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Electromagnetic Water Treatment and Soil Compost Incorporation to Alleviate the Impact of Soil Salinization

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Abstract: This study explores the effects of alternating current-induced electromagnetic field (EMF) on mitigating brackish water irrigation and soil salinization impacts. Greenhouse experiments were conducted to evaluate the effect of EMF on plant growth, soil properties, and leaching of ions under different conditions, including using brackish water and desalinated water for irrigation and soil compost incorporation. The experiment was performed with four types of irrigation water using soil columns representing field soil layers. EMF-treated brackish water maintained a sodium adsorption ratio of 2.7 by leaching Na^+ from the soil. EMF-treated irrigation columns showed an increase in soil organic carbon by 7% over no EMF-treated columns. Compost treatment reduced the leaching of NO_3^- from the soil by more than 15% using EMF-treated irrigation water. EMF-treated brackish water and compost treatment enhanced plant growth by increasing wet weight by 63.6%, dry weight by 71.4%, plant height by 22.8%, and root length by 115.8% over no EMF and compost columns. EMF-treated agricultural water without compost also showed growth improvements. The findings suggest that EMF treatment, especially combined with compost, offers an effective, low-cost, and eco-friendly solution to mitigate soil salinization, promoting plant growth by improving nutrient availability and soil organic carbon.

Keywords: electromagnetic field water treatment; compost; brackish water irrigation; agricultural irrigation; soil salinization; plant growth

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1. Introduction

Freshwater scarcity and low-quality irrigation water impaired by high salinity, sodium adsorption ratio (SAR), and contaminants, are becoming increasingly common in many regions, which has led to elevated soil salinity and reduced food production [1]. Soil salinization arises from natural sources and anthropogenic activities. Naturally, it results from mineral weathering, saltwater intrusion, changes in rainfall that limit salt removal, higher evaporation rates, and specific minerals in the geological formation of groundwater aquifers [2]. Human-induced salinization typically results from irrigation with low-quality water and the overuse of fertilizers, worsened by poor drainage and salt build-up from irrigation and fertilizers [3]. Developing crop systems that can grow and produce economically sufficient yields in saline conditions offers a sustainable solution to minimizing the detrimental effects of soil and water salinity [4,5]. Various methods and technologies have been developed to overcome the effects of soil salinity, improve soil physicochemical properties, increase soil water retention, and deliver mineral nutrients accessible to plants [6]. For example, brackish water desalination has been implemented to provide high-quality water for irrigation or excess irrigation beyond the crop requirement to reduce soil salinity and salt accumulation [7,8]. In addition, several techniques have been used to reduce soil salinity, such as treating the soil with gypsum (calcium sulfate) or lime, and leaching out the soil with low-salinity water [8]. In the gypsum or lime treatment, Ca^{2+} replaces the Na^+ salt from the soil exchange sites and helps remove the salt into an aqueous solution [9]. This approach is costly and chemically intensive. Its effectiveness depends on soil type, crop variety, and magnitude of sodification. New technologies are needed to reduce salt accumulation and remove salts near the root zones of plants compared to physical remedies such as tilling, removing the top layer of soil, and installing artificial subsurface drainage systems [10]. However, these technologies are expensive and short-term remedies.

Another method to alleviate the impact of salinity on soil health is organic amendments [11]. Compost is an effective soil conditioner that improves all aspects of soil structure and contains the essential nutrients for plant growth by improving soil permeability and leaching salts from the root zone [8]. Using fertilizer and saline manures may result in soil salinization [8], accumulation of heavy metals in the soil, and the mobilization and release of metals from the soil parent materials [12]. Compost treatment has increasingly been used for soil conditioning instead of chemical fertilizers. Compost treatment can increase crop yield by increasing soil microbial composition and reducing fertilizer usage [13,14]. The organic matter content of compost-incorporated soil leads to a higher water-holding capacity and maintenance of moisture levels for plants. Faucette et al. suggested that incorporating compost could control the loss of nutrients from sandy and clay loam soil due to runoff [15].

Electromagnetic field (EMF) provides a non-chemical alternative to conditioning saline water, and can increase crop yield and reduce soil salinity. EMF was reported to increase water use efficiency due to its effect on the physical and chemical properties of water and soil [16]. EMF could alter the distribution of salts among soil layers and reduce their concentrations in the upper layers [17,18]. The growth and development of plants are influenced by the Earth's geomagnetic field (GMF), like all other organisms on the planet. Externally applied electromagnetic forces, although different from GMF, were reported to affect plant growth and development [19]. EMF has been used in agricultural lands to increase crop yield [20] and water utilization efficiency, induce seed germination, and improve livestock health [21]. The effect of EMF on crop systems depends on the types of plants and soil, the EMF devices, types and properties, and treatment conditions [22].

EMF treatment was reported to significantly increase the soil moisture compared to the soil irrigated with no-EMF treatment [23]. EMF may cause fundamental changes in the physical properties of water, such as viscosity, surface tension, and associated soil permeability, which could impact osmotic pressure, thereby improving the plant's ability to uptake water or improve soil moisture retention. EMF-treated municipal water could increase soil water sorption, maintain high soil moisture content, and reduce negative soil matric potential, i.e., increased soil water availability to plants compared to a control group of water not treated with EMF [24]. Some of these parameters could impact osmotic potential and positively affect nutrient uptake [25]. EMF treatment has been used for soil salinization control. It helps counteract the effect of harmful Na^+ build-up in plants when less irrigation water is used because EMF reduces the Na^+ and Cl^- salinity by leaching them below the root zone [24–26]. EMF-treated water can remove excess soluble salts, lower pH, and dissolve slightly soluble minerals such as phosphates, carbonates, and sulfates in the soil. EMF treatment of saline irrigation water has been reported to be an effective method for soil desalinization [20,27].

It was reported that magnetically treated water improved desert soils with high salinity and calcification, resulting in higher yields for tomatoes [20], pepper, maize, and wheat [27]. EMF-treated saline water reduced the amounts of Na^+ absorbed by the potato plants compared to irrigation with raw saline water. It was found that two varieties of spunta potato had reduced levels of Na^+ in all tissues examined. EMF treatment might help reduce Na^+ toxicity at the cellular level by reducing the absorption of Na^+ by plant roots or by restricting the entry of Na^+ at the membrane level [28]. Applying magnetic treatment of irrigation water improved plant yields and growth parameters for cowpeas and brinjal [29]. Oil in canola plants, seed yield, and oil yield increased by 14.3%, 38.7%, and

58.5%, respectively, when using magnetized water to irrigate the canola plants. Biological yield increased when magnetized tap, normal, and saline water were used for all types of plants studied [30].

Previous studies demonstrated that EMF is an environmentally friendly, non-chemical treatment that minimizes chemical usage, reduces cost (saving time, money, and manpower), and is easy to install with no maintenance and low or no energy consumption [31,32]. It is anticipated that EMF could improve nutrient uptake, plant yield, water efficiency, and soil desalination [31–35]. Studies showed positive effects of EMF-treated synthetic saline irrigation water on plant yield [28,29] and seed germination [36] when different types of EMF devices were used. It is vital to compare the effect of different types of available irrigation water and EMF treatment because brackish water is abundant and predominant in groundwater resources. Currently, there is no systematic study to evaluate the impact of EMF on soil properties, plant yield, and leaching of ions during irrigation with different types of water. In addition to using EMF as a standalone treatment technology, EMF can be combined with soil compost incorporation.

This study aims to assess the effects of EMF treatment on plant nutrient uptake, growth, and yield through a comparative analysis with conventional methods like using low-salinity water and compost treatment to overcome the effect on soil salinity. It is crucial to investigate further the impacts of these treatments on soil nutrient availability, fertility, and their temporal changes, as well as their influence on plant uptake. In addition, this study examined the potential of EMF treatment and compost application to reduce nutrient runoff and leaching of salts that cause soil salination, which have not been previously explored. Another goal of this study is to evaluate the necessity of desalination. If the combination of EMF water treatment and compost soil treatment can mitigate the implications of brackish water irrigation, crop production costs will be reduced by eliminating the brackish water desalination step. Therefore, this study is focused on investigating the effects of EMF-treated brackish water and desalinated water for irrigation, along with soil compost incorporation, on soil properties, plant yields, and leaching of ions from soil with varying treatment combinations.

2. Materials and Methods

2.1. Experimental Setup

Fourteen combinations of irrigation water and soil compost treatments were conducted for two months to assess the impact on soil properties and plant growth parameters under greenhouse conditions (Figure 1). This study involved 42 soil columns (3 replicates for each condition) irrigated with 4 different types of water (brackish water and agricultural water with and without EMF treatment), with and without plants, as depicted in Figure 1. The environment for the plant growth was simulated under greenhouse conditions with the utilization of agro-lamps (model: AgroMax F54T5HO and GROW SPECTRUM EM-H20, HTG supply, Callery, PA, USA). The greenhouse study was closely monitored, and the room temperature was maintained at 18 °C to promote successful seed germination.

