Research article

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Soil thermal, physical, and chemical responses to low-rank coal amendment in saline-sodic conditions: biomass outcomes

Dinámica térmica, física y química de suelo salino-sódico tratado con carbón de bajo rango: implicaciones en biomasa vegetal

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ABSTRACT
Soil salinization is a major constraint to agricultural productivity in the Caribbean region of Colombia. Low-rank coals (LRC), characterized by their high humic acid content, have been proposed as amendments capable of improving the physical and chemical conditions of degraded soils; however, their influence on soil thermal conductivity, a key property governing heat flow, soil microclimate, and plant performance, remains poorly understood. This study assessed the thermal, physical, and chemical responses of saline-sodic soils in Cesar following LRC application. A field experiment was conducted using three LRC application rates: 0, 2, and 4 t ha^{-1}. Measurements included thermal conductivity, soil physical and chemical properties, and plant biomass. Based on the results, LRC significantly decreased soil thermal conductivity by 36%, from 1.25 to 0.60 W m^{-1} K^{-1} (P<0.05), while increasing organic matter, aggregate stability, and porosity. Significant reductions (P<0.05) were also observed in pH, electrical conductivity, sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP), and cation exchange capacity (CEC). Plant biomass increased by 200%, from 1 g to 9 g (P<0.05), indicating a strong positive response under saline-sodic conditions. Correlation analyses indicated a negative association between aggregate content and thermal conductivity and a positive association between bulk density and thermal conductivity. Overall, the results suggest that LRC improves soil physical and chemical conditions while modifying thermal behavior to enhance plant growth. This study provides evidence that LRC is an effective amendment capable of improving soil functionality and strengthening agricultural resilience in vulnerable regions.

KEYWORDS: Soil salinization, Sodicity, Organic amendments, Soil thermal properties, Aggregate stability, Lignite

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RESUMEN
La salinización del suelo limita significativamente la productividad agrícola en la región Caribe de Colombia. Los carbones de bajo rango (CBR), ricos en ácidos húmicos, se han propuesto como enmiendas capaces de mejorar las condiciones físicas y químicas de suelos degradados; sin embargo, su efecto sobre la conductividad térmica, propiedad clave para el flujo de calor, el microclima del suelo y el desarrollo vegetal, aún es poco conocido. Este estudio evaluó las respuestas térmicas, físicas y químicas de suelos salino-sódicos del Cesar tras la aplicación de CBR. Se desarrolló un experimento de campo con tres dosis:

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0, 2 y 4 t ha^{-1}. Se midieron conductividad térmica, propiedades físicas y químicas del suelo y biomasa vegetal. El CBR redujo la conductividad térmica en un 36%, de 1,25 a 0,60 W m^{-1} K^{-1} (P<0,05), y aumentó la materia orgánica, la estabilidad de agregados y la porosidad. También disminuyeron significativamente pH, conductividad eléctrica, relación de adsorción de sodio (SAR), porcentaje de sodio intercambiable (ESP) y capacidad de intercambio catiónico (CEC) (P<0,05). La biomasa vegetal aumentó un 200%, de 1 g a 9 g (P<0,05), evidenciando una respuesta positiva bajo condiciones salino-sódicas. Los análisis de correlación indicaron una relación negativa entre agregados y conductividad térmica, y positiva entre densidad aparente y conductividad térmica. En conjunto, los resultados sugieren que el CBR mejora las condiciones del suelo y su comportamiento térmico, favoreciendo el crecimiento vegetal y fortaleciendo la resiliencia agrícola en regiones vulnerables.

PALABRAS CLAVE: Salinización del suelo, Sodicidad, Enmiendas orgánicas, Propiedades térmicas del suelo, Estabilidad de agregados, Lignito

INTRODUCTION

Soil degradation, particularly because of salinization, gains an increasing concern in Colombia, at it is posing significant threats to biodiversity, agricultural productivity, and food security. According to IDEAM (2019), approximately 46.6% of the country's continental and insular territory exhibits some degree of soil degradation. Among the various strategies for soil restoration, the use of organic amendments rich in humic substances (HS) has shown considerable promise, particularly for improving soil structure, water retention, and plant development (Zhao and Naeth 2022; Akimbekov et al. 2020). In this context, the low rank coals (LRC), a material of lower coalification generated as a by-product during the extraction and beneficiation of high-rank thermal coals in regions such as Cesar and La Guajira, has attracted attention due to its high HS content and potential use as a sustainable soil amendment (Anemana et al. 2019). Although unsuitable for energy production due to its low calorific value, this by-product constitutes a valuable source of humified organic matter. Its physicochemical characteristics, including high carbon content, abundant oxygenated functional groups, and a porous internal structure, make it particularly suitable for agricultural applications.

