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Challenges of Organic Amendments: Impact of Vermicompost Leachate and Biochar on Popcorn Maize in Saline Soil

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Abstract

Organic amendments provide a sustainable strategy to enhance soil quality in degraded environments while also helping to reduce greenhouse gas emissions, for example, by improving soil structure, minimizing the use of synthetic fertilizers, and promoting a green economy. This study assessed the comparative effects of two organic amendments—vermicompost leachate and biochar—on the performance of popcorn maize (*Zea mays* L. var. everta) cultivated in saline soil conditions. Four treatments were evaluated: T0 (Control), T1 (Vermicompost leachate), T2 (Biochar), and T3 (Vermicompost leachate + Biochar), each with 10 replicates arranged in a Completely Randomized Design (CRD). Although various soil physicochemical, microbiological, and agronomic parameters displayed no significant differences compared to the control, the application of biochar resulted in considerable improvements in soil total organic carbon, the microbial community (mesophilic aerobic bacteria, molds, and yeasts), and increased seed length and diameter. In contrast, vermicompost leachate alone negatively impacted plant growth, leading to decreases in leaf area, stem thickness, and grain yield. Specifically, grain yield declined by 46% with leachate alone and by 31% when combined with biochar, compared to the control. These findings emphasize the superior effectiveness of biochar over vermicompost leachate as a soil amendment under saline conditions and highlight the potential risks of widely applying compost teas in stressed soils. It is recommended to conduct site-specific assessments and screenings for phytotoxins and phytopathogens prior to use. Additionally, the combined application of leachate and biochar may not be advisable given the tested soil characteristics.

Keywords: circular economy; microbial community; agricultural waste; carbon

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1. Introduction

Approximately one billion hectares of land worldwide are affected to varying degrees by salinity and related threats. The increasing demand for the expansion of intensive irrigated agriculture, rising temperatures, more frequent droughts, and water scarcity have led to the accumulation of salts in soils irrigated with saline water. These conditions exacerbate salinization, sodication, and high sodium adsorption ratios (SARs), degrading the chemical environment and the physical health of soils [1]. Salinity adversely affects crop growth and yield, posing serious challenges to food security and economic stability in affected regions [2,3]. Numerous studies have demonstrated the detrimental effects of salinity on crop productivity. For example, maize grain yield has been reported to decline by up to 34% when soil salinity increases from 3.8 to 7.4 dS m^{-1} [4]. Additionally, crop yields generally decrease in proportion to rising soil electrical conductivity (EC), with estimated reductions of 10% at 2.5 dS m^{-1}, 25% at 3.8 dS m^{-1}, 50% at 5.9 dS m^{-1}, and 100% at 10 dS m^{-1} [5].

In Peru, salinization has been reported on approximately 300,000 hectares of irrigated land, with nearly 150,000 hectares exhibiting high salinity levels. It is estimated that around 40% of the total agricultural area along the Peruvian coast is affected by soil salinity [6]. The strategies for managing saline soils include deep plowing or subsoiling, profile washing, calcium salts, acids, acidifying salts, and the addition of organic amendments [7]. More sophisticated methods, such as drip irrigation, are extensively encouraged in Peru due to their water-saving benefits and effectiveness in reducing soil salinity. This approach supplies water straight to the root zone, which helps limit evaporation and prevents salt from accumulating on the surface [8].

In this context, there is a need to develop sustainable agricultural practices that can improve soil quality in saline environments while contributing to circular economy models. Among such practices, the use of biochar, a stable, carbon-rich byproduct from pyrolysis, has gained attention for its capacity to improve soil health and mitigate environmental stress. Biochar has demonstrated residual effects in reducing sodium (Na^+) uptake under saline stress conditions, through mechanisms such as Na^+ sorption, increased soil moisture retention, and the supply of essential nutrients that could reduce Na^+ uptake by plants [9]. Additionally, its alkaline nature, structural stability, and potential to sequester carbon make it a promising tool for improving agricultural productivity, reducing greenhouse gas (GHG) emissions, and promoting soil regeneration [10].

Similarly, previous studies had mentioned that vermicompost and organic amendments are a cost-effective and sustainable approach to improving soil quality in salt-affected regions and boosting crop yields in areas with severe salinity issues [11,12]. Also, vermicompost is rich in essential nutrients, humic acids, growth-regulating hormones, and enzymes, enhancing plant nutrition, boosting photosynthesis, improving overall crop quality, and offering potential benefits for pest control [13]. In this sense, vermicompost leachate (or “vermiwash”) has demonstrated noticeable effects on plants and soil. It was found to possess properties that function as a liquid organic biofertilizer and a biopesticide [14]. Both amendments originate from agricultural residues, aligning with the principles of circular agriculture by promoting resource efficiency, reducing waste, and enhancing soil resilience.

Nevertheless, despite their benefits, knowledge gaps remain regarding the comparative performance of biochar and vermicompost leachate under salinity stress conditions, especially in coastal agroecosystems. Moreover, potential limitations have been reported. For biochar, ecotoxicological impacts and interactions with soil microbiota, such as negative effects on nitrogen-fixing Rhizobium and phosphorus-mobilizing mycorrhizal fungi, have been observed under arid conditions; however, these may be mitigated when combined with microbial inoculants [15,16]. Applying organic amendments is a practical strategy to mitigate salinization, so these amendments boost bacterial diversity and promote the growth of beneficial, salt-tolerant microbes, thereby strengthening microbial interactions within the soil; the composition of microbial taxa changes in response to the presence of both easily degradable and resistant organic carbon in the amendments. Additionally, organic amendments enhance soil conditions by increasing nutrient availability, water retention, and aeration [17]. Although rich in nutrients, vermicompost may pose environmental risks due to nutrient leaching, unpleasant odors, insect proliferation, and GHG emissions during decomposition, especially when not properly managed [18].