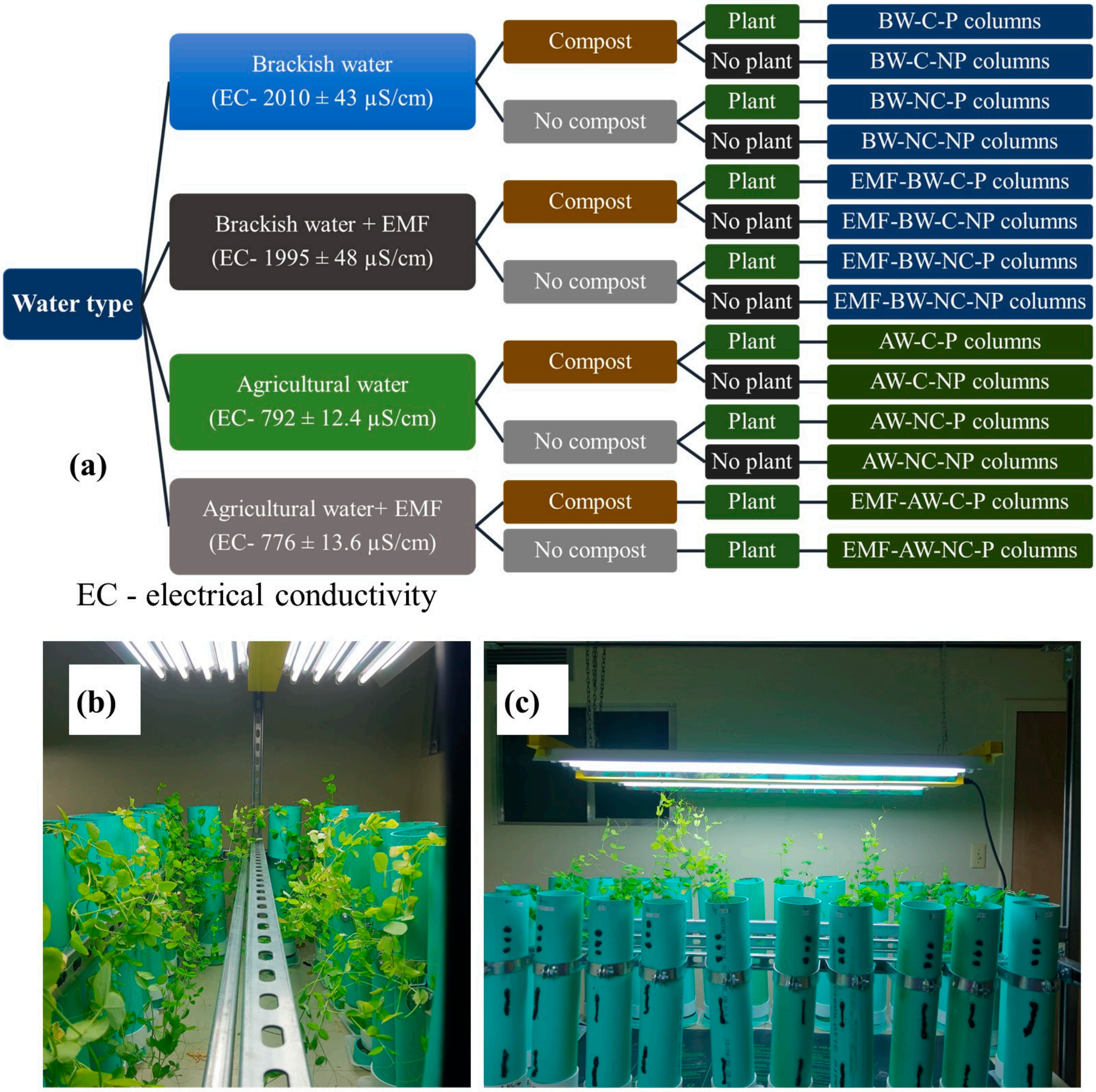

Figure 1. Types of treatment combinations (**a**) studied in the greenhouse experiments with triplicate soil columns (**b**,**c**) for each condition, and the notations for the columns.

2.2. Water Treatment and Irrigation Water Quality

Four types of irrigation water were studied, as summarized in Tabls 1 and S1: (1) groundwater collected from Well-1 at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, representing brackish water with electrical conductivity (EC) of 2010 ± 43 µS/cm and pH of 8.05 ± 0.2; (2) EMF-treated Well-1 groundwater; (3) agricultural water prepared by mixing Well-1 brackish water with desalinated Well 1 water using reverse osmosis (RO), simulating freshwater with EC 792 ± 12.4 µS/cm and pH of 7.08 ± 0.2; and (4) EMF-treated agricultural water. The desalinated water was collected from a renewable-energy-powered autonomous RO desalination system developed by the INFEWS (Innovations at the Nexus of Food, Energy, and Water Systems) project operated at BGNDRF. The water was supplied to a reverse osmosis (RO) system through a pump operating ~8 bar and ~8 L per minute powered with a DC motor connected to an off-grid hybrid solar and wind energy system. The system included three 4-inch RO membranes arranged in series, incorporating recirculation to achieve about 90% water recovery. This high recovery rate was facilitated by adding acid and anti-scalant to the feed water to prevent scale formation. Agronomic field experiments were also conducted at BGNDRF as part of the INFEWS project.

Table 1. Variation in the mean ± standard deviation of the water quality parameters (n = 50) across different types of irrigation water treated with varying EMF exposure time.

Water Type	pH		EC (μS/cm)	
	Before EMF	**After EMF**	**Before EMF**	**After EMF**
EMF treatment of 5 min				
Brackish water	8.05 ± 0.2	8.36 ± 0.15	2010 ± 43	1995 ± 48
Agricultural water	7.08 ± 0.2	7.20 ± 0.1	792 ± 12.4	776 ± 13.6
EMF treatment of 20 min				
Brackish water	7.03 ± 0.4	7.20 ± 0.5	1747 ± 15	1694 ± 27
RO permeate	6.86 ± 0.3	6.45 ± 0.7	333 ± 5	322 ± 9

An alternating current-induced electric field with pulsed signals of 120–130 kHz and peak-to-peak voltage of 12–14 volts was applied to the water pipe by circulating the water for 5 min with a flow rate of 2 L/min using a gear pump (Cole-Parmer North America, Vernon Hills, IL, USA) to treat the brackish water and agricultural water with EMF. The EC and pH of the water were measured daily before and after the EMF treatment.

At the onset of the study, the columns were irrigated with 300 mL/day of water for 6 days until saturation was achieved and water started to leach from the columns. Subsequently, 100–150 mL/day of irrigation water was applied to ensure the soil moisture content remained above 0.200 m^3/m^3 in volumetric water content (VWC) during the experimental period. The TEROS 12 sensor (Meter Environment, Meter Group, Inc., Pullman, WA, USA) was used to measure the soil moisture content daily.

A preliminary study was conducted (without replicates) using brackish water (1747 ± 15 μS/cm) and desalinated water (RO permeate, 333 ± 5 μS/cm) with and without EMF treatment. The EMF treatment was conducted with a 20 min exposure time by circulating the water before irrigation. The same procedures and methods described above were employed during this preliminary experiment.

2.3. Pre-Processing and Treatment of Soil and Analysis of Soil Parameters

The soil utilized in this greenhouse study was collected from agricultural testing plots at the Arkansas Valley Research Centre (AVRC) in Rocky Ford, Colorado. Agronomic field experiments and irrigation with brackish water and desalinated water were also conducted at AVRC as part of the INFEWS project. The study aimed to examine the effects of different water types (brackish versus agricultural) and compost incorporation on plant yield at AVRC. The AVRC soil material, collected from different layers, was transported to the New Mexico State University (NMSU) laboratory. The soil was packed into PVC columns, representing field soil layers, with dimensions of 50 cm in height and 10 cm in diameter. Gravimetric determination of bulk density was employed to ensure the desired dry weight for each layer prior to soil packing. Soil moisture content and electrical conductivity were assessed using a TEROS 12 probe. Leached water samples were collected through the holes at the bottom of the columns. Soil samples were collected before and after the irrigation experiments and shipped to a commercial laboratory to analyze soil properties, including physical, chemical, and organic parameters, encompassing texture, pH, major ions, NO_3^-, total−N, organic matter, and organic carbon. The mass of Na^+, Cl^-, NO_3^-, and total−N in the soil was calculated using the mass balance equation.

Compost-treated columns were prepared by mixing compost of 70% moisture content with soil at a weight ratio of 10% (i.e., 3% in dry mass) prior to packing. The compost used in the experiments was collected from a Johnson-Su composting bioreactor. Compost was maintained in an aerobic, undisturbed static composting environment and added with *Eisenia fetida* worms after the compost bioreactor temperature decreased to below 28 °C, and the compost was allowed to mature for one year in the bioreactor. The compost was irrigated daily to maintain 70% moisture content (w/w) throughout the composting process [37].

2.4. Analysis of Irrigation Water and Leached Water

Flood irrigation was performed twice on columns using 300 mL of water, and the leached water was collected in sample bottles. The first flood irrigation was carried out on the 6th day when the columns were saturated, and the second flood irrigation took place on the 56th day before harvesting. Leached water was stored at 4 °C and filtered before analyzing physicochemical parameters, while pH, EC, and alkalinity were analyzed onsite.

pH and EC were measured using a PCD 650 pH/Conductivity/Dissolved Oxygen Meter (Oakton Instruments, IL, USA). Major anions were analyzed using ion chromatography (Dionex ICS-2100, Thermo Fisher Scientific, Pleasanton, CA, USA), and total metals and trace elements were determined through inductively coupled plasma optical emission spectroscopy (Optima 4300 DV, PerkinElmer, Waltham, MA, USA). Alkalinity, the capacity of water to neutralize acids [38], was analyzed using specific test kits (Hach, Loveland, CO, USA), as it influences soil chemistry and plant health. Dissolved organic carbon (DOC) analysis was performed using TOC-V CSH Total Organic Carbon Analyzer (Shimadzu, Kyoto, Japan), and UV absorbance and visible light absorbance scans of the water samples were carried out using a spectrophotometer (DR6000; Hach Company, Loveland, CO, USA). Specific UV absorbance (SUVA) was calculated by dividing the UV absorbance by the DOC concentration of the water sample. Data quality was ensured through charge balance calculations, keeping the percentage error below 10%. The mass balance of major cations, anions, nutrients, and DOC was calculated by defining the mass retained or leached by the soil as the difference between the mass of the constituent in the input water/raw soil and the mass of the constituent in the leached water/in the soil at the end of the experiment. The percentage change of a constituent was determined with $(b - a)/b \times 100\%$, which compares the new value a with the baseline b [39].

2.5. Analysis of Plants

Preliminary experiments were conducted to evaluate the germination and growth of six plant species in each column under greenhouse conditions. The dundale pea (*Pisum sativum*) was chosen out of six species for the long-term irrigation experiments due to its shorter germination period, faster growth, sensitivity to water stress, and tolerance to irrigation water salinity levels up to 600 µS/cm. The seeds were planted at a depth of one inch after six days of flood irrigation and harvested after 50 days. Four healthy seedlings were retained to minimize errors from defective seeds.

The wet weight of the harvested biomass, dry weight of biomass, plant height, and root length were measured using the standard methods described in the reference [39]. Plant tissue analysis was conducted for composite samples of dried biomass. All sample collection, preservation, shipping, and analyses followed the guidance and standards set by the United States Environmental Protection Agency (EPA). The percentage increase in the plant growth parameters was calculated using the formula $(a - b)/b \times 100\%$, where a represents the new value of the parameter after treatment and b is the baseline value of the parameter before treatment.