Through microbial activity, LRC can be gradually released, producing humified organic matter that significantly enhances soil properties such as aggregation, water-holding capacity, fertility, and microbial activity (Akimbekov et al. 2020; Pantoja-Guerra et al. 2019). HS, the main active fraction of this organic matter, plays a vital role in key soil processes, promoting plant growth by activating root transporters and proton pumps, mechanisms directly linked to nutrient uptake and root development (Piccolo and Drosos et al. 2025). Recent evidence indicates that the biostimulant activity of HS is strongly associated with their carboxylic and phenolic functional groups, which regulate nutrient availability and influence essential physiological responses in plants, including root growth and metabolic activation (Lamar et al. 2024). Empirical evidence shows that HS enhances nutrient uptake, stimulates root growth (especially fine roots and H^+-ATPase activity), and increase plant biomass (Zandonadi et al. 2025). Specifically, HS derived from LRC are linked to improved seed germination, nutrient absorption, lignin solubilization in biomass substrates (Sarlaki et al. 2023), and enhanced crop growth on sandy soils (Zhao and Naeth 2022). Reported benefits include biomass increases of up to 44% and micronutrient availability gains of 73% (Khan et al. 2014). Nevertheless, these effects are dose-dependent; moderate applications (e.g., 60 mg kg^{-1} of soil) are beneficial, while higher doses (e.g., 90 mg kg^{-1}) may negatively affect plant growth and nutrient uptake (Pantoja-Guerra et al. 2019).

In addition to its role in fertility improvement, LRC has been evaluated for the rehabilitation of post-mining landscapes in the Cesar region. Field applications (5 kg m^{-2}) have reduced soil electrical conductivity (EC), sodium adsorption ratio (SAR), and exchangeable sodium percentage (ESP), while increasing CEC without significant changes in pH or bulk density (Cubillos Hinojosa et al. 2017). These findings underscore the potential of LRC-derived HS not only to improve plant productivity but also to mitigate salinity stress in degraded soils. However, despite these advances, a critical knowledge gap persists: the effect of LRC on soil thermal conductivity has not been systematically investigated, even though this property regulates soil heat transfer, water dynamics, and germination (Usowicz et al. 2020).

While materials such as biochar, also carbon-rich and characterized by porous structures, proved to reduce soil thermal conductivity and bulk density (Zhao and Naeth 2022), the specific effects of LRC remain largely unexplored. Both materials share relevant physical and chemical traits, including large surface area, porosity, and the presence of humic substances, all of which may influence heat transfer.

Therefore, the present study aims to evaluate the effect of LRC application on the thermal conductivity of saline-sodic soils in the Department of Cesar. It was hypothesized that LRC will reduce soil thermal conductivity by increasing organic matter content and aggregate porosity, improving the functionality of saline soils.

MATERIALS AND METHODS

The field experiment followed a completely randomized design (CRD) with three LRC application rates (0, 2, and 4 t ha^{-1}), and four replicates per treatment, for a total of 12 experimental units. Each experimental unit consisted of a 20 m^2 plot, and all measurements were analyzed based on plot-level averages obtained from subsamples collected within each unit.

The lignite-type low-rank coal used was collected at the "El Cerrejón" open-pit mine (La Guajira, Colombia), located at approximately 11.0881°N, 72.7635°W. The material exhibited high moisture (28.44%), a low calorific value (20 MJ kg^{-1}), and abundant oxygenated functional groups, features characteristic of LRC. These properties are reported on the same basis in which they were determined and correspond to the sample in its original 'as-received' condition. The physical and chemical properties of the material, as reported by Ortiz and Ramírez (2022), are presented in Table 1.

Table 1. LRC characteristics of the "El Cerrejón" open-pit coal mine.

Parameter	Value
Moisture (%)	28.44
Ashes (%)	11.12
Volatiles (%)	47.79
Calorific value (MJ kg^{-1})	20.00
Fixed carbon (%)	41.09
Sulfur (%)	0.13
Carbon (%)	46.04
Nitrogen (%)	4.38
Hydrogen (%)	6.26
Oxygen (%)	42.95

The field trial was established in plot 10 of the Centro Biotecnológico del Caribe (Valledupar, Cesar, 10°23'57"N latitude and 73°13'35"W longitude). The soil corresponds to an Ustic Psamment, sampled at 0-20 cm. Its initial physical and chemical conditions were sandy loam texture (57% sand, 24% silt, 19% clay), pH=10.7, EC 6.2 dS m^{-1}, ESP 64.15%, SAR 7.36, OM 0.45%, and Mg (0.4 cmol(+) kg^{-1}). The properties of the material, as reported by Ortiz and Ramírez (2022), are presented in Table 2.