Yellow hard corn is cultivated nearly year-round in Peru, particularly along the Peruvian coast. It is a short-cycle crop with a vegetative period ranging from 4.5 to 5.5 months, depending on the variety and sowing date. Popcorn varieties are characterized by small, round kernels with a soft, starchy core and a hard, glassy outer shell; when heated, the moisture within the starchy core expands and bursts through the hard shell, producing popcorn. These varieties account for less than 1% of global corn production [19]. The consumption of popcorn maize (*Zea mays* var. everta) in Peru has increased significantly, particularly in recent years, with an annual growth rate of 5527.6 tons (2016–2020). However, Peru imports popcorn maize from three main countries; in descending order of volume, these are Argentina, Brazil, and the United States [20].

Considering the growing salinization of coastal agricultural soils and the increasing interest in sustainable crop production, this study aimed to evaluate the effects of two organic amendments—biochar and vermicompost leachate—on soil quality, microbial community, and the growth and yield performance of popcorn maize. The objective was to assess their comparative performance under saline soil conditions in popcorn maize plants, observe if there is any alteration or disadvantage with their use, and contribute to the understanding of how organic inputs derived from agricultural residues influence crop productivity and soil health in salt-affected environments of the Peruvian coast.

2. Materials and Methods

2.1. Experimental Site

This study was conducted at the Agricultural Research and Technology Transfer Unit in Organic Solid Waste Management of the "Instituto Nacional de Innovación Agraria" (INIA). The geographic coordinates are 12°04′29.2′′ S, 76°56′26.3′′ W, and the altitude is 241 m.s.n.m.

The greenhouse where the experiment was conducted had the following dimensions: 10.2 × 8 × 2.7 m. Figure 1 shows the climatic values of temperature and relative humidity. The entire crop cycle was from November 2023 to March 2024.

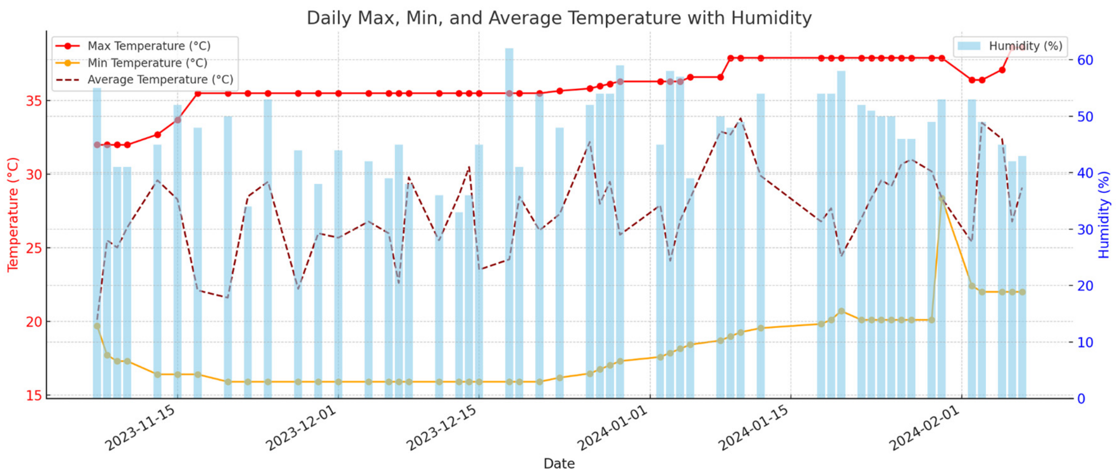

Figure 1. Greenhouse values of temperature and relative humidity.

Soil salinity was monitored using electrical conductivity (EC) measurements taken periodically from soil samples. Any deviations from the desired salinity were corrected by adjusting the irrigation water's salt content. In addition, pots were arranged in a way to prevent cross-contamination between treatments, and drainage was managed to avoid salt leaching.

2.2. Substrates, Water, and Seed Characteristics

2.2.1. Soil

Soil from the "Fertilizantes Orgánicos S.A.C" (FOSAC) company located in the Pachacamac district, province, and department of Lima was used. The geographic coordinates are 12°13′34.3′′ S, 76°52′37.4′′ W. Sampling was conducted at a depth of 0 to 20 cm. The soil was then moved to INIA–Lima, and the soil was extended, homogenized, and air-dried for a week. After this time, it was de-clumped and homogenized again.

A sample was analyzed to obtain the soil characterization, which was realized by the "Laboratorio de Análisis de Suelos, Aguas y Foliares" at INIA–Lima (Table 1).

Table 1. Physico-chemical characterization of soil.

Characteristics	Unit	Value	Method
Sand	%	69.3	Sedimentation
Silt	%	16.3	Sedimentation
Clay	%	14.4	Sedimentation
Textural Class		Sandy loam	Hydrometer Method
$pH_{(1:1)}$	---	7.7	Potentiometer Method (inoLab® pH 7310)
$EC_{(e)}$	$dS\ m^{-1}$	14.2	Potentiometer Method (inoLab® Cond 7310)
$CaCO_3$	%	2.8	Titration Method
OM	%	0.38	Dry Combustion (LECO CN828, LECO Ltd., St. Joseph, MI, USA)
TC	%	0.83	Dry Combustion
TOC	%	0.22	Dry Combustion
P_a	$mg\ kg^{-1}$	71.7	Modified Olsen Method
K_a	$mg\ kg^{-1}$	594	Ammonium Acetate Extract
CEC	$Cmol\ kg^{-1}$	23.3	Ammonium Acetate Extract
Ca^{2+}	$Cmol\ kg^{-1}$	16.8	Inductively Coupled Plasma Mass Spectrometry (ICP–MS) (Perkin Elmer NexION 2000 Series P, Perkin Elmer Inc., Shelton, CT, USA)
Mg^{2+}	$Cmol\ kg^{-1}$	2.8	ICP–MS
K^+	$Cmol\ kg^{-1}$	1.5	ICP–MS
Na^+	$Cmol\ kg^{-1}$	2.2	ICP–MS
As	$mg\ kg^{-1}$	22.34	ICP–MS
Ba	$mg\ kg^{-1}$	62.76	ICP–MS
Cd	$mg\ kg^{-1}$	0.14	ICP–MS
Cr	$mg\ kg^{-1}$	5.4	ICP–MS
Hg	$mg\ kg^{-1}$	0.24	ICP–MS
Pb	$mg\ kg^{-1}$	10.58	ICP–MS

Information Source: "Laboratorio de Suelos, Agua y Foliares" (INIA). EC: Electrical conductivity from a saturated soil paste extract, OM: Organic matter, TC: Total carbon, TOC: Total organic carbon, Pa: Available phosphorus, Ka: Available potassium, CEC: Cation exchange capacity.