2.6. Statistical Data Analysis

Parametric statistical tests were conducted after confirming normal distribution. The results of plant growth parameters from different treatments were compared using a two-sample t-test in MINITAB version 17.0. The growth parameters of plant data and soil organics (organic matter OM and organic carbon OC) from different treatments were compared to check the interaction between the factors using three-way ANOVA in MINITAB version 17.0. A four-way ANOVA was used to compare soil moisture content and electrical conductivity, soil chemical parameters, and leached/retained mass of Na^+, NO_3^-, Cl^-, DOC, and other ions across treatments. Tukey's pairwise comparisons were performed when rejecting null hypotheses in the ANOVA. Different superscript letters indicated significantly different mean values ($p < 0.05$), while common letters indicated non-significant differences, with descending alphabetical letters representing decreasing mean values (e.g., $a > b > c > d$). A principal Component Analysis (PCA) was used to visualize and compare different categories within the treatments using leached/retained mass of Na^+, NO_3^-, Cl^-, DOC, and other ions.

3. Results and Discussion

3.1. Impact of EMF Treatment on Water Quality

The variation in basic water quality parameters is summarized in Table 1. The EMF treatment at 120–130 kHz for 5 min led to a slight reduction in EC from 2010 ± 43 to 1995 ± 48 µS/cm (0.75%) for brackish water and from 792 ± 12 to 776 ± 14 µS/cm (2%) for agricultural water. EMF water treatment resulted in a slight increase in pH; the percentage increase was 3.85% and 1.69% for brackish water and agricultural water, respectively. The 20 min EMF treatment lowered the EC by 3% for brackish water, a slightly higher reduction than the 5 min EMF treatment (0.75%) for brackish water, whereas the EC was lowered by 3.3% for RO permeate. This observation was probably due to changed rates of chemical reactions, which facilitate the formation and decomposition of colloidal particles [40]. The pH of the EMF-treated water showed a slight rise for agricultural water (5 min—1.69%) and brackish water (3.85% for 5 min and 2.42% for 20 min). However, the pH was reduced for RO permeate by 5.98% (Table 1). A similar pH trend was observed when an Aqua4D magnetic device (a type of electromagnetic water conditioner) was used to treat the water for 15 min, and no significant differences were observed in other water quality parameters [28]. The finding was confirmed with a pH increase of 6% to 34% with increasing magnetic field intensity due to the absorption of H^+ ions and increasing number of OH^- ions in water [41].

Based on the water quality in Table 1 described in the reference [39], no significant permeability concerns for agricultural irrigation were expected, as evidenced by its SAR of 6.4. However, brackish water with a SAR of 9 may have potential permeability problems and elevated SAR levels in the soil. The high SAR levels in irrigation water indicate that substituting the Ca^{2+} and Mg^{2+} sites in the soil with Na^+ ions could lead to the breakdown of soil structure over time and result in permeability issues [42].

3.2. Impact of EMF Water Treatment on Soil Moisture Content and Soil EC

Table 2 presents the soil moisture content (SM) as VWC and soil EC of the columns irrigated with and without EMF treatment of brackish and agricultural water. The SM of each layer of the soil columns was maintained above 0.200 m^3/m^3 (Figures S1 and S3 illustrate the detailed trend graph). EMF water treatment, compost incorporation, and the presence of plants were significant factors impacting the SM in all three soil layers, while the interaction of EMF and irrigation water type influenced SM of the top and middle layers, with p-value (WT, C, P, WT × IW) < 0.05. The interaction between EMF and irrigation water type positively impacted the columns irrigated with brackish water by increasing SM for brackish water columns, and by reducing SM for agricultural water columns. EMF-BW-C-P and EMF-AW-C-P columns exhibited significantly higher SM in the bottom layer when compared to BW-C-P and AW-C-P columns. The presence of plants and compost reduced the SM in the top and middle layers while increasing the SM in the bottom layers (due to enhanced infiltration) regardless of the EMF treatment, irrigation water type, and soil treatment.

Table 2. Differences in mean ± standard deviation for soil moisture content (as volumetric water content, VWC) and soil electrical conductivity for columns with different water and soil treatments for brackish and agricultural water irrigation (four-way ANOVA).

Irrigation Water Type	**Water Treatment**	**Soil Treatment**	**Plant**	**Soil Electrical Conductivity (mS/cm)**			**Soil Moisture Content (m^3/m^3)**		
				0–15 cm	**15–30 cm**	**30–45 cm**	**0–15 cm**	**15–30 cm**	**30–45 cm**
Brackish water	No EMF	No compost	No plant	3.000 ± 0.554 ^{abc}	2.401 ± 0.235 ^{g}	2.557 ± 0.280 ^{e}	0.252 ± 0.037 ^{a}	0.237 ± 0.012 ^{c}	0.245 ± 0.012 ^{h}
Brackish water	EMF	No compost	No plant	2.654 ± 0.729 ^{cde}	2.642 ± 0.179 ^{ef}	2.485 ± 0.217 ^{ef}	0.248 ± 0.042 ^{ab}	0.248 ± 0.011 ^{a}	0.247 ± 0.021 ^{gh}
Brackish water	No EMF	No compost	Plant	2.930 ± 0.597 ^{bc}	2.756 ± 0.296 ^{de}	3.063 ± 0.336 ^{cd}	0.231 ± 0.015 ^{bcd}	0.222 ± 0.014 ^{ef}	0.275 ± 0.021 ^{de}
Brackish water	EMF	No compost	Plant	2.748 ± 0.757 ^{bc}	3.179 ± 0.312 ^{b}	3.091 ± 0.337 ^{cd}	0.238 ± 0.028 ^{abc}	0.239 ± 0.013 ^{bc}	0.269 ± 0.013 ^{def}
Brackish water	No EMF	Compost	No plant	2.752 ± 0.505 ^{bc}	2.942 ± 0.287 ^{cd}	3.541 ± 0.399 ^{ab}	0.242 ± 0.019 ^{abc}	0.246 ± 0.014 ^{ab}	0.300 ± 0.014 ^{a}
Brackish water	EMF	Compost	No plant	2.684 ± 0.602 ^{bcd}	3.155 ± 0.349 ^{bc}	3.546 ± 0.372 ^{ab}	0.232 ± 0.020 ^{bcd}	0.221 ± 0.011 ^{ef}	0.275 ± 0.013 ^{de}
Brackish water	No EMF	Compost	Plant	3.058 ± 0.350 ^{ab}	3.666 ± 0.364 ^{a}	3.663 ± 0.498 ^{a}	0.230 ± 0.013 ^{bcd}	0.224 ± 0.009 ^{ef}	0.280 ± 0.016 ^{cd}
Brackish water	EMF	Compost	Plant	3.383 ± 0.739 ^{a}	3.378 ± 0.445 ^{b}	3.770 ± 0.337 ^{a}	0.227 ± 0.013 ^{cd}	0.222 ± 0.009 ^{ef}	0.295 ± 0.014 ^{ab}
Agricultural water	No EMF	No compost	No plant	2.249 ± 0.243 ^{f}	2.090 ± 0.388 ^{h}	2.245 ± 0.376 ^{fg}	0.252 ± 0.023 ^{a}	0.248 ± 0.011 ^{a}	0.257 ± 0.023 ^{fgh}
Agricultural water	No EMF	No compost	Plant	2.112 ± 0.384 ^{f}	1.852 ± 0.123 ^{i}	2.167 ± 0.203 ^{g}	0.246 ± 0.027 ^{ab}	0.234 ± 0.015 ^{cd}	0.271 ± 0.024 ^{def}
Agricultural water	EMF	No compost	Plant	2.286 ± 0.559 ^{def}	1.740 ± 0.195 ^{i}	2.352 ± 0.291 ^{efg}	0.235 ± 0.023 ^{abcd}	0.221 ± 0.007 ^{ef}	0.260 ± 0.018 ^{efg}
Agricultural water	No EMF	Compost	No plant	2.076 ± 0.267 ^{f}	2.430 ± 0.414 ^{fg}	3.209 ± 0.650 ^{cd}	0.244 ± 0.024 ^{abc}	0.253 ± 0.008 ^{a}	0.300 ± 0.016 ^{a}
Agricultural water	No EMF	Compost	Plant	2.277 ± 0.301 ^{ef}	2.670 ± 0.298 ^{e}	3.320 ± 0.497 ^{bc}	0.230 ± 0.015 ^{bcd}	0.228 ± 0.008 ^{de}	0.283 ± 0.028 ^{bcd}
Agricultural water	EMF	Compost	Plant	1.918 ± 0.462 ^{f}	2.265 ± 0.213 ^{gh}	3.014 ± 0.545 ^{d}	0.217 ± 0.013 ^{d}	0.218 ± 0.008 ^{f}	0.295 ± 0.026 ^{ab}
p-value		WT		0.013	0.647	0.3	0	0	0.011
		IW		0	0	0	0.324	0.355	0.744
		C		0.111	0	0	0	0	0
		P		0	0	0	0.001	0	0
		WTxIW		0.174	0	0.158	0.008	0	0.314
		WTxC		0.289	0.021	0.023	0.491	0	0.611
		WTxP		0.021	0.022	0.268	0.099	0	0
		WTxIWxC		0	0.003	0.002	0.421	0	0.772

Notes: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean value $a > b$ value, n = 3 replicates. The mean values sharing common letters are not significantly different from each other. *p*-value; WT—water treatment, IW—significance of irrigation water type, C—significance of compost, P—significance of plants, and x shows the interaction between the factors.

EMF and compost-treated columns with both irrigation water types showed a higher SM above 0.275 m^3/m^3 for the bottom layer of soil, whilst the no-compost columns with plants also recorded a higher SM of 0.260 m^3/m^3 (Table 2, Figures S1b,d and S3b) compared to the top and middle layers of the soil. In a different study, treatment with magnetized water resulted in approximately a 7.5% increase in soil moisture content compared to non-magnetized water [43]. Our parallel studies demonstrated that compost treatment enhanced the water-holding capacity of the soil. However, the EMF and compost-treated columns recorded slightly lower SM in the top and middle layers of the soil, except the bottom layer. This observation can be explained by the increased water infiltration due to EMF treatment of irrigation water; however, this impact was reduced by plant growth for both types of irrigation water. The penetration of plant roots enhanced the soil aggregate stability [44].

The EMF treatment of brackish water significantly increased the SM in the middle layer of soil from 0.237 ± 0.012 to 0.248 ± 0.011 m^3/m^3 in no-compost columns without plants. Similarly, the BW-NC-P columns had an SM of 0.222 ± 0.014, and EMF-BW-NC-P columns had a value of 0.239 ± 0.013 m^3/m^3 due to increased infiltration where water salinity did not affect the water flow to the deeper layers. The lowest SM was recorded for the EMF-AW-C-P columns with the values of 0.217 ± 0.013 m^3/m^3 and 0.218 ± 0.008 m^3/m^3 in the top and middle layer of the soil, whereas the compost treatment led to high SM in the bottom layer when compared with other agricultural-water-irrigated columns. The impact of EMF treatment on SM was reduced by compost treatment and did not influence the plant growth parameters of the EMF-AW-C-P columns (Table 5). The compost-treated columns showed higher SM in the bottom layers of the soil columns than the top and middle layers for the columns irrigated with EMF-treated water (Figures S1b,d and S3b).