Table 2. Properties of soil samples.

Parameter	Value
Texture	Sandy loam
pH	10.70
Electrical conductivity (dS m^{-1})	6.20
Exchangeable sodium (%)	64.15
Mg (cmol (+) kg^{-1})	0.40
Ca (cmol (+) kg^{-1})	8.00
S (mg kg^{-1})	61.60
Organic matter (%)	0.45
K (cmol (+) kg^{-1})	0.35
Na (meq L^{-1})	15.65
CEC eff	24.40
P (mg kg^{-1})	36.00
Fe (mg kg^{-1})	4.50
Mn (mg kg^{-1})	5.60
Zn (mg kg^{-1})	1.00
Cu (mg kg^{-1})	1.60
B (mg kg^{-1})	0.76
CEC pH 7	12.48
RAS (meq L^{-1})	7.36

Treatments consisted of LRC application rates of 0, 2, and 4 t ha^{-1} (C0, C1, and C2). The LRC was manually incorporated into the upper 20 cm of soil, after which *Megathyrsus maximum* (Jacq.) B.K. Simon & S.W.L. Jacobs was sown at a rate of 2 kg ha^{-1}. Soil and LRC were then homogenized using hand tools (hoes and rakes) following a cross-directional mixing procedure, first along the length of the plot and subsequently across its width. This method ensured uniform incorporation of the amendment and minimized spatial variability within each experimental unit.

For each plot, four 1-kg subsamples were collected and composited to obtain a representative sample. A total of 48 soil samples were processed during the study (initial sampling, months 2, 4, and 6). For all variables, the results are presented with their corresponding standard deviations (SD) to reflect variability among replicates and to strengthen the statistical reliability of the dataset.

Bulk density was measured using the cylinder method, true density via gas pycnometry, and pore size distribution using moisture retention curves (0.01–1.5 MPa) following the Richards approach (IGAC 2006).

Chemical variables (pH, EC, OM, Ca, Mg, K, Na, P, CEC, texture) were determined following Colombian Technical Standards (NTC) with year of publication. Particle-size analysis by the Bouyoucos hydrometer method (NTC 6299:2018), Organic matter determination by Walkley–Black wet oxidation (NTC 5526:2007), Extraction of exchangeable bases (Ca, Mg, K) and available P using ammonium acetate (NTC 5349:2016), Effective cation exchange capacity by ammonium displacement (NTC 5268:2014), and Electrical conductivity measurement in saturated paste extract (NTC 5596:2008).

The chemical parameters were determined using the methodologies shown in Table 3.

Table 3. Methods applied for the determination of soil characteristics.

Variable	Value	Method
Silt	%	NTC-6299-2018
Clay	%	NTC-6299-2018
Sand	%	NTC-6299-2018
pH		NTC-6299-2018
Organic matter	%	NTC 5526-2007
Ca	cmol (+) kg^{-1}	NTC 5349-2016
K	cmol (+) kg^{-1}	NTC 5349-2016
P	mg kg^{-1}	NTC 5349-2016
CEC eff	cmol (+) kg^{-1}	NTC 5268-2014
Electrical conductivity	dS m^{-1}	NTC 5596-2008

Leaf and root sampling were conducted at 2, 4, and 6 months after LRC application. In each experimental unit, five plants were randomly selected along a diagonal transect to avoid border effects. Plant growth was assessed bimonthly by leaf and root biomass production, determined by constant dry weight at 60 °C. Leaf and root biomass were reported as the per-plant mean: for each plot, root dry weights of the five sampled plants were averaged to obtain a single plot mean, representing the experimental unit used for statistical analysis.

