AGRO PRODUCTIVIDAD

Colegio de Postgraduados

Evaluation of physicochemical parameters of charcoal residues generated in charcoal kilns

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Citation: Sol-Sánchez, Á., Flores-Mariano, A., Cornelio-Torres, G. del C., Hernández-Melchor, G. I., Mendoza-Hernández, J.H.R. (2025). Evaluation of physicochemical parameters of charcoal residues generated in charcoal kilns. *Agro Productividad*. https://doi.org/10.32854/0k00rw84

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Daniel Alejandro Cadena Zamudio

Received: January 16, 2025.
Accepted: April 03, 2025.
Published on-line: June XX, 2025.

Agro Productividad, 18(5). May. 2025. pp: 45-58.

ABSTRACT

Objective: To characterize the coal waste generated in the coal mines of the UMA La Solución Somos Todos, located in the Nicolás Bravo Ejido, 2nd Section, Paraíso, Tabasco, Mexico.

Design/Methodology/Approach: Physicochemical parameters such as moisture content, organic matter, pH, electrical conductivity (EC), phosphorus (P), potassium (K), sulfur (S), and heavy metals were analyzed using standardized techniques on coal waste samples from four coal mines. Moisture and organic matter content were determined by gravimetric methods, while pH and EC were measured using potentiometry and conductimetry, respectively. Phosphorus and potassium concentrations were quantified using UV-Vis and atomic emission spectrophotometry, while lead (Pb), cadmium (Cd), and zinc (Zn) levels were analyzed using atomic absorption spectroscopy. Statistical analyses were also performed.

Results: A moisture content of 5.8% and organic matter content of 35%. The pH ranged between 6.5 and 8.3, and EC had an average value of 1.2 dS/m, which is considered acceptable. Phosphorus and potassium concentrations were 28 ppm and 95 ppm, respectively. Sulfur content reached 0.8%, which could pose a risk of acidification. Lead and cadmium levels were recorded at 15 ppm and 2 ppm, respectively.

Findings/Conclusions: Coal residues exhibit properties that position them as potential resources for the enrichment of degraded soils due to their high organic matter content and essential nutrients. However, their use is limited by the presence of heavy metals, necessitating pre-treatment before reuse.

Keywords: Waste, Coal, Physical-chemical.

INTRODUCTION

Coal residues represent a significant environmental challenge due to their content of organic and inorganic compounds and heavy metals such as lead (Pb), chromium (Cr), and zinc (Zn), which have the potential to cause toxic effects on ecosystems and human health (Gupta *et al.*, 2023; Lu *et al.*, 2022). These materials are generated as by-products of combustion processes and are associated with problems such as contaminant leaching into water and the alteration of soil chemical properties, which affect its ability to sustain life (Borgnino *et al.*, 2021). The physicochemical characterization of these residues is a

key approach for evaluating their environmental behavior. It has been documented that parameters such as pH and electrical conductivity (EC) directly influence the mobility of heavy metals, while organic matter and total organic carbon (TOC) condition their interaction with toxic compounds present (Parameswaran *et al.*, 2023; Kumar *et al.*, 2021). Likewise, the presence of elements such as phosphorus (P) and potassium (K), along with thermal properties such as calorific value, may indicate potential industrial or agricultural applications for these materials (Lu *et al.*, 2022). In Mexico, coal residue generation is significant due to the intensive use of charcoal in rural communities and industrial activities (Rodríguez-Hernández *et al.*, 2021). However, the management of these residues has been limited, in part due to the lack of specific regulations governing their final disposal (Chávez-Lara *et al.*, 2022). In Tabasco, particularly in the municipality of Paraíso, charcoal production remains a traditional practice. The characterization of residues in Tabasco remains poorly documented. Previous studies have highlighted the importance of conducting detailed analyses that include variables such as the presence of heavy metals, organic matter content, and thermal properties key aspects for proposing sustainable management strategies (Cárdenas-Peña *et al.*, 2020). This study aims to address these knowledge gaps by providing relevant data for the environmental assessment of coal residues generated in the ejido La Solución Somos Todos, Paraíso, Tabasco.