Irrigation water type, presence of plants, EMF treatment, and compost were significant factors impacting soil EC in all three layers, p (IW, P, and WTxIWxC) < 0.05. Compost treatment of soil significantly increased the soil EC in the middle and bottom layers of soil. Remarkably lower soil EC was recorded for agricultural-water-irrigated columns than for the brackish-water-irrigated columns in all three layers, p-value (IW) = 0.000. The impact of EMF treatment was more significant for brackish water than agricultural water irrigation on soil EC in the middle layer of soil. The EMF-treated brackish water columns had significantly lower soil EC than no-EMF brackish water columns (denoted by different superscript letters). The measurements for soil EC were lower for agricultural water due to the leaching of ions from columns and reduced EC of irrigated water (Table 3).

EMF water treatment caused increased soluble salts due to the increased leaching of compost and organic matter in columns when brackish water was used for irrigation. Mohamed [45] noted that applying magnetically treated irrigation water following plant harvest led to an increase in soil EC and available phosphorus (P) levels, supporting the results observed in this present study. The topsoil layer of the BW-NC-NP columns measured 3.000 ± 0.554 mS/cm; however, the EMF-BW-NC-NP columns recorded 2.654 ± 0.729 mS/cm due to the leaching of ions to deeper soil layers. The columns with plants showed higher soil EC in all layers for the compost-treated columns, where compost contributed 1.45 mS/cm with soluble salts. This may be related to the mineralization of compost enabled by the root penetration of plants [46]. Soil EC showed high fluctuation during the study until 30 days of irrigation (Figures S2a–d and S4a,b).

Table 3. Differences in mean ± standard deviation for the leached ions and DOC and SAR values from columns of different treatments (four-way ANOVA) for two types of irrigation water with and without EMF treatment.

Irrigation Water	Soil Treatment	Plant	Total Mass of Leaching (mg)							SAR in 6 Days	SAR after 56 Days
			NO_3^-	Cl^-	Na^+	K^+	Mg^{2+}	Ca^{2+}	DOC		
Brackish water	No compost	No plant	1012 ± 34^{abc}	604 ± 11^{ab}	991 ± 37^{ab}	37 ± 6^{cdef}	248 ± 21^{cde}	952 ± 41^{cdef}	133 ± 15^{c}	1.8 ± 0.1^{a}	4.4 ± 0.2^{b}
Brackish water, EMF	No compost	No plant	1174 ± 132^{a}	683 ± 19^{a}	1085 ± 31^{a}	49 ± 4^{bc}	274 ± 5^{cde}	1062 ± 44^{abcd}	133 ± 10^{c}	1.8 ± 0.1^{a}	4.5 ± 0.2^{b}
Brackish water	No compost	Plant	996 ± 110^{abcd}	488 ± 42^{bcd}	694 ± 64^{cd}	40 ± 5^{cde}	392 ± 28^{ab}	1206 ± 148^{abc}	80 ± 1^{fg}	1.9 ± 0.2^{a}	3.3 ± 0.2^{d}
Brackish water, EMF	No compost	Plant	1166 ± 123^{a}	590 ± 9^{abc}	769 ± 11^{bc}	45 ± 8^{bcd}	419 ± 47^{a}	1388 ± 110^{a}	84 ± 5^{efg}	1.7 ± 0.2^{a}	3.3 ± 0.3^{d}
Brackish water	Compost	No plant	570 ± 50^{e}	562 ± 39^{abcd}	1114 ± 92^{a}	65 ± 6^{a}	309 ± 28^{bc}	1293 ± 92^{ab}	248 ± 13^{ab}	1.8 ± 0.3^{a}	4.2 ± 0.3^{bc}
Brackish water, EMF	Compost	No plant	702 ± 40^{de}	606 ± 17^{ab}	1045 ± 16^{a}	54 ± 5^{ab}	293 ± 3^{cd}	1251 ± 119^{abc}	287 ± 15^{a}	1.8 ± 0.2^{a}	3.8 ± 0.2^{cd}
Brackish water	Compost	Plant	759 ± 7^{cde}	426 ± 80^{d}	855 ± 133^{bc}	20 ± 3^{g}	152 ± 33^{f}	999 ± 230^{bcde}	72 ± 16^{g}	2.0 ± 0.1^{a}	5.6 ± 0.2^{a}
Brackish water, EMF	Compost	Plant	728 ± 45^{de}	438 ± 56^{cd}	444 ± 56^{e}	26 ± 3^{fg}	268 ± 48^{cde}	1205 ± 148^{abc}	120 ± 12^{cde}	1.7 ± 0.1^{a}	2.7 ± 0.1^{e}
Agricultural water	No compost	No plant	1078 ± 155^{ab}	525 ± 31^{abcd}	524 ± 33^{cde}	34 ± 2^{def}	219 ± 22^{def}	717 ± 39^{ef}	121 ± 14^{cde}	1.7 ± 0.1^{a}	2.6 ± 0.2^{e}
Agricultural water, EMF	No compost	Plant	1093 ± 115^{ab}	425 ± 13^{d}	312 ± 10^{e}	20 ± 0^{g}	206 ± 4^{def}	634 ± 35^{f}	67 ± 4^{g}	1.7 ± 0.2^{a}	2.6 ± 0.1^{e}
Agricultural water	No compost	Plant	804 ± 124^{cde}	494 ± 49^{bcd}	345 ± 23^{e}	24 ± 4^{fg}	222 ± 37^{cdef}	696 ± 92^{ef}	84 ± 5^{efg}	2.0 ± 0.1^{a}	2.2 ± 0.1^{ef}
Agricultural water	Compost	No plant	910 ± 78^{abcd}	553 ± 20^{abcd}	504 ± 15^{de}	47 ± 3^{bcd}	229 ± 6^{cdef}	826 ± 45^{def}	245 ± 15^{b}	2.0 ± 0.2^{a}	2.1 ± 0.1^{f}
Agricultural water, EMF	Compost	Plant	877 ± 51^{bcd}	478 ± 42^{bcd}	321 ± 37^{e}	24 ± 4^{fg}	232 ± 25^{cdef}	753 ± 62^{def}	124 ± 14^{cd}	1.8 ± 0.0^{a}	2.2 ± 0.1^{ef}
Agricultural water	Compost	Plant	593 ± 33^{e}	448 ± 56^{bcd}	391 ± 6^{e}	27 ± 3^{efg}	197 ± 17^{ef}	623 ± 50^{f}	118 ± 8^{cdef}	1.7 ± 0.1^{a}	3.3 ± 0.2^{d}
	WT		0.003	0.401	0.051	0.004	0.496	0.308	0.793	0.354	0
	IW		0.152	0.02	0	0	0	0	0.008	0.515	0
	C		0	0.429	0.208	0.014	0.001	0.388	0	0.111	0
	P		0	0	0	0	0.07	0.756	0	0.644	0
p-value	WTxIW		0.263	0.051	0.475	0	0.019	0.146	0.001	0.579	0
	WTxC		0.446	0.424	0.988	0.517	0.906	0.95	0	0.192	0
	WTxP		0.796	0.886	0.105	0.18	0.01	0.087	0.976	0.082	0
	WTxIWxC		0.004	0.061	0.001	0.025	0.389	0.525	0.244	0.139	0
	WTxCxP		0.71	0.703	0.171	0.004	0.011	0.337	0.725	0.919	0

Notes: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean value $a > b > c$ value, n = 3 replicates. The mean values sharing common letters are not significantly differ from each other. *p*-value; WT—water treatment, IW—significance of irrigation water type, C—significance of compost, P—significance of plants, and x shows the interaction between the factors.

3.3. Impact of EMF Water Treatment, Soil Compost Incorporation, and Plant Growth on Leaching of Ions and Organics from Different Soil Columns

The impacts of EMF-treated water on the leaching of ions and DOC, as well as SAR values of the soil columns, are compared in Table 3. The highest values of mass leached of NO_3^-, Cl^-, Na^+, DOC, Ca^{2+}, Mg^{2+}, and K^+ were 1174 ± 34 mg, 683 ± 19 mg, 1114 ± 92 mg, 287 ± 15 mg, 1388 ± 110 mg, 419 ± 47 mg, and 65 ± 6 mg, whereas the lowest values were recorded as 570 ± 50 mg, 425 ± 13 mg, 312 ± 10 mg, 67 ± 4 mg, 623 ± 50 mg, 152 ± 33 mg, and 20 ± 0 mg, respectively. The higher values were measured in brackish water irrigation, whereas the lowest values were recorded for agricultural irrigation with and without EMF treatment, excluding NO_3^- and Mg^{2+}. EMF-treated water was a significant factor for the leaching of NO_3^-, K^+, and SAR after 56 days of irrigation (p (WT) < 0.05). The plant growth reduced the leaching of NO_3^-, DOC, Na^+, and Cl^- (p (P) < 0.05) when there was no compost. Plant growth significantly lowered the leaching of Na^+ and DOC regardless of the irrigation type and soil treatment (p-value (P) = 0.000). The statistical analysis on the interaction of water treatment with compost and plant, and the interaction with water treatment and irrigation water, showed significant differences for leaching of Mg^{2+}, K^+, and SAR after 56 days of irrigation (p (WTxIW and WTxCxP) < 0.05).

The leaching of NO_3^- from soil was reduced due to compost incorporation. The reduction was by 4.6% and 24.9% for the EMF-BW-C-NP and BW-C-NP columns, whereas it was reduced by 19.8% and 26.2% for the EMF-AW-C-P and AW-C-P columns, respectively. There was no significant difference in mass of leached NO_3^- amongst EMF-BW-NC-NP, EMF-BW-NC-P, BW-NC-NP, and BW-NC-P columns; however, there was significance between compost- and no-compost-treated columns. The AW-NC-P columns showed a considerably lower mass of NO_3^- 804 ± 124 mg, although no compost was added to the soil. EMF water treatment and compost treatment showed significant interaction for the leaching of DOC and SAR after 56 days of irrigation (p-value (WTxC) = 0.000). Drastically, the lowest leaching of NO_3^- was estimated for the BW-C-NP columns, where the value was 570 ± 50 mg compared to all 14 treatments. Compost-incorporated columns were measured with significantly higher leaching of DOC compared to no-compost columns due to high OM (16.6%) and OC (9.9%) in compost. However, plant growth reduced the leaching of DOC.