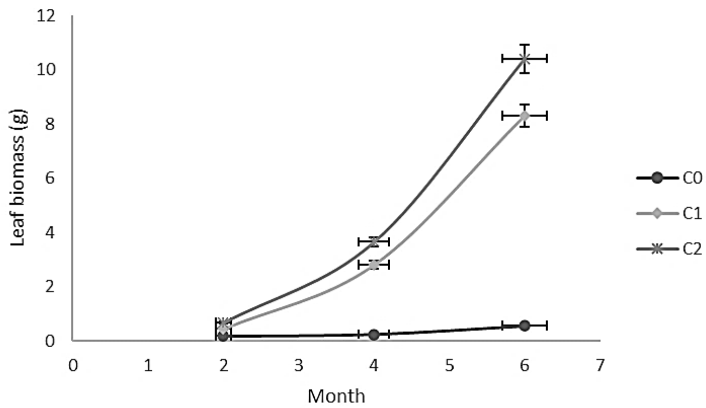
Soil thermal conductivity was measured in situ 2, 4, and 6 months after the establishment of the trial, using the KD2 PRO equipment employing a 10-cm sensor. Four thermistor-type sensors were installed per experimental unit for continuous monitoring of soil conditions, recording soil temperature and humidity hourly.

Prior to analysis, the data were tested for normality (Shapiro–Wilk test) and homoscedasticity (Levene test). Because variables did not meet parametric assumptions even after transformation, non-parametric methods were justified. Differences among treatments were evaluated using the Kruskal–Wallis test, followed by Dunn's post hoc test with Holm correction at $\alpha=0.05$; all analyses were performed in R version 4.3.2 (R Core Team 2023).

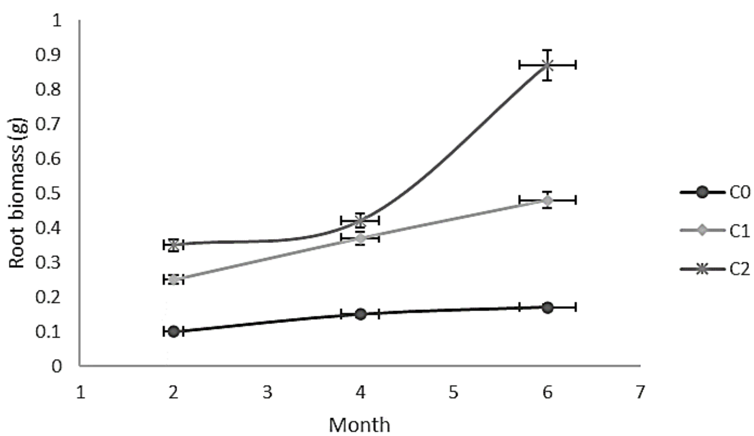
RESULTS AND DISCUSSION

LRC significantly enhanced both leaf and root biomass in plants compared to the control treatment ($P<0.05$) (Figures 1A and B, 2A and B). For instance, Kaya et al. (2018) observed a significant increase in both fresh and dry biomass of maize grown under saline conditions following the application of humic acids. Zhao and Naeth (2022) also reported substantial biomass increase in alfalfa (749%), barley (250%), and sea buckthorn (147%) upon application of HS.

The beneficial effects of LRC are primarily attributed to the presence of humic acids, which enhance nutrient uptake, mitigate ionic toxicity, and improve salinity tolerance (Pantoja-Guerra et al. 2019; Cubillos Hinojosa et al. 2017). Moreover, humic acids contain bioactive compounds with hormone-like activity that stimulate plant growth and alleviate stress caused by ions such as sodium, thereby promoting ionic balance essential for optimal plant development (Khaled and Fawy 2011).



A. Leaf biomass (g)



B. Root biomass (g)

Figure 1. Effect of varying low-rank coal dosages on leaf (**A**) and root biomass (**B**) in sodic-saline soil at 2, 4, and 6 months post-application.

A. without LRC

B. with LRC

Figure 2. Visual comparison of experimental plots four months after the beginning of the trial. **A.** Control plot without LRC application, and **B**. Plot treated with LRC at a rate of 4 t ha^{-1}.

LRC application increased soil porosity from 10% in the control to 20% in the LRC-treated soils (Figure 3). These results are consistent with previous studies by Pantoja-Guerra et al. (2019), and Sarlaki et al. (2023), who reported enhanced water holding capacity in soils amended with LRC or lignite. Similarly, Lohar et al. (2024) found that the porous structure of carbonaceous materials facilitated both water and nutrient retention, allowing for their gradual release according to plant demand. This effect is mainly attributed to the high intrinsic porosity of LRC and the presence of oxygenated functional groups in lignite such as hydroxyl, carbonyl, carboxyl, methoxy, and ether phenolic bonds, which play a crucial role in water adsorption and retention.