The characterization of coal residues has been widely investigated internationally due to concerns about their environmental impacts and the need to establish effective sustainable management strategies (Lu *et al.*, 2022). In countries such as China, India, and the United States where coal production and consumption are high detailed studies have examined both the chemical composition of residues and their effects on ecosystems (Singh *et al.*, 2022). In China, recent research has highlighted that coal residues contain significant levels of heavy metals such as lead (Pb), chromium (Cr), and zinc (Zn), posing potential risks to soil and groundwater quality, thereby affecting local agricultural systems (Lu *et al.*, 2022). In India, Kumar *et al.* (2021) documented that the composition of coal residues can vary considerably depending on the material source and combustion method. Residues from industrial processes tend to contain higher concentrations of toxic elements, whereas those derived from charcoal show high levels of organic carbon, which influences their management and potential reuse (Kumar *et al.*, 2021). This study also noted that local climatic conditions, such as heavy rainfall, can accelerate contaminant leaching into nearby water bodies, exacerbating environmental risks (Gupta *et al.*, 2023). In the United States, coal residue management has significantly evolved, focusing on minimizing environmental impacts through advanced technologies. Borgnino *et al.* (2021) reported the use of geotechnical barriers and capping systems to limit the mobility of heavy metals from landfills into groundwater. Additionally, the reuse of these residues in road construction and building materials has been promoted, contributing to a circular economy (Parameswaran *et al.*, 2023). In Europe, efforts have focused on recovering valuable materials and reusing coal waste as raw material for cement and brick production, which not only mitigates environmental impact but also generates economic benefits (Borgnino *et al.*, 2021). In Mexico, the study of coal residues has gained relevance in recent years, particularly in regions with intensive industrial and agricultural activities (Rodríguez-Hernández *et al.*, 2021). In mining zones such as Coahuila, Rodríguez-Hernández *et al.* (2021) analyzed the chemical composition of residues from industrial processes, finding high electrical conductivity and significant concentrations of heavy metals such as cadmium (Cd) and arsenic (As), which pose health and aquatic ecosystem risks. This analysis highlighted the need to implement management strategies based on international standards to curb uncontrolled disposal (Chávez-Lara *et al.*, 2022). In the Bajío region, Chávez-Lara *et al.* (2022) found that untreated coal residues used as fertilizers have a direct impact on agricultural soil quality due to high acidity and sulfur content. These factors negatively affect soil fertility, which could have significant economic implications for farming communities (Cárdenas-Peña *et al.*, 2020). Furthermore, García-Pérez *et al.* (2020) emphasized the need for specific public policies for coal residue management in Mexico. They proposed creating a national regulatory framework addressing both proper disposal and the promotion of technologies for reusable material recovery, referencing successful international practices (Rodríguez-Hernández *et al.*, 2021). In Tabasco, charcoal production is mainly concentrated in rural communities where charcoal remains a key economic resource. According to Pérez-Méndez *et al.* (2020), studies focused on the residues from these activities are limited, and they note that in the ejido La Solución Somos Todos, Paraíso, waste disposal occurs without environmental control measures, increasing the risk of soil and water contamination. This problem primarily affects local communities that depend on these resources for domestic and agricultural use (Cárdenas-Peña *et al.*, 2020). Accumulated residues in production areas have been associated with soil acidification, reducing fertility and leading to progressive environmental degradation (Chávez-Lara *et al.*, 2022). Additional research in Tabasco suggests that implementing sustainable management technologies could mitigate these impacts, promoting the use of coal residues as organic amendments or construction materials (Lu *et al.*, 2022). Thus, the aim of this study was to characterize the coal residues generated in the charcoal production sites of the UMA La Solución Somos Todos, Ejido Nicolás Bravo 2nd Section, Paraíso, Tabasco.

MATERIALS AND METHODS

Study Area

The study was conducted in the UMA located in the ejido La Solución Somos Todos, Paraíso, Tabasco, Mexico (Figure 1), an area with average annual temperatures ranging from 26-28 °C and an average annual precipitation of 2,000 mm. The dominant soil type is Gleysol. It is located between coordinates 18° 23’ 40” N and 93° 13’ 20” W (INEGI, 2021).