The soil had a sandy loam texture, a slightly alkaline reaction, and a low $CaCO_3$ content, and was strongly saline. The organic matter, total carbon, and total organic carbon were low, and the available phosphorus and potassium were high. The cation exchange capacity (CEC) was high and had sufficient Ca^{2+}, Mg^{2+}, K^+, and Na^+ levels. Concerning the metal concentration, the soil was not contaminated according to Peruvian legislation (Supreme decree N° 011-2017-MINAM); however, it had an elevated concentration of As according to the Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health (>12 $mg\ kg^{-1}$).

2.2.2. Biochar

The technology employed for biochar production was based on a Top-Lit UpDraft (TLUD) micro-gasifier and biochar was produced from rice husks. This method loads biomass into a combustion chamber and ignites from the top (top-lit). As the combustion progresses downward, pyrolysis gases are released and move upward (updraft) through the unburned biomass. These gases are subsequently combusted in the upper zone of the reactor under limited oxygen conditions. This controlled combustion at 700 °C resulted in the partial conversion of biomass, allowing a solid carbon-rich residue known as biochar. TLUD systems offer several advantages, including high energy efficiency, reduced smoke emissions, low operational costs, and suitability for small-scale or decentralized applications. The total pyrolysis time was 50 min, with a holding time of 5 min, which gave us a heating rate of 15.6 °C min^{-1}.

This amendment was characterized by a proportion of 1:10 [16], obtaining pH 9.9 and EC 11.22 dS m^{-1}. Also, the content in Cu (1.26 mg kg^{-1}), Zn (30.48 mg kg^{-1}), Mn (274.43 mg kg^{-1}), Pb (0.62 mg kg^{-1}), Cd (0.06 mg kg^{-1}), and Cr (4.43 mg kg^{-1}) was under the maximum permissible limit. The organic matter was 65.1%, total carbon 48%, total organic carbon 42%, and total nitrogen 0.65%.

2.2.3. Vermicompost Leachate

The vermicompost, derived from pre-compost (*Cavia porcellus* manure and harvest residues), was processed using earthworms (*Eisenia foetida*). The production bed had a width of 1.75 m, a length of 3.65 m, a depth of 70 cm, a channel of 16 cm, and an outlet of 50 cm. Earthworms were incorporated at a ratio of 1 kg per 4 kg of pre-compost and maintained under composting conditions for three months. Subsequently, the resulting vermicompost was flushed with water to extract the leachate, which was then brewed for 48 h and collected in the system's reservoir. The fermentation process for vermicompost leachate involves aerobic or anaerobic incubation after mixing it with brown sugar as a carbon source. The leachate was placed in a semi-sealed container and fermented for five days. The characterization was carried out following a proportion of 1:5 [21], obtaining a pH of 8.40 and an EC of 3.34 dS m^{-1}.

2.2.4. Irrigation Water

The water that supplies the entire La Molina Experimental Center at the INIA headquarters had an almost constant pH of 7.7 and EC of 0.619 dS m^{-1}.

2.2.5. Plant Material

PMC.S1 × 8-8 maize seeds were used in this study. This is an experimental hybrid resulting from the cross of two S1 lines. PMC is an S1 line derived from commercial popcorn, while 8-8 is another S1 line obtained from a segregating population originating from the cross between the races Kculli × Confite Puneño. These seeds were provided by the Maize Program of the Universidad Nacional Agraria La Molina (UNALM).

2.3. Treatments and Experimental Design

The dosage of biochar and leachate was selected according to the recommendations of the "Agricultural Research and Technology Transfer Unit in Organic Solid Waste Management", and we also followed the guidelines of the International Biochar Initiative [22] and the European Biochar Certificate [23] to ensure we did not exceed the limits. We used 5 L pots, and a volume of 4 L was filled with soil and amendments according to treatments (Table 2).

Table 2. Applied treatments and substrate proportions.

Treatments	Proportion in Volume	
	Soil	Biochar
T0	4.0	0
T1	4.0	0
T2	3.2	0.8
T3	3.6	0.4

For T1, the vermicompost leachate was fermented with sugar (40 g) per 2 L of solution for 72 h; then we applied 500 mL at the beginning of each week, for one month. The first application occurred one week before sowing. The total volume increased each week to approximately one liter per day by the end of the treatment period.

In T2, biochar was mixed into the top 15 cm of soil depth [24] at a rate of 150 g per pot. In T3, biochar (18.75 g), vermicompost leachate (500 mL), and sugar (10 g) were mixed and fermented for 72 h. The mixture was applied in the same manner as T1, four times over one month. The first application was made one week before sowing, with the subsequent applications carried out around the base of the plant.

The experimental design was a Completely Randomized Design (CRD) with three treatments and one absolute control. Each treatment had ten replicates with two plants per pot, for a total of 40 experimental units.

2.4. Installation Procedure

Each pot was filled with 5.6 kg of air-dried (equivalent to 4 L), previously crumbled soil. Three maize seeds were sown in each pot, and one week after germination, the two most vigorous plants were selected and the third was removed. Each pot received the recommended fertilizer dose for popcorn maize, corresponding to 150–80–100 kg ha^{-1} of NPK (UNALM Maize Program), using the chemical fertilizers urea, diammonium phosphate, and potassium nitrate, where urea application was split into two doses, and weeds were removed manually. The entire crop cycle was from November 2023 to March 2024.