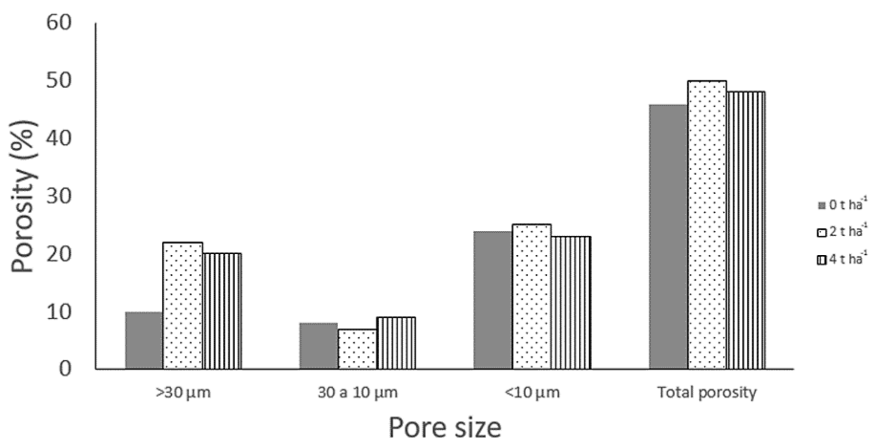


Figure 3. Effect of the amount of LRC on pore distribution in a sodic saline soil.

LRC had a significant effect on soil organic matter accumulation four months after the experiment was established ($P<0.05$), with organic matter content doubling compared to the control (0.3%-0.6%) (Figure 4). However, in subsequent evaluations, no significant differences were observed among treatments, possibly due to mineralization processes resulting in the reduction of the organic matter stability over time (Pantoja-Guerra et al. 2019). These findings are consistent with Qin et al. (2023) who reported a sustained increase in soil organic matter following the application of lignite-derived HS over two years. Similarly, Solek-Podwika et al. (2023) observed increases ranging from 13 to 26% in total organic carbon with the application of lignite derivatives. This effect is mainly attributed to the high organic carbon content of LRC and the stabilizing role of humic substances, which enhances soil aggregation and nutrient retention, thereby promoting long-term organic matter accumulation.

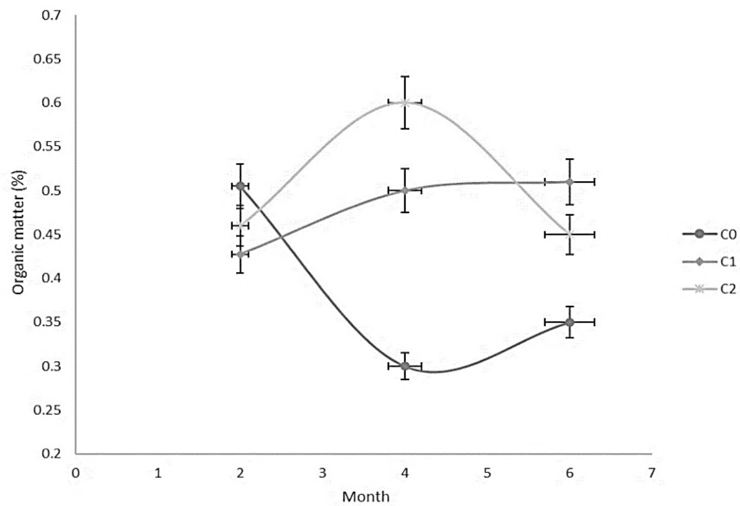
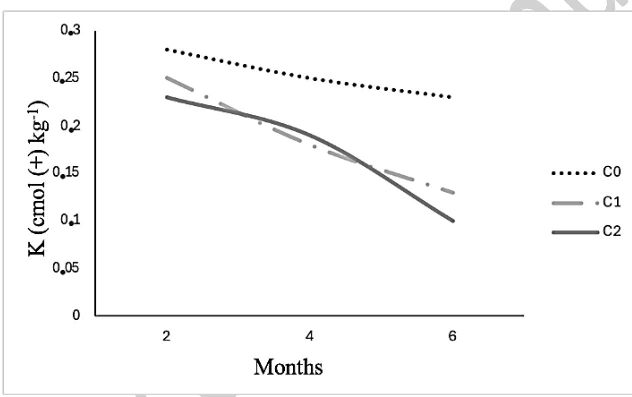
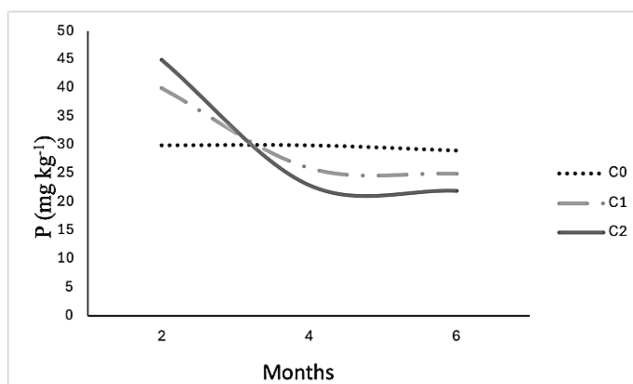


Figure 4. Effect of the amount of LRC on the percentage of organic matter in a sodic soil after 2, 4 and 6 months of application.