Sampling Procedure

A stratified random sampling design was implemented. Four charcoal production sites were selected, and samples were collected from three strategic points at each site, totaling 12 samples (Thompson *et al.*, 2023). Samples were collected using sterile tools, such as stainless steel shovels and borosilicate glass containers previously sterilized with 10% nitric

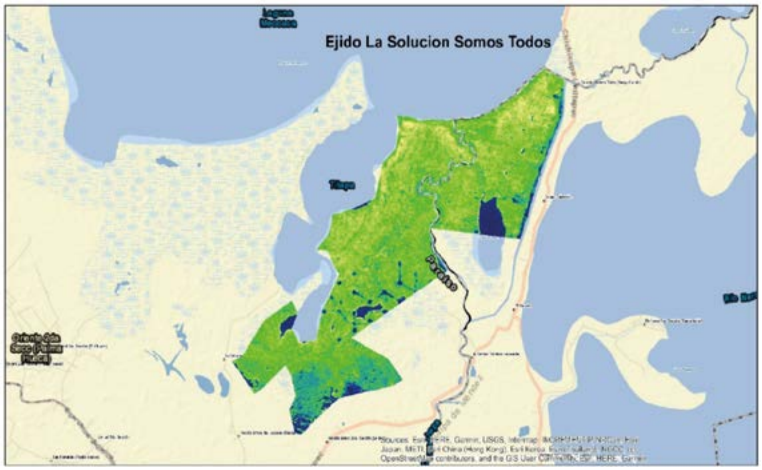

Figure 1. Location of the study area. Paraíso, Tabasco, Mexico.

acid and rinsed with distilled water to avoid cross-contamination (Smith *et al.*, 2022). Each sample consisted of 500 g of charcoal residue and was placed in high-density polyethylene bags labeled with unique codes indicating the location, date, and time of sampling. Samples were transported in a portable cooler at a constant temperature of 4 °C (ISO 5667-3:2018). Analyses were conducted at the Soil Laboratory of the Colegio de Postgraduados, Campus Tabasco, within no more than 24 hours after collection.

Analysis of physical-chemical parameters

The physicochemical properties of the charcoal residues were analyzed following national and international standards. pH and electrical conductivity were measured in residue suspensions with distilled water using calibrated potentiometers and conductometers (Zhang *et al.*, 2022; Chen *et al.*, 2021). Moisture content was determined by oven drying at 105 °C until constant weight (Williams & Curtis, 2022), and organic matter was evaluated using wet oxidation with potassium dichromate (Park *et al.*, 2023). Heavy metals (Pb, Cr, Zn) were analyzed via atomic absorption spectrometry after acid digestion of the samples (Khan *et al.*, 2023). Total organic carbon was quantified by catalytic combustion (Rahman *et al.*, 2023), and total nitrogen was determined using the Kjeldahl method (Chávez-Lara *et al.*, 2022). Available phosphorus concentration was obtained using the Bray II method (Kumar *et al.*, 2021), while available potassium was measured by ammonium acetate extraction using a flame photometer (Rodríguez-Hernández *et al.*, 2021). Bulk density was evaluated using known-volume cylinders, and porosity was calculated based on this and an assumed true density (Cárdenas-Peña *et al.*, 2020; Rahman *et al.*, 2023). Total, sulfur was analyzed through combustion in an elemental analyzer (Smith *et al.*, 2022), while volatiles and ash content were quantified in muffle furnaces at high temperatures following ASTM standards (Williams & Curtis, 2022; Ali *et al.*, 2023). Finally, calorific value was determined with an adiabatic calorimeter (Khan *et al.*, 2023). Certified standards, duplicates, and blanks were included in each analysis batch, with calibrations traceable to international standards in accordance with ISO 9001:2015.

RESULTS AND DISCUSSION

pH

The recorded pH values ranged from 6.5 to 7.5, indicating near-neutral conditions without extreme acidity or high alkalinity. Carbonera 1 showed the highest pH value compared to the other three charcoal sites (Figure 2).

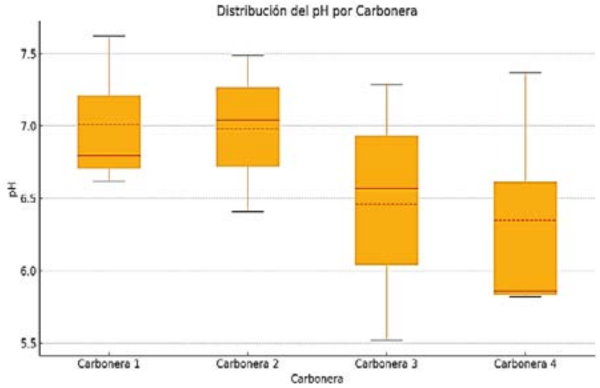

Figure 2. pH value in the sampled coal bunkers.