2.5. Soil Characteristics Analysis

At harvest, soil from each experimental unit was removed from the pots. Samples were sent to the "Laboratorio de Suelos, Agua y Foliares" at INIA (Lima) for physico-chemical analysis, and to the "Laboratorio de Ecología Microbiana y Biotecnología" at UNALM for microbiological analysis. The analysis was conducted for each soil pot.

The physico-chemical analysis included determination of texture using the Bouyoucos method [25], pH measurement with an inoLab® pH 7310 m, and the assessment of electrical conductivity (EC) in the saturation extract using an inoLab® Cond 7310. Total carbon (TC), total organic carbon (TOC), and total nitrogen (TN) were quantified through dry combustion with an elemental analyzer (LECO CN828, LECO Ltd., St. Joseph, MI, USA). Extractable phosphorus (P_a) was analyzed using the Olsen method [26]. Additionally, extractable potassium (K_a) and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were measured using ammonium saturation, while total metal content and heavy metals were determined via inductively coupled plasma mass spectrometry (ICP-MS) with a Perkin Elmer NexION 2000 Series P instrument (Perkin Elmer Inc., Shelton, CT, USA).

The microbiological analysis counted mesophilic aerobes (CFU g^{-1}), molds and yeasts (CFU g^{-1}), actinomycetes (CFU g^{-1}), and *Bacillus* spp. (CFU g^{-1}), and enumerated *Pseudomonas* spp. (MPN g^{-1}) [27,28].

2.6. Agronomic Characteristics Analysis

The biometric variables—plant height (cm) and stem diameter (mm)—were measured at the end of the maize vegetative growth stage, approximately 80 days after sowing. We measured plant height from the plant collar to the last visible node on the stem. A caliper was used to measure stem diameter at the center of the first internode emerging from the soil; an average was taken between the largest and smallest diameters. The total number of leaves per plant was also recorded around 80 days after sowing. Leaf area was calculated using the Montgomery formula, multiplying the length and width of each leaf by a correction factor of 0.75 and then summing the total leaf area per plant [29]. At the end of the experimental period, the aerial parts of the plants were collected and weighed to determine fresh weight. To determine dry weight, the samples were then placed in labeled envelopes and dried in an oven at 70 °C for ~72 h until a constant weight was obtained [30].

2.7. Statistical Analysis

Data analysis was conducted using the R statistical computing environment version 4.3.1, an open-source software environment. The data were analyzed with the Shapiro–Wilk test for normality [31] and Bartlett's test for homogeneity of variances [32] at the significance level of $p < 0.05$. Subsequently, an analysis of variance (ANOVA) was performed, and for mean comparisons, Tukey's test was applied at the significance level of $p < 0.05$.

3. Results

3.1. Soil Parameters

Significant differences were observed in the mean values of soil chemical variables such as electrical conductivity (EC), total organic carbon (TOC), and soil cations. The results indicate that EC did not differ significantly among the Control, Leachate, and Leachate + Biochar treatments. In contrast, the Biochar treatment increased EC significantly ($\geq$1.22 dS m^{-1}) compared to all other treatments. Similarly, for TOC, we found that it increased significantly in the treatments that included biochar (Biochar and Leachate + Biochar). A significant difference was observed between the Biochar treatment and both the Leachate and Control treatments, with TOC values at least 0.43% higher in the Biochar treatment. Additionally, a significant difference of 0.35% was found between the Leachate + Biochar and Leachate treatments, as shown in Table 3.

Table 3. Values of soil chemical parameters.

Treatment	ECe	TN	TOC	Ca	K	Na
	dS m^{-1}	Percentage		cmol kg^{-1}		
Control	4.33 ± 1.75 ab	0.00112 ± 0.00046	0.734 ± 0.095 bc	8.597 ± 0.818 a	0.539 ± 0.201 b	0.574 ± 0.244 ab
Leachate	3.43 ± 1.42 b	0.0009	0.684 ± 0.098 c	7.428 ± 0.568 bc	1.044 ± 0.253 a	0.42 ± 0.104 b
Biochar	5.55 ± 1.44 a	0.00101 ± 0.00035	1.16 ± 0.38 a	8.1 ± 0.290 ab	0.688 ± 0.040 b	0.812 ± 0.266 a
Leachate + Biochar	3.37 ± 1.73 b	0.00093 ± 0.00005	1.037 ± 0.338 ab	7.272 ± 0.590 c	0.996 ± 0.060 a	0.382 ± 0.174 b
p-value	0.0136	0.3451	<0.0004	<0.0001	<0.0001	<0.0002
Significance	*	ns	***	****	****	***

Note: The data in the table express the mean and standard deviation (μ ± σ) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments ($p < 0.05$), Very highly significant (****), Highly significant (***), Significant (*), Not significant (ns). ECe: Electrical Conductivity in saturation extract, TN: Total Nitrogen, TOC: Total Organic Carbon.

We analyzed some general groups of microorganisms and indicator genera. Table 4 shows the microbial communities identified in the soil according to the tested treatments. The incorporation of biochar significantly improved the quantity of mesophilic aerobes, molds, and yeasts. Moreover, significant differences ($\geq$0.15 and $\geq$0.24 $\log_{10}$CFU g^{-1}) were observed between the Biochar treatment and the Control and Leachate treatments for mesophilic aerobes, respectively. Similarly, molds and yeasts showed significant increases

($\geq$0.25 and $\geq$0.45 log_{10} CFU g^{-1}, respectively) in the Biochar treatment relative to the Control and Leachate treatments, respectively.

Table 4. Quantification and enumeration of microbial composition.