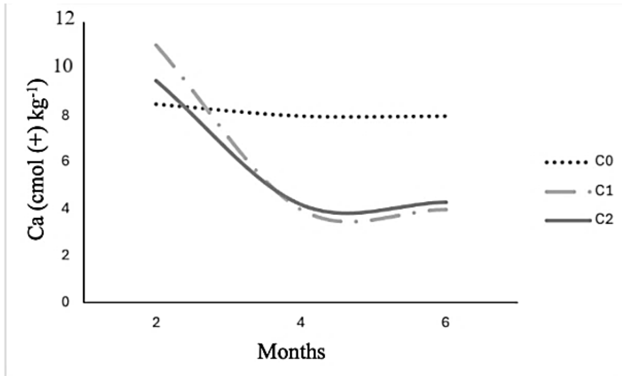
LRC significantly reduced soil concentrations of Ca, K, and P four months after the experiment was initiated, particularly at application rates of 2 and 4 t ha^{-1} (P<0.05) (Figure 5A, B and C). Calcium decreased from 12 to 4 cmol(+) kg^{-1}, phosphorus from 45 to 25 mg kg^{-1}, and potassium from 0.25 to 0.10 cmol(+) kg^{-1}. This decline is attributed to the biostimulant action of HS released by LRC, which enhances plant root nutrient uptake (Canellas et al. 2015). Pantoja-Guerra et al. (2019) have reported similar results, specifically regarding calcium uptake.



A. concentration of K



B. Concentration of P



C. Concentration of Ca

Figure 5. Effect of the LRC on the amount of P(**A**), K(**B**) and Ca(**C**) in a sodic saline soil after 2, 4, and 6 months of application.

Additionally, the observed decline in organic matter suggests ongoing mineralization processes, which may increase nutrient availability and facilitate subsequent plant uptake. HS further modulates this dynamic by enhancing the bioavailability of key nutrients such as Ca, K, and P (Canellas et al. 2015).

LRC influences nutrient dynamics through multiple mechanisms, including the formation of chelate complexes with metal ions, improvement of soil structure via stable aggregate formation (Pantoja-Guerra et al. 2019), and stimulation of microbial activity, which accelerates the mineralization of organic matter and the release of inorganic nutrients (Khan et al. 2014).

The application of LRC significantly reduced soil EC compared to the control (P<0.05) (Table 4), a result similar to that obtained with the application of LRC or lignite-derived humic substances (Cubillos Hinojosa et al. 2017; Manasa et al. 2020; Guo et al. 2022). This reduction in EC may be attributed to increased hydraulic conductivity resulting from improved soil structure (Guo et al. 2022), as well as to the exchange of sodium ions with divalent cations released by the amendment (Chaganti and Crohn 2015). Furthermore, the buffering capacity of LRC, particularly in terms of ammonium (NH_4^+) retention and reduced nitrate (NO_3^-) leaching, may also contribute to the observed decline in EC (Paramashivam et al. 2016).

Table 4. Variation of chemical variables with the application of LRC in a sodic saline soil, including standard deviation.

Treatments	pH			EC (dS m^{-1})			SAR			ESP (%)		
	Months											
	2	4	6	2	4	6	2	4	6	2	4	6
C2	9.8±0.26	9.4±0.5	9.6±0.8	3.9±1.15	3.6±0.54	4.4±0.04	22±0.25	24±0.83	28±1.8	36.2±5.96	34.5±0.23	36.7±1.34
C1	9.6±0.45	9.5±0.23	9.3±0.10	4.5±0.05	4.3±0.2	4.2±0.35	23±0.25	25±0.83	29±1.8	39.4±4.16	42.51±1.43	44±0.72
C0	11±0.7	10.4±0.05	10.5±0.11	7.8±02	7.9±0.05	7.8±0.3	46±0.25	48±0.83	50±1.8	59.3±0.32	58±1.45	59.5±0.66

A mean reduction of approximately one pH unit was also observed following LRC application (P<0.05). This finding aligns with those of Manasa et al. (2020) and Guo et al. (2022), who attributed the acidifying effect to the nutrient composition of lignite-derived humic acids. The decrease in pH may also be explained by the release of protons (H^+) during organic matter decomposition and the ionization of lignite functional groups in aqueous solution (Qi et al. 2011). In addition, Chen et al. (2023) highlighted that the low pH and abundance of functional groups in HS contribute to both structural and nutritional improvements in saline soils.