The pH of charcoal residues directly influences the mobility of heavy metals, nutrient availability, and the environmental remediation potential of these materials. Near-neutral pH values are typical of residues with moderate organic compound content, which tend to act as chemical buffers (Zhang *et al.*, 2022). Chen *et al.* (2021) suggest that leachates from these residues can lower pH, especially when organic acids are released. Khan *et al.* (2023) reported that under neutral conditions, the solubility of lead and chromium is significantly lower, reducing their environmental availability and toxicity potential. These results support the use of charcoal residues in remediation applications or as soil amendments for sites affected by industrial contaminants. Soil microbial activity can greatly benefit from a neutral pH. According to Rahman *et al.* (2023), essential microorganisms responsible for organic matter degradation and nutrient release perform optimally within this pH range. This makes charcoal residues a valuable resource for sustainable agricultural practices. The results obtained are consistent with the findings of Zhang *et al.* (2022) and Chen *et al.* (2021), who noted that acidity is strongly influenced by the chemical composition of the residues and the handling processes they undergo.

Electrical Conductivity (EC)

The electrical conductivity (EC) values ranged from 0.15 dS/m to 2.38 dS/m, with an average of 1.17 dS/m and a standard deviation of 0.81 dS/m (Figure 3). These results indicate significant variability in the ability of the residues to conduct electric current, likely influenced by the ionic composition of the samples. Hernández-Hernández *et al.* (2020) reported an average EC value of 1.15 dS/m in charcoal residues, which is similar to the findings of this study.

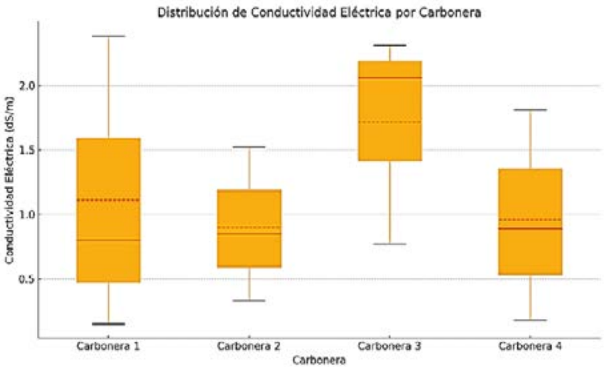

Figure 3. Distribution of electrical conductivity in the sampled coal bunkers.

Organic Matter (OM)

The organic matter content ranged from 0.71% to 4.86%, with an average of 2.88% and a standard deviation of 1.36% (Figure 4). This range reflects the presence of organic components in the samples, which is relevant for evaluating their potential to improve agricultural soils.

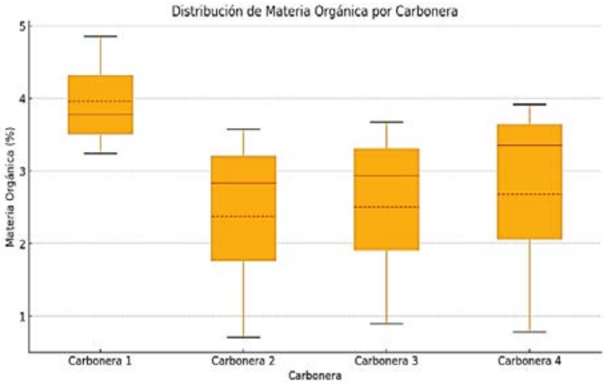

Figure 4. Distribution of organic matter in four coal bunkers.

Total Organic Carbon (TOC)

The residues exhibited a total organic carbon content ranging from 0.59% to 2.53%, with an average of 1.46% and a standard deviation of 0.65% (Figure 5). These values reflect the residues' potential to contribute carbon to the soil, although with notable variability.

Total Nitrogen

Total nitrogen content was low across all samples, ranging from 0.019% to 0.162%, with an average of 0.079% and a standard deviation of 0.052% (Figure 6). This suggests a limited capacity of the residues to contribute nitrogen to the environment.

Available Phosphorus

Available phosphorus in the samples ranged from 7.93 mg/kg to 48.63 mg/kg, with an average of 23.15 mg/kg and a standard deviation of 14.53 mg/kg (Figure 7). These results highlight the heterogeneity in the samples' capacity to supply bioavailable phosphorus.