There was no significance for leaching of Cl^- among different treatments, excluding the compost-incorporated columns irrigated with brackish water. EMF-treated brackish water indicated slightly higher leaching of Cl^-, regardless of the presence of plants and compost treatment. Compost alone did not influence the leaching of Cl^-; rather, compost and plant growth simultaneously reduced the leaching of Cl^- regardless of irrigation water type and treatment. The EMF-BW-NC-NP columns leached 683 ± 19 mg of Cl^-, slightly higher than other columns. EMF-treated brackish water resulted in significantly lower (48.1%) leaching of Na^+ 444 ± 56 mg compared to 855 ± 133 mg for BW-C-P and EMF-BW-C-P columns, respectively (denoted by different superscript letters). An opposite trend was observed for no-compost treated brackish water columns. A significant amount of Na^+ leaching was controlled with EMF-treated brackish and agricultural water irrigation and compost-incorporated soil in the presence of plants. Higher Na^+ was reported in plant tissue analysis (Table S5), which contradicts a study where lower Na^+ was recorded in plant tissues for magnetized water with a different magnetic field (permanent magnets) over non-magnetized water [24]. The Na^+ toxicity can damage the root and plant; however, the treatment columns in the present study had the highest values for plant growth parameters despite high Na^+ in plants.

A higher mass of Ca^{2+} was leached from brackish-water-irrigated no-compost columns, as the Ca^{2+} input by irrigation water was approximately 62 mg/L. Although Ca^{2+} is an essential plant nutrient, excessive Ca^{2+} in the root zone can lead to Ca^{2+} toxicity by affecting other nutrient uptake and reducing plant growth [47]. Soil sodicity will be reduced by replacing the Na^+ sites with Ca^{2+} and Mg^{2+} [48]. The lowest mass leaching of Ca^{2+} was 623 ± 50 mg from agricultural water irrigated soil with compost treatment due to plant uptake (Table S5). Magnesium contributes to the functioning of cellular enzymes and amino acid synthesis [49] in plants. A slightly lower mass of Mg^{2+} was leached from the columns irrigated with brackish and agricultural water with varying water treatment due to compost treatment and plant uptake. The result was a contrast between the columns with brackish water and without compost incorporation (p-value (C) = 0.001).

There was a significant increase in SAR value to 3.3 ± 0.2 for agricultural water AW-C-P columns compared to 2.2 ± 0.1 for the EMF-AW-C-P columns. Similar results were observed for brackish water that EMF treatment reduced SAR from 5.6 ± 0.2 for BW-C-P to 2.7 ± 0.1 for EMF-BW-C-P columns. These results indicated that EMF treatment significantly favored leaching the ions responsible for SAR, reducing the damage effects of brackish water irrigation. EMF water treatment, irrigation water type, presence of plants, compost, and the interaction of these factors impacted SAR after 56 days of irrigation. The columns with compost and plants were calculated with significantly lower mass leaching of Mg^{2+} (152 ± 33 mg), which ensures the availability of Mg^{2+} to replace Na^+ sites and reduce the SAR and soil salinity for brackish-water-irrigated columns. Hence, the EMF-treated water helped leach out the Na^+ in no-compost brackish water columns, avoid replacing Ca^{2+} and Mg^{2+} absorbed in the soil by Na^+, and keep the soil in a permeable and granular structure.

Potassium is vital to maintaining the movement of water and nutrients in plant tissue, and is associated with enzyme activation of ATP production and regulating photosynthesis [50]. The presence of plants and compost treatment significantly reduced the leaching of K^+ by more than 50% for brackish-water-irrigated columns, irrespective of EMF treatment. However, it was not significant when there was no compost. Agricultural-water-irrigated columns showed significant K^+ reductions of 29.4% and 42.5% due to plant growth for compost-treated and no-compost columns, respectively. The leaching of ions during two flood irrigation periods and the leaching or retaining of ions are shown in mass balance graphs for each ion (Figures S5–S7 for brackish water; Figures S8–S10 for agricultural water; Figures S11–S13 for compost-incorporated columns).

The preliminary study results with 20 min of EMF treatment of brackish water demonstrated relatively higher leaching of NO_3^- and Na^+ over no-EMF treatment for no-compost columns. EMF treatment of brackish water for 20 min was beneficial for leaching out Na^+ from the soil with compost treatment when there were no plants. The irrigation with RO permeate resulted in higher leaching of ions when there was no compost. The leaching of Na^+ was beneficial, but the leaching of NO_3^- was detrimental compared to EMF treatment for 5 min (Table S8, Figures S14–S19).

Principal component analysis (PCA), the multivariate relationship between soil and leached water ions, specifically NO_3^-, Cl^-, Na^+, Ca^{2+}, Mg^{2+}, K^+, DOC, and SAR, was explored (Table S2), and the score plot is shown in Figure 2. The PCA revealed that the first principal component (PC1) accounted for 44.4% of the variance, while the second (PC2) explained 18.7%, cumulatively capturing 63.1% of the total variability in the dataset. Notably, Na^+, Cl^-, Ca^{2+}, and K^+ had strong positive loadings on PC1, indicating their substantial contribution to the variance along this axis, while NO_3^- displayed a significant loading on PC2, highlighting its differentiation along the second axis. Treatments involving brackish and agricultural water with various combinations of EMF treatment, plants, and compost were analyzed. The treatment groups BW + EMF + NC + P, BW + EMF + NC + NP, BW + EMF + C + NP, and BW + C + NP clustered towards the positive side of PC1, suggesting a higher association with the Na^+, Cl^-, Ca^{2+}, and K^+, which correlated with the data in Table 3. In contrast, BW + EMF + NC + P is more dispersed along PC2, indicating diverse effects of these treatments on NO_3^-, as shown in Table 3 and Table S3. Compost-treated brackish-water-irrigated columns dispersed under lower leaching of NO_3^-, where PC1 had positive loadings and PC2 had negative loadings. The brackish-water-irrigated columns, except BW + EMF + C+P columns, leached out higher K^+, Na^+, and Cl^-, which showed a strong positive loading of PC1.

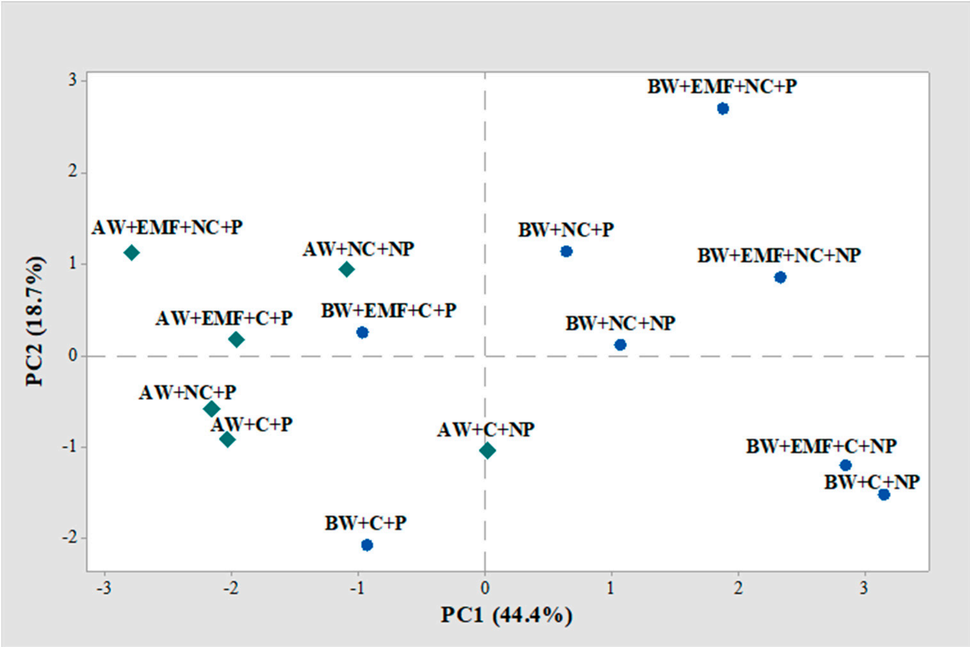

Figure 2. Principal Component Analysis (PCA) Score Plot displaying the clustering of treatment groups based on the multivariate impact of EMF treatment and compost incorporation on soil ion dynamics. Each point represents a treatment combination, with brackish water (BW) and agricultural water (AW) treatments distinguished by color.

3.4. Impact of EMF Treatment of Irrigation Water and Soil Compost Incorporation on Organic Content of Soil and Leached Water

The analysis of organics for all 14 treatment combinations with varying plant, soil, and water treatment is illustrated in Figure 3. The UV_{254} and SUVA were higher during the first 6 days of irrigation than the values during the 7–56th days of irrigation after planting, indicating natural organic matter in water. In addition, the values were higher for compost-treated columns irrespective of the irrigation water types throughout the study period, indicating the higher amount of natural organic matter in soil. Compost treatment showed SUVA values ranging between 2.0 and 4.0, indicating the mixture of aquatic humic and non-humic matter; and a mixture of low to high molecular-weight substances found in compost (Figure 3b). This was also observed in the studies by Duong (2013) [51] and Staff (2011) [52]. The SUVA values decreased to less than 2, which shows a high fraction of non-humic matter in leached water after 56 days of irrigation for non-compost columns for both brackish and agricultural water irrigation with and without EMF treatment.

The organic matter (OM) and organic carbon percentage (OC) of the columns with different soil and irrigation water treatments, and the percentage increase in OM and OC from the initial soil samples, are summarized in Table 4. The OM refers to all organic components in the soil, including decomposed plants and animal residues. The OC specifically represents the carbon element within this organic matrix. While OM includes all organic elements, OC focuses on the carbon component, which is critical for assessing soil health and carbon cycling dynamics. The contribution of OM and OC from compost to the soil was subtracted in the calculation, which was 6.3% and 24.2%, respectively [39]. Soil compost treatment significantly enhanced the soil OM and OC (p-value (C) = 0.000). The highest OM and OC percentages were estimated as 23.5 ± 1.8% and 9.7 ± 1.6%, respectively, for the EMF-BW-C-NP columns, whereas the lowest values were recorded as 15.1 ± 0.5% and 3.9 ± 0.3% for the BW-NC-NP columns, respectively, when considering all 14 treatment conditions. EMF water treatment significantly enhanced OC in EMF-AW-C-P columns to 9.6 ± 0.8% from 7.4 ± 0.4% for AW-C-P columns (p-value (WT) = 0.004). The compost significantly improved the OM and OC by greater than 27% and 30%, respectively, for all the compost-treated columns. This trend was observed in a previous study, which showed that the OM increased in the void spaces [53].