Treatment	Mesophilic Aerobes	*Bacillus* spp.	Actinomycetes	Molds and Yeasts	*Pseudomonas* spp.
	log_{10} (CFU g^{-1})				log_{10} (MPN g^{-1})
Control	6.4 ± 0.13 b	6.04 ± 0.17	6.19 ± 0.26	4.18 ± 0.18 c	1.99 ± 0.77
Leachate	6.49 ± 0.15 b	6.08 ± 0.13	6.25 ± 0.14	4.38 ± 0.24 bc	1.44 ± 0.75
Biochar	6.64 ± 0.1 a	6.25 ± 0.2	6.3 ± 0.26	4.63 ± 0.18 a	1.49 ± 0.84
Leachate + Biochar	6.53 ± 0.12 ab	6.11 ± 0.14	6.12 ± 0.11	4.49 ± 0.27 ab	1.72 ± 0.81
p-value	0.0021	0.1585	0.2029	0.0012	<0.4741
Significance	**	ns	ns	**	ns

Note: The data in the table express the mean and standard deviation (μ ± σ) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments. $p < 0.05$ (**), Not significant (ns).

A similar trend was observed in the Leachate + Biochar and Leachate treatment, which also showed increased populations of mesophilic aerobes, molds, and yeasts compared to the Control treatment. The Leachate + Biochar treatment exhibited a significant increase of 0.31 log_{10} CFU g^{-1} in molds and yeasts relative to the Control.

3.2. Agronomic Parameters

The data on aerial fresh weight, number of leaves, stem diameter, and leaf area across the different treatments are presented in Table 5. The Biochar treatment caused higher fresh weight, leaf dry weight, and stem diameter compared to the other treatments. Nonetheless, none of these results were significant when compared with the Control treatment. However, a significant difference was observed between the Biochar and Leachate treatments, with Biochar increasing fresh weight by 26.2% compared to Leachate. Similarly, the Leachate and Leachate + Biochar treatments slightly increased leaf dry weight relative to the Control, although no improvements were observed in the other measured variables. For some parameters, such as the number of leaves and leaf area, the combined Biochar + Leachate treatment had a significantly detrimental effect, resulting in decreases of 11.9% and 29.4%, respectively, compared to the Control.

Table 5. Morphological variables of popcorn maize plants.

Treatment	Fresh Weight	Leaf Dry Weight	Number of Leaves	Stem Diameter	Leaf Area	Height
	g		n°	cm	cm^2	cm
Control	74.48 ± 13.08 ab	0.05052 ± 0.00037	6.7 ± 0.5712 a	10.97 ± 1.198 ab	1199 ± 279.9 a	145.7 ± 16.93
Leachate	62.74 ± 12.76 b	0.05055 ± 0.000491	6.4 ± 0.6806 ab	9.61 ± 1.429 c	929 ± 278.7 b	137.5 ± 17.56
Biochar	79.17 ± 11.22 a	0.05063 ± 0.00032	6.1 ± 0.6407 b	11.83 ± 1.592 a	972.8 ± 300.4 ab	143.9 ± 16.08
Leachate + Biochar	68.27 ± 7.69 ab	0.05057 ± 0.00029	5.9 ± 0.5525 b	10.4 ± 1.23 bc	847.6 ± 228.6 b	145.7 ± 12.21
p-value	0.0153	0.9268	0.0006	<0.0001	0.0009	0.3114
Significance	*	ns	***	****	***	ns

Note: The data in the table express the mean and standard deviation (μ ± σ) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments. ($p < 0.05$), Very highly significant (****), Highly significant (***), Significant (*), Not significant (ns).

The agronomic quality and productivity were evaluated. Table 6 shows the corncob variables and popcorn yield. Overall, the evaluated treatments had a significant detrimental effect on all measured parameters compared to the Control treatment, with reductions observed in grain weight per corncob ($\geq$27.6%), corncob length ($\geq$8.8%), corncob diameter ($\geq$1.9%), and popcorn yield ($\geq$20.8%). However, among the treatments, the Biochar treatment showed better performance than the Leachate + Biochar treatment, and both outperformed the Leachate treatment. In general, the leachate treatment had a negative impact on all evaluated variables, showing the lowest values for grain weight (10.68 g), corncob length (5.739 cm), diameter (2.367 cm), and popcorn yield (13.06 g plant^{-1}). In contrast, the Biochar treatment showed the best overall performance, with higher values for corncob diameter (2.721 cm) and popcorn yield (19.02 g plant^{-1}), and significantly greater corncob length (7.681 cm), compared to the Leachate treatment. The Leachate + Biochar treatment showed intermediate values, with partial recovery of corncob length (6.879 cm), diameter (2.655 cm), and popcorn yield (16.65 g plant^{-1}), suggesting a mitigating effect of biochar on the negative influence of leachate.

Table 6. Corncob variables and popcorn yield.

Treatment	Grain Weight per Corncob	Corncob Length	Corncob Diameter	Popcorn Yield
	g	cm		g Plant^{-1}
Control	20.9 ± 6.66 a	8.424 ± 1.603 a	2.773 ± 0.26 a	24.01 ± 7.89 a
Leachate	10.68 ± 5.94 b	5.739 ± 1.286 c	2.367 ± 0.333 b	13.06 ± 7.69 c
Biochar	15.12 ± 6.84 b	7.681 ± 1.967 ab	2.721 ± 0.295 a	19.02 ± 6.53 ab
Leachate + Biochar	14.14 ± 4.17 b	6.879 ± 1.126 bc	2.655 ± 0.248 a	16.65 ± 4.78 bc
p-value	<0.0001	<0.0001	0.0003	<0.0001
Significance	****	****	***	****

Note: The data in the table express the mean and standard deviation (μ ± σ) of the evaluated parameters. Those values with different letters in the same column indicate significant differences between the treatments. ($p < 0.05$), Very highly significant (****), Highly significant (***).

A Pearson correlation was realized with a significance level of $p < 0.05$ (Figure 2).