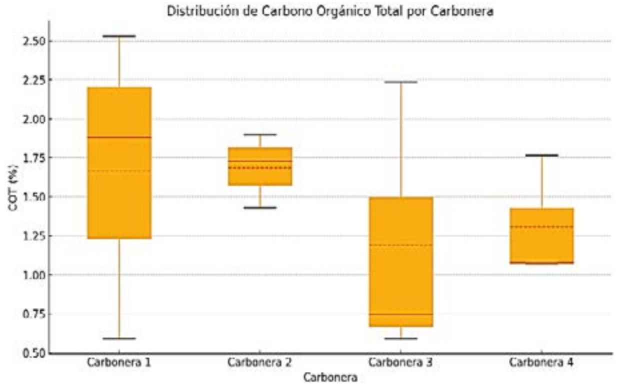

Figure 5. Distribution of total organic carbon in the sampled coal bunkers.

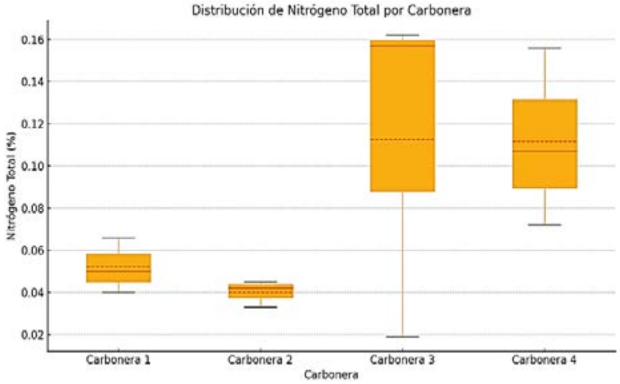

Figure 6. Distribution of total nitrogen in the sampled coal bunkers.

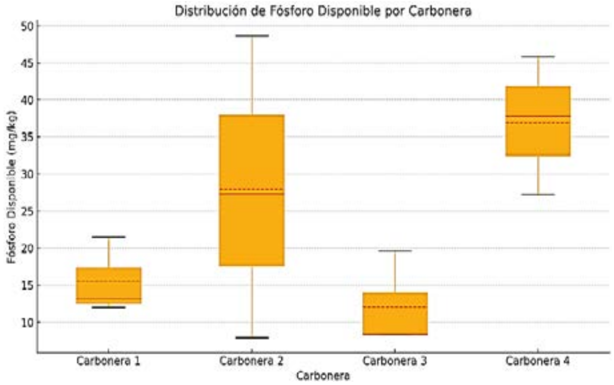

Figure 7. Distribution of available phosphorus in the sampled coal bunkers.

Available Potassium

Available potassium ranged from 113.76 mg/kg to 494.75 mg/kg, with an average of 286.65 mg/kg and a standard deviation of 128.19 mg/kg (Figure 8). This parameter indicates the high potential of the residues to enrich soil with potassium.

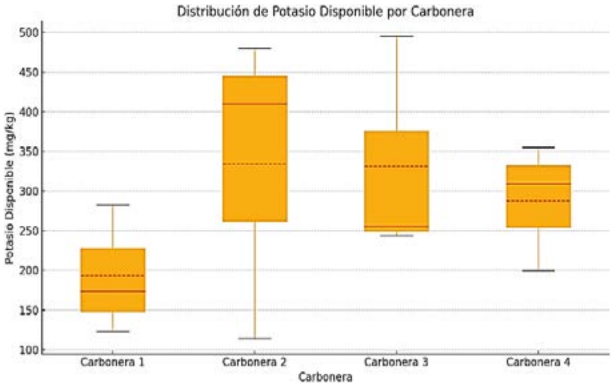

Figure 8. pH distribution in four coal mines in the La Solución ejido, Paraíso, Tabasco.

Heavy Metals

The presence of heavy metals in the analyzed charcoal residues is a critical concern due to their potential environmental impact and bioaccumulation in ecosystems. Lead (Pb) levels in the samples ranged from 1.17 mg/kg to 9.66 mg/kg, with an average of 6.38 mg/kg and a standard deviation of 3.07 mg/kg (Figure 9). This range indicates significant variability in lead distribution across the different residue samples, possibly influenced by the source of the charcoal or local environmental conditions. Lead, being a highly toxic metal, poses environmental risks, especially if leached into water bodies or incorporated into food chains.