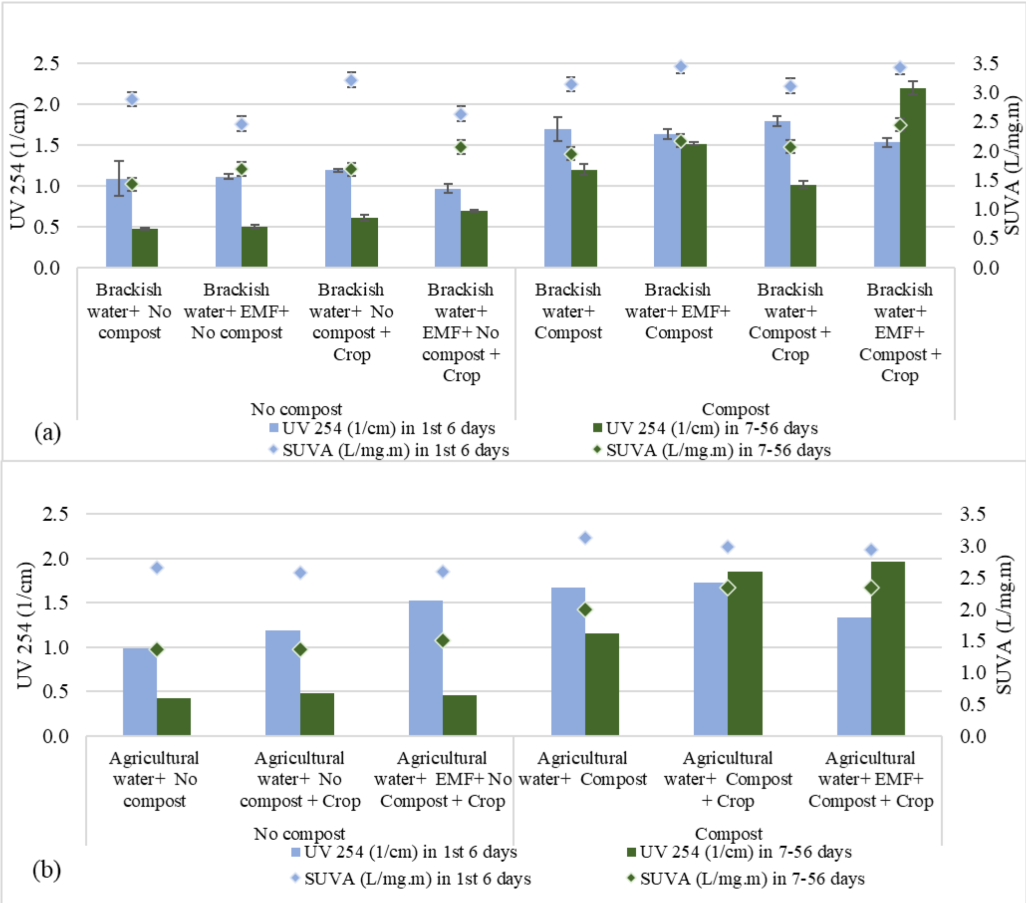

Figure 3. Organic analysis of leached water using UV 254 and specific UV absorbance (SUVA) for brackish water (**a**) and agricultural water irrigation (**b**) with and without EMF treatment.

The columns without compost treatment resulted in lower OM and OC than the initial soil, which led to negative values; however, the level of reduction decreased when there were plants. The effect of EMF treatment was insignificant when there was no compost for brackish water irrigated columns; however, an increase in OC by 3.7% was observed for EMF-AW-NC-P columns. EMF-treated irrigation columns showed a higher percentage of OC increase than no-EMF-treated columns for composted columns. The percentage increases in OC for the columns irrigated with and without EMF treatment were greater than 55% and 30%, respectively. EMF-treated brackish water columns with and without plants and EMF-treated agricultural water columns with plants showed an increment of 18.2%, 7.1%, and 29.7% in OC compared to no-EMF-treated columns than the OC of compost itself. The percentage increase was slightly higher at 35.4% and 32.1% for EMF-BW-C-NP and EMF-BW-C-P columns, respectively. These results may be attributed to enhanced carbon fixing by plants, as the plant growth parameters also recorded high values (Table 5). The AW-C-P columns showed a slight increase in OM from 22.2 ± 1.5% to 23.0 ± 1.4% for EMF-AW-C-P columns. In contrast, EMF treatment caused an OM reduction from 22.9 ± 1.3% to 22.1 ± 1.8% for BW-C-P and EMF-BW-C-P columns, likely due to significant leaching of DOC (Table 3).

Table 4. Impact of compost incorporation on organic matter and organic carbon percentage of soil for brackish and agricultural water irrigation with and without EMF treatment (three-way ANOVA).

Irrigation Water Type	Water Treatment	Soil Treatment	Plant	Organic Matter (%)	Increase OM from Raw Soil (%)	Organic Carbon (%)	Increase OC from Raw Soil (%)
Impact on brackish water-irrigated columns							
Brackish water	No EMF	No compost	No plant	15.1 ± 0.1^{b}	−7.9	3.9 ± 0.3^{b}	−15.5
Brackish water	EMF	No compost	No plant	15.1 ± 0.5^{b}	−7.7	4.2 ± 0.3^{b}	−10.0
Brackish water	No EMF	No compost	Plant	15.5 ± 0.6^{b}	−5.0	4.1 ± 0.2^{b}	−12.1
Brackish water	EMF	No compost	Plant	15.7 ± 0.6^{b}	−4.0	4.3 ± 0.2^{b}	−7.9
Brackish water	No EMF	Compost	No plant	22.5 ± 0.6^{a}	29.4	8.2 ± 0.5^{a}	43.3
Brackish water	EMF	Compost	No plant	23.5 ± 1.8^{a}	35.4	9.7 ± 1.6^{a}	69.3
Brackish water	No EMF	Compost	Plant	22.9 ± 1.3^{a}	32.1	8.4 ± 0.5^{a}	47.3
Brackish water	EMF	Compost	Plant	22.1 ± 1.8^{a}	27.3	9.0 ± 0.9^{a}	56.9
p-value		WT		0.827		0.074	
		C		0.000		0.000	
Impact on agricultural water-irrigated columns							
Agricultural water	No EMF	No compost	No plant	15.5 ± 0.8^{b}	−5.0	3.9 ± 0.3^{c}	−15.6
Agricultural water	No EMF	No compost	Plant	15.8 ± 1.2^{b}	−3.4	4.1 ± 0.5^{c}	−12.1
Agricultural water	EMF	No compost	Plant	15.8 ± 0.3^{b}	−3.4	4.8 ± 1.1^{c}	3.7
Agricultural water	No EMF	Compost	No plant	22.3 ± 2.1^{a}	28.5	7.6 ± 1.0^{b}	32.7
Agricultural water	No EMF	Compost	Plant	22.2 ± 1.5^{a}	27.7	7.4 ± 0.4^{b}	30.2
Agricultural water	EMF	Compost	Plant	23.0 ± 1.4^{a}	32.5	9.6 ± 0.8^{a}	68.4
p-value		WT		0.493		0.004	
		C		0.000		0.000	

Notes: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and mean value $a > b > c$ value, n = 3 replicates. Negative value for percentage indicates the reduction. OM and OC of the initial soil were calculated, and the increase in OM and OC percentage after 56 days of irrigation with different treatments were calculated using the initial soil content as a base value. *p*-value; WT—water treatment, C—significance of compost.

3.5. Impact of EMF-Treated Irrigation Water and Soil Compost Incorporation on the Soil Nutrients and Ions

The mass of NO_3^-, total−N, Na^+, and Cl^- in three soil layers for different soil treatment combinations is illustrated in Figures 4 and 5 for the columns irrigated with and without EMF treatment of brackish water and agricultural water. Compost-treated soil indicated significantly higher NO_3^- and total−N compared to no-compost columns (p (C) < 0.05, Table S2, Figures 4a,b and 5a,b) except for the AW-NC-P columns. The values for NO_3^- and total−N for AW-NC-P columns ranged from 27.0 ± 10.2 mg to 33.7 ± 7.5 mg and 2045 ± 254 mg to 2141 ± 95 mg in all three layers, which were high values, similar to compost-treated soil columns due to the significant positive impact of irrigation water type (p (IW) < 0.05) for top and middle soil layers (Table S4).

The increased inoculation of fungi and bacteria in compost led to enhanced microbial growth and activity in NO_3^- assimilation [51,54]. Higher NO_3^- was recorded in the middle layer (15–30 cm) of soil than in the top (0–15 cm) and bottom (30–45 cm) layers for all treatments except for the BW-NC-NP columns. In comparison, most columns recorded lower NO_3^- and total−N in the bottom layers for agricultural water. The EMF-BW-C-P columns showed slightly lower NO_3^- compared to BW-C-P columns; the values were reduced from 43.1 ± 8.6 mg to 33.4 ± 4 mg, from 42.9 ± 16.2 mg to 34.9 ± 8.1 mg, and from 36.0 ± 15.8 mg to 20.3 ± 9.3 mg for the top, middle, and bottom layers, respectively, due to plant growth (Table 5) and leaching of nitrate (Table 3). The EMF-AW-NC-P columns showed significantly lower total−N of 1527 ± 93 mg, 1519 ± 142 mg, and 1207 ± 393 mg for the top, middle, and bottom layers, respectively, likely due to leaching of NO_3^- (Tables 3 and S4).