In addition, LRC application resulted in an average reduction of 18% in ESP and a decrease of 20 units in the sodium adsorption ratio (SAR) compared to the control. These findings are consistent with previous studies reporting reductions in SAR and ESP in soils amended with lignite and other organic materials (Chaganti and Crohn 2015; Cubillos Hinojosa et al. 2017; Amoah-Antwi et al. 2021). The beneficial effect of LRC is largely attributed to its high specific surface area, which enhances water and nutrient retention, minimizes salt accumulation through reduced leaching, and contributes to improved soil quality and plant productivity (Zhang et al. 2013).

The application of LRC significantly increased the soil's cation exchange capacity (CEC) ($P<0.05$) (Table 5). This finding is consistent with previous research by Cubillos Hinojosa et al. (2017), who reported that LRC, as a source of humified organic matter, enhances CEC. Similarly, Amoah-Antwi et al. (2021) observed a general trend toward increased CEC with lignite application, although the effect was not statistically significant in their study. This response can be attributed to the presence of humic acids in LRC, which are rich in carboxylic and phenolic hydroxyl functional groups. These groups serve as reactive sites that increase the soil's ability to retain cations and buffer pH fluctuations (Skodras et al. 2014).

Table 5. CEC in sodic saline soil after LRC application.

Treatments	**CIC (cmol kg^{-1}) Months**		
	2	4	6
C2	10.4±0.171	10.4±0.420	10.3±0.35
C1	9.50±0.499	9.53±0.764	9.54±0.643
C0	7.01±0.469	7.12±1.83	7.2±1.2

The incorporation of LRC led to a significant reduction in soil thermal conductivity ($P<0.05$) four months after the experiment began, with decreases ranging from 20 to 25% (1.2 a 0.6 W m^{-1} K^{-1}) (Figure 6). This effect is likely associated with increased soil porosity, larger aggregate size, elevated organic matter content resulting from LRC addition, and the inherently low thermal conductivity of the material itself (Khaledi et al. 2023).

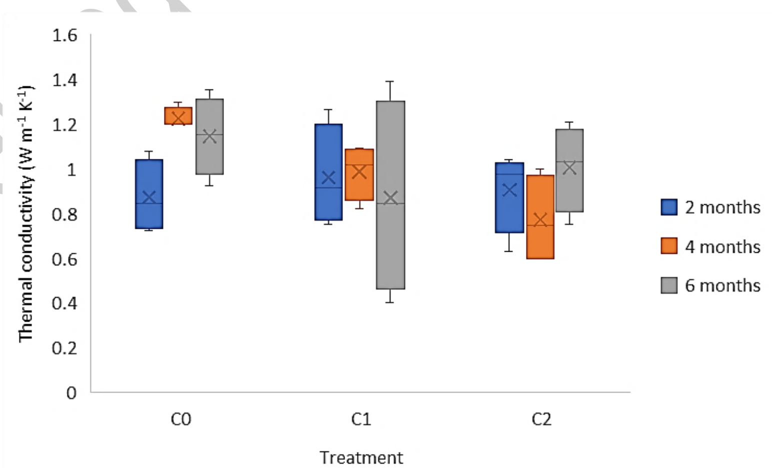


Figure 6. Thermal conductivity (W m^{-1} K^{-1}) of the soil for the control (C0), 2 t ha^{-1} of LRC (C1), and 4 t ha^{-1} of LRC (C2) applied to the soil after 2, 4, and 6 months of application.

These findings are consistent with those of Ortiz and Ramírez (2022), who reported a significant reduction in soil thermal conductivity in a covered cultivation system. Likewise, Li et al. (2023) observed that, under conditions of constant bulk density, both thermal diffusivity and conductivity decreased with increasing biochar application rates. Notably, a 5% biochar incorporation significantly altered ($P<0.05$) soil thermal properties, primarily due to the lower thermal conductivity and specific heat capacity of biochar compared to mineral soil (Khaledi et al. 2023). Biochar additions altered the proportions of solid-phase components with distinct bulk density, particle density, and thermal properties. These changes led to improved soil porosity and moisture retention capacity and resulted in a significant reduction in both thermal conductivity and thermal diffusivity (Usowicz et al. 2020).