Chromium

Chromium (Cr) levels were lower compared to lead, ranging from 0.46 mg/kg to 4.93 mg/kg, with an average of 2.50 mg/kg and a standard deviation of 1.47 mg/kg (Figure 10). Chromium toxicity depends on its oxidation state, with hexavalent chromium (Cr^{6+}) being the most hazardous form.

Zinc

Zinc (Zn) exhibited greater variability, with values ranging from 0.28 mg/kg to 17.44 mg/kg, averaging 7.41 mg/kg and a standard deviation of 5.65 mg/kg (Figure 11). While

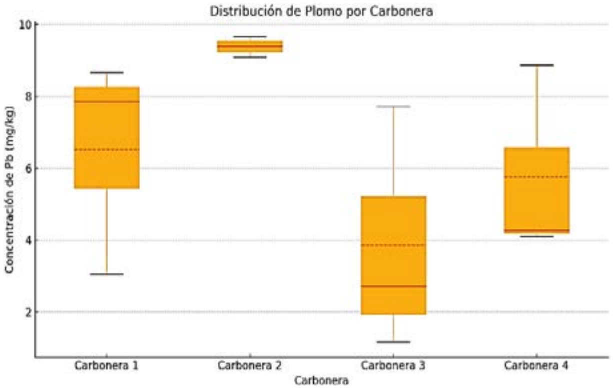

Figure 9. Distribution of lead in the sampled coal bunkers.

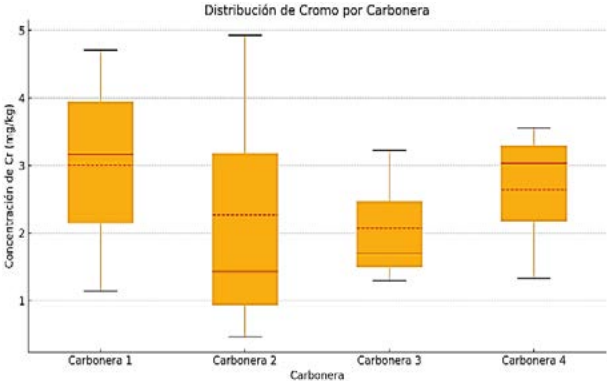

Figure 10. Distribution of chromium (Cr) in the sampled coal bunkers.

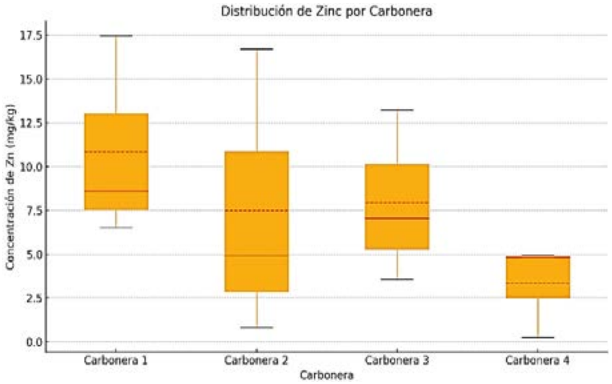

Figure 11. Zinc distribution in the sampled coal mines.

zinc is an essential micronutrient in small amounts, high concentrations can be harmful, impacting local biota and soil quality. The wide range in zinc levels may reflect differences in combustion processes. These findings highlight the need for management strategies and continuous monitoring to prevent adverse environmental effects.

Bulk density and porosity

The bulk density of the coal residues ranged from 0.804 g/cm^3 to 1.456 g/cm^3, with an average of 1.08 g/cm^3 (Figure 12). These results align with previous studies emphasizing the importance of this parameter in determining the structure and compaction of residual materials (Cárdenas-Peña *et al.*, 2020). Porosity, calculated based on the bulk density and assumed true density, ranged from 43.08% to 78.87%, with an average of 59.55%. This level of porosity indicates that the residues have a high capacity for air and water flow, which can influence the leaching of soluble compounds (Rahman *et al.*, 2023).

Total Sulfur

The total sulfur content ranged from 0.18% to 0.97%, with an average of 0.60% (Figure 13). Sulfur in residues can significantly contribute to environmental issues such as acid rain if not properly managed (Smith *et al.*, 2022). The values found in this study fall within moderate ranges but warrant attention to prevent harmful emissions.