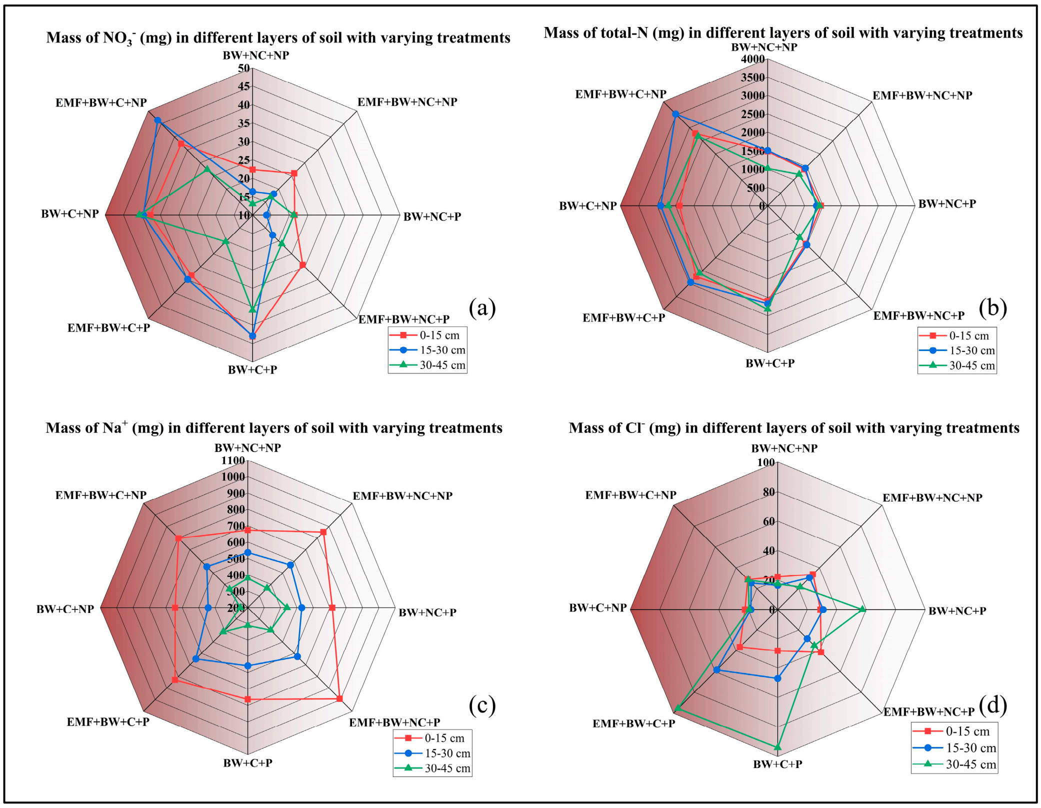

Figure 4. Mass of (**a**) NO_3^-, (**b**) total−N, (**c**) Na^+, and (**d**) Cl^- in soil layers at the end of the experiment for brackish water irrigation with and without EMF treatment.

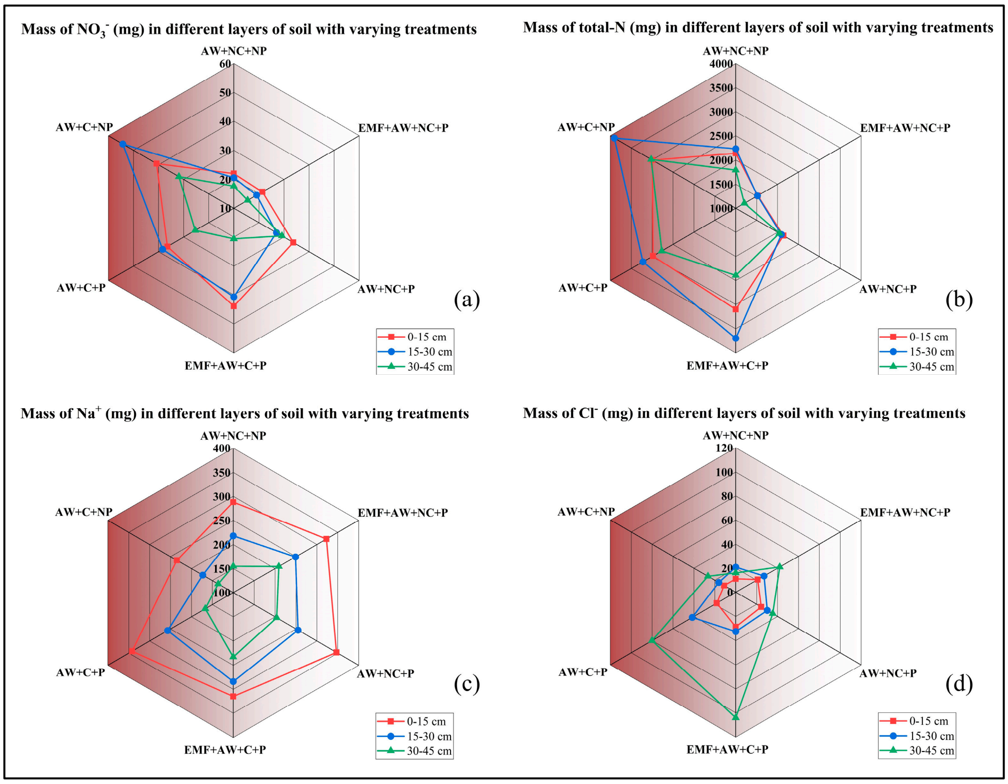

Figure 5. Mass of (**a**) NO_3^-, (**b**) total−N, (**c**) Na^+, and (**d**) Cl^- in soil layers at the end of the experiment for agricultural water irrigation with and without EMF treatment.

Table 5. Differences in mean ± standard deviation for the plant growth analysis of different treatments (two-sample *t*-test) for brackish water irrigation with and without EMF treatment.

Irrigation Water Type	Water Treatment	Soil Treatment	Wet Weight of Biomass (g)	Dry Biomass (g)	Plant Height (cm)	Root Length (cm)
Impact of EMF water treatment on no-compost soil treatment and increase in plant growth (%)						
Brackish water	No EMF	No compost	11 ± 2.3^{a}	2.1 ± 0.25^{a}	114 ± 12^{a}	19 ± 0.4^{a}
Brackish water	EMF	No compost	9 ± 1.2^{a}	2.0 ± 0.2^{a}	110 ± 9^{a}	12 ± 3^{a}
	p-value		0.312	0.871	0.629	0.050
	EMF/No EMF		−18.2%	−1.9%	−3.5%	−36.8%
Impact of EMF water treatment on compost soil treatment and increase in plant growth (%)						
Brackish water	No EMF	Compost	18 ± 2.0^{a}	3.1 ± 0.8^{a}	132 ± 3^{a}	42 ± 2^{a}
Brackish water	EMF	Compost	18 ± 1.5^{a}	3.6 ± 0.4^{a}	140 ± 15^{a}	41 ± 2^{a}
	p-value		0.833	0.379	0.448	0.548
	EMF/No EMF		0 %	17.1%	6.1%	−2.4%
Impact of compost soil treatment on EMF treatment and increase in plant growth (%)						
Brackish water	EMF	No compost	9 ± 1.2^{b}	2.0 ± 0.2^{b}	110 ± 9^{a}	12 ± 3^{b}
Brackish water	EMF	Compost	18 ± 1.5^{a}	3.6 ± 0.4^{a}	140 ± 15^{a}	41 ± 2^{a}
	p-value		0.004	0.027	0.059	0.001
	Compost/No compost		100%	78.8%	27.3%	241.6%
Impact of EMF water treatment on no-compost soil treatment and increase in plant growth (%)						
Agricultural water	No EMF	No compost	10 ± 2.0^{a}	1.9 ± 0.2^{b}	118 ± 9^{a}	33 ± 5^{a}
Agricultural water	EMF	No compost	12 ± 0^{a}	2.8 ± 0.2^{a}	113 ± 12^{a}	24 ± 3^{b}
	p-value		0.235	0.002	0.544	0.082
	EMF/No EMF		20%	48.1%	−4.2%	−27.3%
Impact of EMF water treatment on compost soil treatment and increase in plant growth (%)						
Agricultural water	No EMF	Compost	15 ± 4.2^{a}	3.2 ± 0.9^{a}	128 ± 15^{a}	37 ± 1^{a}
Agricultural water	EMF	Compost	16 ± 2.0^{a}	3.0 ± 0.8^{a}	132 ± 12^{a}	39 ± 1^{a}
	p-value		0.826	0.749	0.714	0.187
	EMF/No EMF		6.6%	−6.25%	3.1%	5.4%
Impact of compost soil treatment on EMF treatment and increase in plant growth (%)						
Agricultural water	EMF	No compost	12 ± 0^{a}	2.8 ± 0.2^{a}	113 ± 12^{a}	24 ± 3^{b}
Agricultural water	EMF	Compost	16 ± 2.0^{a}	3.0 ± 0.8^{a}	132 ± 12^{a}	39 ± 1^{a}
	p-value		0.078	0.410	0.132	0.017
	Compost/No compost		33.3%	8.3%	16.8%	62.5%

Notes: Mean values indicated by different superscript letters are significantly different from each other ($p < 0.05$), and a—higher mean value, b—lower mean value, n = 3 replicates. Negative value for percentage indicates the reduction.

The EMF-BW-C-P columns had a significantly higher mass of Cl^- in the bottom layer (30–45 cm) than the BW-C-P columns, where the values were 95.5 ± 18 mg and 94.1 ± 31 mg. The consistent tendency was accompanied by EMF-AW-C-P and AW-C-P columns with a Cl^- mass of 104.1 ± 16.6 and 80.1 ± 24.6 mg, respectively (Figures 4d and 5d), due to the significant impacting factors of compost and plants (*p* (P) < 0.05, Table S4). A lower mass of Cl^- was recorded for the columns without plants over the columns with plants, irrespective of irrigation water and soil compost incorporation (Table S4).

The mass of Na^+ increased with decreasing depth regardless of the soil and water treatment and type. All three layers had a significant impact on the mass of Na^+ in the soil due to irrigation water type, whereas the top and middle layers of soil were impacted by the presence of plants (*p* (IW and P) < 0.05, Table S4). Figures 4c and 5c show that Na^+ tended to accumulate in the top layer of soil over leaching to the bottom layer during the experimental period, where the mass of Na^+ decreased with increasing depth (Table S4). The mass of Na^+ in soil ranged from 311 ± 54 to 828 ± 96 mg and from 379 ± 39 to 993 ± 111 mg for columns with and without compost treatment, respectively, for brackish water irrigation regardless of EMF treatment. The plants did not show Na^+ toxicity for compost-treated columns due to the chelation of Na^+ by carboxylic groups in compost [55]. The irrigation water type impacted the availability of Na^+ and Cl^- due to the availability of the ions in irrigation water in each layer of the soil (p (IW) < 0.05).