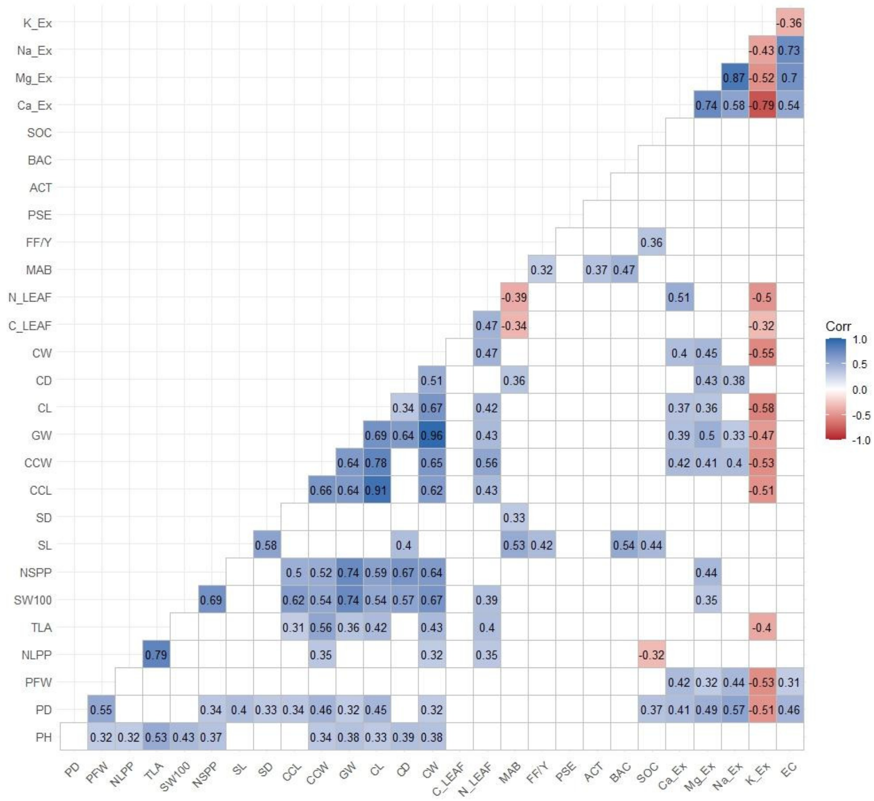

Figure 2. Pearson correlation between soil and agronomic parameters. Plant height (PH), plant diameter (PD), plant fresh weight (PFW), number of leaves per plant (NLPP), total leaf area (TLA), 100-seed weight (100 SW), number of seeds per plant (NSPP), seed length (SL), seed diameter (SD), cob length (CCL), cob weight (CCW), corncob weight (CW), corncob length (CL), corncob diameter (CD), leaf carbon (C_leaf), leaf nitrogen (N_leaf), mesophilic aerobic bacteria (MAB), filamentous fungi and yeast (FF.Y), pseudomonas (PSE), actinomycetes (ACT), Bacillus (BAC), soil organic carbon (SOC), exchangeable cations (Ca_Ex, Na_Ex, Mg_Ex, K_Ex), electrical conductivity (EC).

According to Figure 2, sites with more exchangeable K also tend to have lower exchangeable Ca (r: −0.79), nitrogen in leaves (r: −0.5), corncob weight (r: −0.55), corncob length (r: −0.58), cob weight (r: −0.53), cob length (r: −0.51), plant fresh weight (r: −0.53), and plant diameter (r: −0.51).

Principal component analysis (PCA) is shown in Figure 3, and the differences between treatments were notable. Dimensions 1 (28.2%) and 2 (15.3%) are the first two principal components; together, they explain 43.5% of the total variation in the data.