A clear relationship was observed between bulk density and soil thermal conductivity, where increases in bulk density were associated with higher thermal conductivity. Conversely, a reduction in aggregate size also resulted in an increased thermal conductivity (Figure 7). This behavior can be attributed to the limited heat transfer across contact points and the inter-aggregate spaces, which diminish as aggregate size increases (Usowicz et al. 2020).

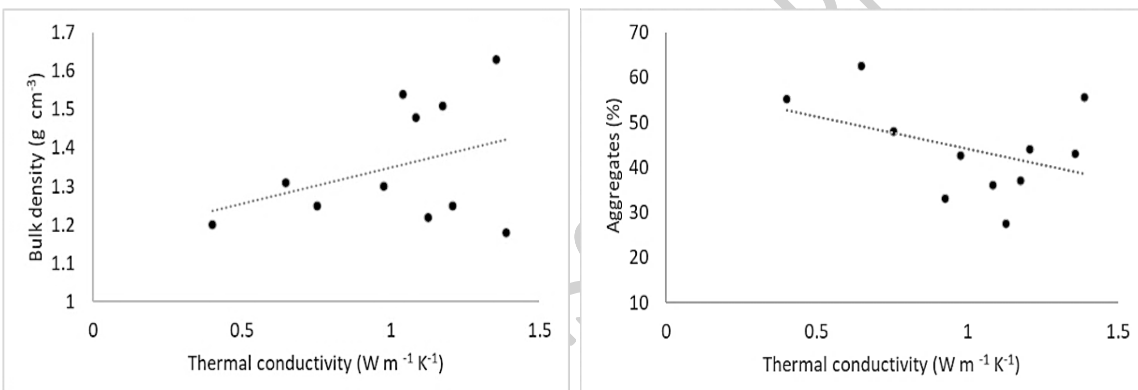


Figure 7. Correlation between the thermal conductivity (W m^{-1} K^{-1}) of soil after 6 months of application of the treatments, the percentage of aggregates and the bulk density.

In high-density soils, particles are more closely packed, facilitating heat conduction through the solid matrix. In contrast, the formation of intra-aggregate pores reduces particle contact and, consequently, heat flow through the soil (Usowicz et al. 2020).

The application of LRC appeared to influence soil temperature in certain cases, with reductions of up to 10 °C compared to the control. This suggests that LRC may contribute to moderating fluctuations in soil temperature. However, the absence of a linear relationship between average daily soil temperature and the temperature differences among treatments indicates that additional factors may be influencing the thermal behavior of the soil.

These findings align with previous studies demonstrating the role of biochar in regulating diurnal soil temperature variations. Yeboah et al. (2023) reported that biochar can affect soil temperature by enhancing its thermal and moisture retention capacities. This is attributed to the insulating properties of biochar, which help buffer temperature extremes—keeping soils warmer under cool conditions and cooler under hot climates. Furthermore, biochar applications can improve soil health and stimulate microbial activity, both of which may also influence soil thermal dynamics. In addition, reports by Zhang et al. (2013) showed that the incorporation of biochar helped to reduce daily and seasonal fluctuations in soil temperature. The influence of biochar on soil temperature can be explained by changes in soil thermal conductivity and reflectance, which interact together.

CONCLUSION

Under the conditions evaluated, the incorporation of LRC produced measurable improvements in key soil and plant variables. Leaf and root biomass, as well as leaf area, increased by 200–400% compared with the control. Temporary increases in soil organic matter were detected, along with reductions in soil pH, electrical conductivity, SAR, and ESP. LRC application also decreased soil thermal conductivity by 20–25%, although no significant differences were observed between application rates. Changes in porosity and aggregation were recorded; however, conclusions are limited to the variables measured and should not be extrapolated to unmeasured processes.

The duration of the experiment (6 months), the plot size (20 m²), and the number of replicates impose constraints on the spatial and temporal extrapolation of these results. Within these limitations, the observed changes indicate that LRC application modified several measured soil properties and enhanced plant growth under saline–sodic conditions. Long-term and multifactorial studies conducted across different soil types and management conditions are recommended to assess the persistence, scalability, and broader agronomic relevance of LRC effects.

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CONFLICT OF INTERESTS

The authors declare no potential conflicts of interest.

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