3.6. Impact of Soil Compost Incorporation on Reduction of Nutrient Leaching for EMF-Treated Irrigation Water

The percentage reduction in nutrient (NO_3^-) leaching by compost treatment for EMF-treated water is summarized in Table 6. Compost application significantly mitigated NO_3^- leaching, particularly when combined with EMF-treated water. Compost alone reduced NO_3^- leaching by 23.6% for brackish water and 25.7% for agricultural water, demonstrating its effectiveness across water types. EMF water treatment alone increased NO_3^- leaching by 18.7% and 37.1% for brackish and agricultural water, respectively, highlighting the potential adverse effects of EMF treatment on nutrient retention. The root zone of the plants could mobilize NO_3^- from soil and compost for plant uptake; however, water flow will leach out NO_3^-. Leaching of NO_3^- from fertilizers is one of the sources for groundwater nitrate contamination [56,57]. However, the combination of compost and EMF treatment showed an improved reduction in NO_3^- leaching to 24.9% for brackish water and a decrease to −15.3% for agricultural water, indicating that the synergistic effect of compost and EMF treatment could offset the negative impact of EMF alone.

Compost incorporation to sandy loam and clay loam soil was reported with reduced leaching of nutrients [15]. Compost incorporation into soil showed a consistent tendency for the preliminary study, which assisted in leaching reduction when RO permeate and brackish water were used for irrigation regardless of EMF treatment. The compost reduced NO_3^- leaching by greater than 65% and 47% for the columns with brackish water and RO permeate irrigation (Table S7). The compost treatment of soil can counteract the impact of EMF water treatment on NO_3^- leaching by slowing down the release of mobilized NO_3^- which will facilitate reducing groundwater contamination by NO_3^-.

Table 6. Percentage reduction in NO_3^- leaching by compost, EMF water treatment, and compost + EMF water treatment with different types of irrigation water.

Irrigation Water	Leaching Reduction by (%)		
	Compost	EMF Water Treatment	Compost + EMF Water Treatment
Brackish water	23.6	−18.7	24.9
Agricultural water	25.7	−37.1	−15.3

Notes: Percentage reduction in NO_3^- leaching by compost, EMF water treatment, and compost+ EMF water treatment were calculated over no EMF treatment, no compost, and plant treatment.

3.7. Impact of EMF-Treated Irrigation Water and Soil Compost Incorporation on Plant Growth

The impacts of EMF-treated irrigation water on plant growth parameters with varying soil treatment for two sample t-tests are summarized in Table 5. The highest values for wet weight of biomass, dry biomass, plant height, and root length were measured as 18 ± 1.5 g, 3.6 ± 0.4 g, 140 ± 15 cm, and 42 ± 2 cm, whereas the lowest values were recorded as 9 ± 1.2 g, 1.9 ± 0.2 g, 110 ± 9 cm, and 12 ± 3 cm, respectively. According to three-way ANOVA for the plant growth parameters, EMF treatment and brackish water irrigation were significant factors that negatively impacted the root length of the plants, whereas interaction between compost and EMF treatment and interaction between irrigation water and compost had a significant impact on root length (p (WT, IW, WTxC, and IWxC) < 0.05). The highest values for wet and dry weight of biomass and plant height were estimated for the EMF-BW-C-P columns, whereas the lowest values for plant height and root length were for the EMF-BW-NC-P columns. The lowest value for root length was due to EMF treatment and irrigation with brackish water (p-value (WT and IW) = 0.002 and 0.000, respectively, three-way ANOVA). These results are consistent with the preliminary study using RO permeate and brackish water (Tables S9 and S10), as well as reported results by Surendran et al. [29] that the application of magnetic treatment to irrigated water profiles led to improved plant yields and growth parameters for cowpea and brinjal.

Compost incorporation facilitated the plant height and root length by 27.3% and 241.6% due to decreased leaching of ions and nutrients from the soil (Table 3). The decrease in wet weight of biomass and root length was 18.2% and 36.8%, respectively; however, it was not significant ($p > 0.05$) for no-compost columns irrigated with EMF-treated brackish water. A similar comparison was observed for compost treatment columns as well. There was no significance for EMF-AW-NC-P columns compared to EMF-AW-C-P columns, excluding the root length where the values increased from 24 $\pm$ 3 cm to 39 $\pm$ 1 cm with the increment of 62.5% due to compost (p-value = 0.017). There was no significant difference between compost-treated soil for the columns with and without EMF treatment for agricultural and brackish water irrigation ($p > 0.05$). However, there was a slight increase in the plant parameters for EMF-treated agricultural and brackish water irrigation columns (Table S6).

EMF-treated water supported the increase in the dry biomass and plant height by 17.1% and 6.1%, respectively, for brackish water irrigation. Compost treatment of soil resulted in an increase in wet weight, dry biomass, plant height, and root length by 100%, 78.8%, 27.3%, and 241.6% for brackish water irrigation, and 33.3%, 8.3%, 16.8%, and 62.5% for agricultural water irrigation, respectively. Compost incorporation of soil withstands the effect of soil salinity by brackish water irrigation and the EMF, as the previous study found that compost treatment can alleviate the impact of soil salinity [58]. A similar trend was observed for compost treatment for the preliminary study when the water was EMF treated for 20 min. EMF-treated brackish water and compost treatment enhanced the plant growth by increasing the wet weight by 63.6%, dry weight by 71.4%, plant height by 22.8%, and root length by 115.8% over no-EMF and compost columns. Combined EMF and compost treatment mitigate the effect of high salinity and calcification. Hilal and Hilal reported that magnetized water for irrigation resulted in higher yields for tomatoes, pepper, maize, and wheat [27].

4. Conclusions

This study assesses the effects of EMF treatment and soil composting on soil properties, plant growth, and ion leaching. EMF treatment of brackish water with compost improved water infiltration, nutrient availability, soil organic content, and compost mineralization while maintaining a low soil SAR. EMF treatment of brackish water with compost and plants can maintain the soil SAR at 2.7. EMF minimized the accumulation of Na^+ and reduced the replacement of Ca^{2+} and Mg^{2+} absorbed in the soil. In addition, EMF accelerated the leaching of toxic Cl^- to the bottom layer of soil. Compost incorporation into soil increased organic matter and carbon by 27% and 30%, enhancing nutrient availability irrespective of the irrigation water and reducing nitrate leaching by over 35% when using EMF-treated brackish water. This boosted plant growth by over 63%, indicating compost's role in mitigating soil salinity effects. Even without compost, EMF treatment increased biomass by 20% for agricultural water irrigation. EMF-treated brackish water and brackish water irrigation with compost incorporation significantly alleviated the impact of soil salinity on plant growth.

Although EMF treatment enhanced the biomass yield, contradictorily, it adversely affected plant root growth and nutrient retention if compost was not applied during brackish water irrigation. Both 5 and 20 min of EMF water treatments resulted in beneficial Na^+ leaching and detrimental NO_3^- leaching. However, 5 min EMF treatment has fewer effects on ion leaching than the 20 min treatment. Further research is required to optimize EMF treatment conditions for field applications, such as EMF contact time, strength and intensity, and the impacts on salt-sensitive crops. This study did not show a significant benefit associated with brackish water desalination over brackish water irrigation. The non-chemical treatment with the combination of EMF and compost can alleviate the impact of brackish water irrigation and avoid desalination if the water salinity is moderate, such as 2000 μS/cm in this study. However, the need for desalination will depend on the feedwater salinity and salt tolerance of plants.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16111577/s1. Table S1: The water quality parameters of irrigation water. Table S2: Soil chemical parameters. Table S3: Principal Component Analysis: NO_3^-, Cl^-, Na^+, DOC, Ca^{2+}, Mg^{2+}, K^+, SAR in 6 days, SAR after 56 days of irrigation. Table S4: Mass of ions in soil for varying treatment combinations for brackish water irrigated columns with and without EMF treatment (four-way ANOVA). Table S5: Plant tissue analysis. Table S6: Differences in mean ± standard deviation for the plant growth analysis of plants of different treatments (2-way ANOVA) for compost-treated columns. Table S7: Impact of compost on NO_3^- leaching reduction with different types of irrigation water (Preliminary study). Table S8: Mass of ions in leached water from varying combinations of treatment columns for brackish water and RO permeate (Preliminary study). Table S9: Impact of EMF on plant yield over no EMF treatment of irrigation water (Preliminary study). Table S10: Impact of EMF on plant yield for soil treatment (Preliminary study). Figure S1: Soil moisture content trend of different treatments during the study period (Brackish water+ EMF). Figure S2: Soil EC trend of different treatments during the study period (Brackish water + EMF). Figure S3: Soil moisture content trend of different treatments during the study period (Agricultural water + EMF). Figure S4: Soil EC trend of different treatments during the study period (Agricultural water + EMF). Figure S5: Mass balance of NO_3^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of NO_3^- leached during different irrigation period for brackish water irrigated columns with and without EMF treatment. Figure S6: Mass balance of Na^+ in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Na^+ leached during different irrigation period for brackish water irrigated columns with and without EMF treatment. Figure S7: Mass balance of Cl^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Cl^- leached during different irrigation period for brackish water irrigated columns with and without EMF treatment. Figure S8: Mass balance of NO_3^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of NO_3^- leached during different irrigation period for agricultural water irrigated columns with and without EMF treatment. Figure S9: Mass balance of Na^+ in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Na^+ leached during different irrigation period for agricultural water irrigated columns with and without EMF treatment. Figure S10: Mass balance of Cl^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Cl^- leached during different irrigation period for agricultural water irrigated columns with and without EMF treatment. Figure S11: Mass balance of NO_3^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of NO_3^- leached during different irrigation period for EMF treated columns. Figure S12: Mass balance of Na^+ in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Na^+ leached during different irrigation period for EMF treated columns. Figure S13: Mass balance of Cl^- in greenhouse experimental columns; (a) during 1st 6 days of irrigation, (b) during 7th–56th days of irrigation, and (c) % of mass of Cl^- leached during different irrigation period for EMF treated columns. Figure S14: Mass of NO_3^- leached from different treatments for RO permeate irrigated columns (Preliminary study). Figure S15: Mass of NO_3^- leached from different treatments for Brackish water irrigated columns (Preliminary study). Figure S16: Mass of Na^+ leached from different treatments for RO permeate irrigated columns (Preliminary study). Figure S17: Mass of Na^+ leached from different treatments for brackish water irrigated columns (Preliminary study). Figure S18: Mass of Cl^- leached from different treatments for brackish water irrigated columns (Preliminary study). Figure S19: Mass of Cl^- leached from different treatments for brackish water irrigated columns (Preliminary study).

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