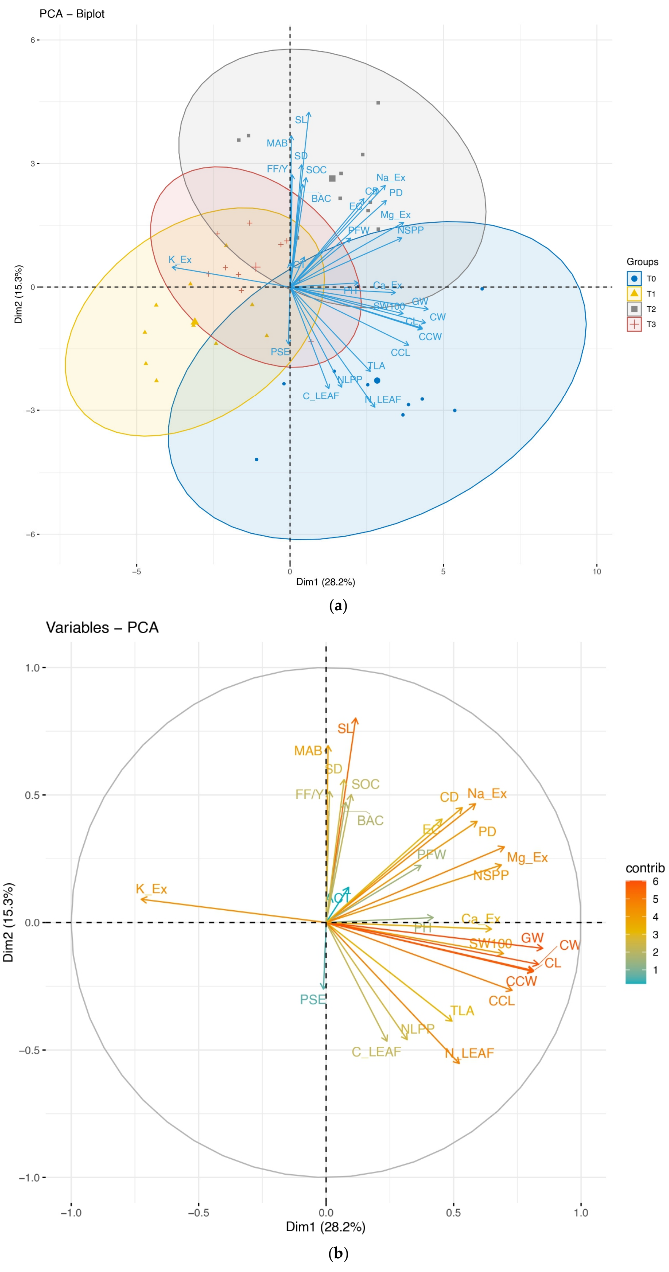

Figure 3. Biplot of principal component analysis (PCA): (**a**) Individuals and variables for each treatment; (**b**) variables contributions. Plant height (PH), plant diameter (PD), plant fresh weight (PFW), number of leaves per plant (NLPP), total leaf area (TLA), 100-seed weight (100 SW), number of seeds per plant (NSPP), seed length (SL), seed diameter (SD), cob length (CCL), cob weight (CCW), corncob weight (CW), corncob length (CL), corncob diameter (CD), leaf carbon (C_leaf), leaf nitrogen (N_leaf), mesophilic aerobic bacteria (MAB), filamentous fungi and yeast (FF.Y), *Pseudomonas* (PSE), actinomycetes (ACT), *Bacillus* (BAC), soil organic carbon (SOC), exchangeable cations (Ca_Ex, Na_Ex, Mg_Ex, K_Ex), electrical conductivity (EC).

The Control treatment (T0) stood out in terms of plant growth and yield attributes. Among the organic amendments, vermicompost leachate (T1) was associated with higher levels of soil nutrients such as potassium, as well as, increased abundance of *Pseudomonas* spp. Biochar (T2) was notable for improving soil characteristics, microbial communities, and plant biomass. The combined vermicompost leachate plus biochar treatment (T3) exhibited an intermediate effect.

4. Discussion

Pearson correlation shows that sites with more soil exchangeable K also tend to have lower exchangeable Ca, nitrogen in leaves, corncob weight, corncob length, cob weight, cob length, plant fresh weight, and plant diameter. This could be because of a nutrient imbalance where one nutrient was more present in the organic amendments, for example, potassium in vermicompost leachate. Principal component analysis indicated that vermicompost leachate (T1) was closely associated with higher levels of potassium and a notable presence of *Pseudomonas* spp., communicating that it may have promoted specific beneficial microbial groups and contributed to soil nutrient enrichment, even if that did not translate into the highest yield. Biochar (T2) stood out for improving soil physical and chemical characteristics, enhancing microbial community diversity, and supporting greater plant biomass, suggesting a more balanced and sustained impact on soil–plant interactions. The combined treatment (T3) showed intermediate performance, implying that the interaction between the two amendments might not have been fully synergistic. This pattern highlights that biochar alone may offer more consistent and broad-spectrum benefits, while vermicompost leachate may require careful management to optimize its effectiveness. The dosage of biochar and leachate was selected according to the recommendations of the “Agricultural Research and Technology Transfer Unit in Organic Solid Waste Management”. In the case of biochar, we also followed the guidelines of the International Biochar Initiative and the European Biochar Certificate guideline. Relative to these documents, the biochar was under the maximum permissible limit for organic and conventional agriculture. However, the EC was 11.22 dS m^{-1}, so this could affect the performance of maize popcorn, and we did not observe notable differences in comparison with the Control.

Previous studies have shown that the foliar application of vermicompost leachate can enhance growth and physiological responses in crops under saline conditions. For instance, it promoted the development of pomegranate seedlings by improving tolerance to salinity stress [33]. Similarly, other research demonstrated that a low dose of solid vermicompost applied before planting improved strawberry yield in the first year; however, in the absence of further fertilization, yields declined to control levels in subsequent years. Although vermicompost leachate did not improve yield, it was associated with better fruit quality [34]. In our study, a slight reduction in electrical conductivity (EC) was observed in the leachate treatments, although this difference was not statistically significant, suggesting limited efficacy under the experimental conditions.

The chemical characterization of the leachate has an approximate organic matter content of 60%, with total humic substances representing 80% of the organic matter, total nitrogen at 2%, and total organic nitrogen at 1.5%. Also, the leachate has an interesting microbial community, including amylolytic, cellulolytic, nitrosant, nitricant, sulfate reducers, sulfur oxidants, aerobic nitrogen-fixing, anaerobic nitrogen-fixing, denitrifying, ammonifying, actinomycetes, aerobic, and anaerobic bacteria [35]. Additionally, a pH of 8.40 and EC of 3.34 dS m^{-1} enabled microbial growth, particularly of bacteria, for example, *Pseudomonas* spp., as could be seen in the PCA for T1. Some authors mentioned that the microbial biomass nitrogen and dehydrogenase enzyme activity were higher after the incorporation of vermicompost [36]. All of this leads to the inference that the high concentration of applied bacteria but the low content of organic matter in the soil caused a lot of pressure in the microbial ecosystem, and it is presumed that immobilization was caused by them.

In addition, vermicompost leachate may contain microbial populations indicative of an incomplete stabilization process, potentially posing phytotoxic or phytopathogenic risks. A study of high-throughput 16S rRNA gene pyrosequencing of fresh leachate samples revealed a dominance of Mollicutes, particularly *Acholeplasma*, a genus associated with plant pathogenicity. Over time, the storage declined the Mollicutes and enriched plant-beneficial taxa, including members of the Rhizobiales and the genus *Pseudomonas*. These results underscore the importance of a maturation or storage phase to mitigate potential phytopathogenic risks and enhance the presence of beneficial microbial consortia [37]; also, the leachate should be characterized in terms of its phytotoxic and phytopathogenic composition to prevent adverse effects. The decrease in pH observed during vermicomposting is primarily attributed to the breakdown of organic matter, the accumulation of nitrate (NO_3^-) ions and humic substances, the release of CO_2 and ammonium (NH_{4+}), and the formation of organic acids. High ammonium concentrations can be toxic to plants and soil microbes, especially under saline conditions. Fermentation could produce toxic anaerobic byproducts, like organic acids or methane, which can harm root systems and beneficial microbes. Also, a dominance of opportunistic or non-beneficial microbes could disrupt soil microbiota or fail to support plant stress tolerance [38]. Ammonia has been found to inhibit plant growth when it is the dominant N source [39]. It is known that incompletely stabilized leachate may contain ammonium or volatile organic acids. These substances inhibit root function and nutrient absorption, reducing foliar and stem growth. On the other hand, leachate with unbalanced nutrient profiles could impair structural development and increase the risk of environmental issues [40].

