Mg^{2+} compared to the sodium content in the compost, limiting its ability to counteract the sodium introduced.

Contrary to our findings, Huang et al. [65] found that biochar amendment notably reduced soil SAR values under saline water irrigation. They explained the reduction in SAR in soil amended with biochar by the excess of Ca^{2+} and Mg^{2+} content into the soil solution.

The CROSS values aligned well with those of SAR. Emami et al. [63] found that CROSS value was 32 in the control treatment, which was significantly decreased due to application of soil conditioners.

The incorporation of organic amendments like compost and biochar increases the cation exchange capacity of soils due to their contribution of OM, associated with an increase in functional groups, surface area, and improvements in microbial activity [66]. In this regard, Mensah et Frimpong [54] reported that sole application of compost and in combination with biochar significantly increased the CEC. Liu et al. [67] indicated that compost amendments raise CEC due to the input of stabilized OM being rich in functional groups such as carboxylic and phenolic acid groups released into the soil exchange site. The Welt ratio is an indicator of the decomposition status and molecular size of SOM. In the second year, a significant increase in the E4/E6 ratio was observed after applying the three treatments. The E4/E6 ratios were less than five, indicating the presence of humic acids rather than fulvic acids in the soil's organic fraction [68]. This corresponds to the ratios observed in all amended soils. This is because these low ratios suggest the presence of larger, more complex molecules, such as humic substances and polymerized carbon structures, which are typically formed during the advanced stages of OM humification [69]. These compounds indicate a higher degree of molecular complexity and stability, reflecting advanced decomposition processes. This is in line with the results reported in the study by Malou et al. [70], who showed that the thermal stability of SOM from an Arenosol was particularly high, even in soils amended with organic inputs. The authors suggested that the lack of SOM protection in sandy soils favors quick mineralization of OM inputs.

Our findings suggest that the application of compost, either alone or in combination with biochar or Ramial chipped wood, did not induce significant changes on most of the measured barley parameters. No significant difference in grain yield was observed in all the amended soils in the first year, which is not in line with the positive effects of date palm-based compost on barley and forage corn yields reported by [28,71]. The relatively low TN content in the compost used in the present study could be at the origin of the absence of a significant effect on grain yields. Moreover, high barley adaptation to saline and arid conditions, particularly the variety 'Ardhaoui', was probably able to reduce the potential effects on the plant's response.

During the second crop year, C treatment and BCC and RCWC combinations resulted in higher grain yield and straw biomass compared to the unamended soil. These improvements in crop performance may be mainly attributed to the improvement of nutrients availability, since the effects of these organic amendments on soil water retention capacity are generally not significant at biochar levels <30 t·ha^{-1} [72]. No additive effect was observed in BCC and RCWC treatments, in agreement with previous studies [71,73].

On the other hand, both amended and unamended soils showed a reduction in grain yield in the second year compared to the first year. In the second year, the reduction in biomass and yield can be attributed to the inhibitory effects of osmotic stress caused by salt accumulation in the soil. This was probably due to the very high salt content in the water used for irrigation, as shown by its Na^+, Cl^-, and $SO_4{}^{2-}$ concentrations. Salt accumulation in the root zone leads to osmotic stress by accumulating high levels of Na^+ and Cl^-. Hence, the use of a saline surface water table is not suitable for agriculture purpose, as it was almost at the origin of a ≈50% decline in barley grain yield after only two crop years.

Contrary to our findings, Jin et al. [74] reported a biochar-enhancing effect on soil salinity indices, resulting in a reduction in exchangeable sodium percentage, SAR, and soluble Na^+/K^+ and Na^+/Ca^{2+} ratios six years after a single biochar application. These effects were attributed to the biochar ability to increase CEC and provide the elements K^+, Mg^{2+}, and Ca^{2+}. Although compost had a positive effect on soil CEC, the application of the biochar-compost mixture did not increase CEC compared with compost treatment alone. The potential positive effects of biochar were not observed in our study concerning soil nutrient status, but the lack of long-term studies means that further investigations would be required.

In the present study, the levels of soluble sugars showed an accumulation in all barley plants studied under saline stress conditions in the second year. The accumulation in the grains varied differently between the organic amendments with response to irrigation with salty water. These results were in line with those reported by Mekkaoui et al. [75]. They found that the application of compost, under saline conditions, significantly increased the concentration of soluble sugars in tomato plants.

We conclude that in the second year, the plants were more exposed to salinity than in the first year because, as our results showed, there was an accumulation of sugar in the grain across all treatments. The BCC treatment in the second year presents less accumulation of sugars content in the grain, which could result from a better adaptation to salinity stress. The lack of effect of biochar on short-term yields in carbon-poor soils is in line with the recent paper by [76], which illustrates the idea that the effects of biochar on agricultural production may be more limited than the literature suggests.

5. Conclusions

The aim of this study was to examine the effects of date palm waste compost (C) alone or in combination with biochar (BCC) and with Ramial chipped wood (RCWC) on selected soil physicochemical properties and barley development in a saline-alkali soil. The results showed that, under field experiments, the addition of all three organic amendments led to a partial improvement in soil chemical properties (i.e., TOC, N, P, K, and CEC), but plant parameters (i.e., grain yield, straw biomass) were not positively affected in the first year after soil amending. However, the addition of C and BCC increased soluble Na content in the soil after the second year, due to their high salt content, including Na. Therefore, optimizing the composting process with date palm residues is necessary to avoid salt accumulation and to enrich the amount of nitrogen in the compost.

The use of poor-quality irrigation water reduced barley yield by 50% during the second crop season. Nutrient inputs into the soil in C and BCC treatments seem to have partially countered the salinity effects by maintaining a higher level of yield compared with the unamended soil. A single application of compost and biochar-compost mixture led to the highest grain yield in the second year. This parameter is the most important for farmers, especially under precarious economic conditions. Additionally, the farmers must carefully manage the composting process in drylands to minimize the risk of soil salinization in the longer term. Therefore, special attention should be given to the dose and application frequencies of date palm-based compost.

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