Likewise, biochar in soils with low organic matter content and high aeration, for example, arid environments, can sometimes have limited benefits. In these systems, limited water availability may suppress the positive effects commonly attributed to biochar, particularly its capacity to enhance nutrient uptake [16]. Nonetheless, in our experiment, biochar application was associated with improvements in microbial activity and plant growth, despite saline conditions. Also, the soil organic carbon was higher after its application, which gives us the perspective of a residual effect and the potential for carbon sequestration. Long-term studies are needed to see the residual effect of carbon input on the soil, mesophilic aerobes, bacteria, molds, and yeasts.

The rice husk biochar supplied potassium and enhanced soil physical properties, which helped decrease sodium levels in the salt-affected soil. Previous research suggested that this led to a consistently lower exchangeable sodium percentage (ESP) and a higher K^+/Na^+ ratio, and as a result, biochar significantly increased total aboveground biomass [41]. Using rice husk biochar as a soil amendment can improve both soil quality and agricultural productivity, while also offering substantial potential for climate change mitigation. Its incorporation into soil enhances organic carbon content, cation exchange capacity (CEC), available potassium, and total nitrogen. It promotes soil aggregation, which increases porosity and water retention while reducing bulk density and resistance to root penetration [42]. Transforming rice residues into biochar promotes sustainable agriculture. Rice husk biochar offers several distinct benefits over other types of biochar, including strong adsorption capacity, enhanced nutrient retention, and a high silica content. The elevated silica levels contribute to improved nutrient holding, increased plant turgor, and strengthened structural support [43].

The observed increase in bacterial abundance under biochar treatment aligns with previous reports indicating that bacteria respond rapidly to environments enriched with labile carbon sources. Furthermore, the microbial response can differ by group; for example, Gram-positive bacteria often rely more heavily on carbon derived from soil organic matter (SOM), while Gram-negative bacteria tend to utilize carbon derived from plant biomass [44,45]. Therefore, understanding how biochar influences microbial community structure and metabolism is essential, particularly in degraded or stressed soils. It is well established that organic and biochar-based amendments can significantly reshape the composition and functionality of soil microbial communities, with downstream effects on soil health, nutrient cycling, and crop performance [46]. In general, biochar is considered non-toxic to soil biota and can promote both plant biomass accumulation and microbial abundance. However, these effects are highly context-dependent [47]. Organic amendments can modify the soil's redox potential, affecting the balance between aerobic and anaerobic microorganisms. Moreover, organic inputs have been shown to support the emergence of halotolerant bacterial species and enhance overall microbial diversity. Biochar stands out due to its high carbon content, large surface area, and strong cation exchange capacity; these provide favorable habitats and nutrients for microbial populations. However, the effects vary depending on the type of raw material used and the conditions under which it was pyrolyzed [48].

Interestingly, studies have noted that biochar produced at lower pyrolysis temperatures (<400 °C) may exhibit higher toxicity potential and a greater likelihood of triggering aryl hydrocarbon receptor-mediated responses in soil organisms, highlighting the importance of carefully selecting and characterizing biochar before use in agricultural systems [49]. Also, it is important to choose the stove type. In this study, the Top-Lit UpDraft (TLUD) gasifier, known as a reverse downdraft gasifier, is a type of biomass stove designed for a clean, smokeless flame and efficient combustion of solid biomass fuels. It could be used for small-scale energy generation, especially in off-grid or rural areas [50]. This is important because it is a simple and low-cost biochar production technology suitable for remote areas, and can enhance agricultural production

Previous studies showed that vermiwash, biochar, and their combination had a significant impact on various tomato plant growth parameters. The dry biomass of tomato plants increased by 19.5% and 28.7% in the biochar and biochar + vermiwash treatments, respectively. Similarly, the dry weight of tomato fruits rose by 18.5%, 12.1%, and 37% in the vermiwash, biochar, and combined treatments, respectively [35]. Other studies tested the application of activated biochar by vermicompost leachate, which allowed the colonization and multiplication of bacteria contained in the liquid over biochar particles. It is important to note that the effects of applying activated biochar to soils can differ based on several factors, including the biochar type, soil composition, and the particular microorganisms present [51]. Also, it was reported that high-salinity soils could be managed through salt leaching by improving the formation of aggregates, the aggregate microstructure, and the inhibition of nitrogen losses with vermicompost and humic acid fertilizer [52]; however, this was not evident under the study conditions. Therefore, the combined application would not be the most advisable.

5. Conclusions

A substantial portion of the soil's physicochemical, microbiological, and agronomic parameters did not show statistically significant differences compared to the control; biochar application alone led to improvements in key indicators, including total organic carbon and microbial community (mesophilic aerobes, molds, and yeasts). These results confirm the potential of biochar as an effective amendment for enhancing soil quality and supporting plant development in saline environments, not only as a soil conditioner but also as a tool for resilience-building in degraded agroecosystems; however, long-term experiments are necessary to estimate the benefits. Instead, vermicompost leachate may not be suitable as a standalone or complementary amendment under salinity stress, and its presumed agronomic benefits may be overestimated in such contexts.

From an agronomic perspective, the findings are especially relevant for the sustainable cultivation of popcorn maize, a short-cycle and high-demand crop that is gaining commercial interest in Peru. Future research should focus on the long-term environmental fate of these amendments, particularly their mobility in soil, potential for nutrient leaching, previous analysis of phytopathogens, and risks of surface and groundwater contamination. Additionally, further studies are needed to evaluate synergistic strategies, such as combining biochar with beneficial microbial inoculants, to enhance soil functionality and crop productivity under stress-prone conditions.

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