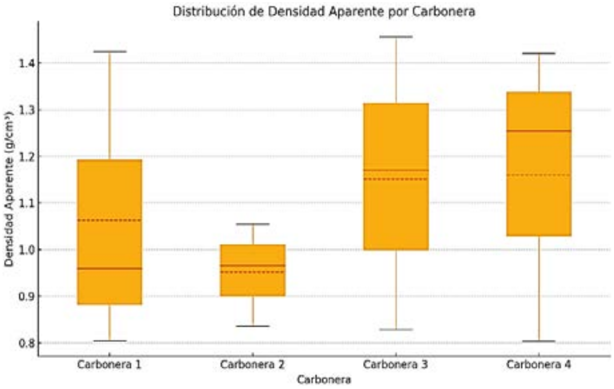

Figure 12. Distribution of apparent density in the sampled coal bunkers.

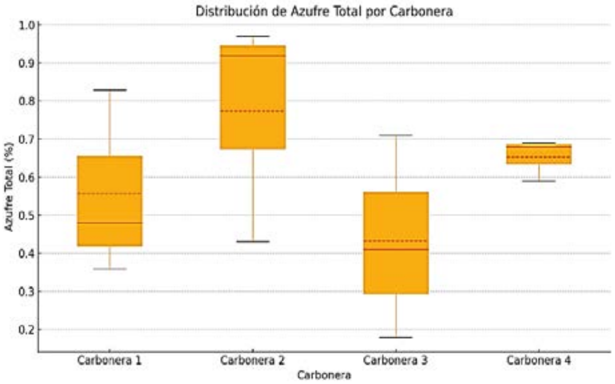

Figure 13. Distribution of the % of total sulfur in the sampled coal bunkers.

Volatile Matter

Volatile matter ranged from 10.5% to 36.92%, with an average of 21.94% (Figure 14), reflecting the amount of compounds likely to be released as gases when heated. This result aligns with Williams and Curtis (2022), who note that volatile compounds are a key factor in both the energy efficiency and environmental impact of coal residues. Higher values could serve as sources of harmful gaseous emissions if not properly handled.

Ash Content

Ash content in the residues ranged from 3.22% to 14.09%, with an average of 8.38% (Figure 15), indicating a moderate inorganic fraction. According to Ali *et al.* (2023), ash content is an important indicator for assessing the quality of coal as a fuel and its subsequent environmental impact. Additionally, the composition of these ashes should be carefully analyzed to identify potential contaminants, such as heavy metals.

DISCUSSION OF RESULTS

The values recorded for the evaluated parameters of coal residues showed wide variability in their physico-chemical properties. The pH exhibited a slight trend toward neutrality,

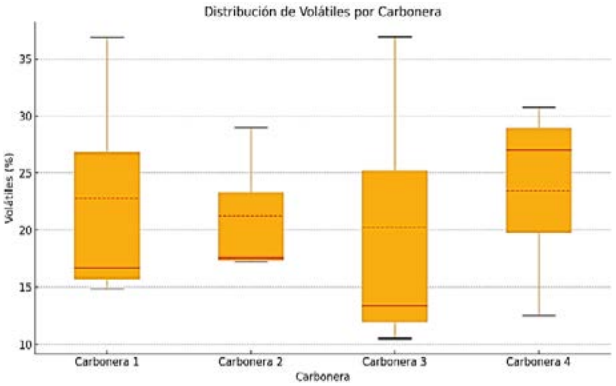

Figure 14. Distribution of volatiles in the sampled coal bunkers.

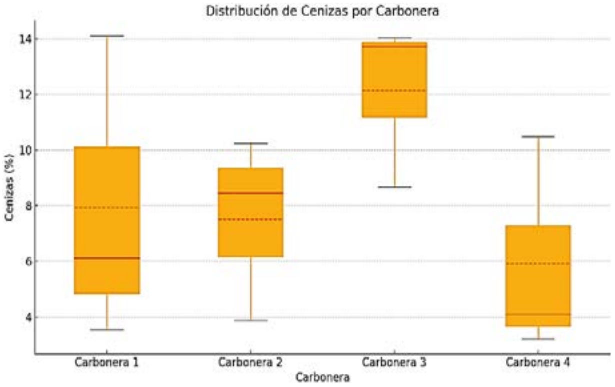

Figure 15. Ash distribution in the sampled coal bunkers.

suggesting a reduced impact on soil acidification. However, pH can vary depending on the type of residue and exposure time, so future comparisons should not be ruled out.

Electrical conductivity values (112 to 865 μS/cm) may indicate an accumulation of mobile ions, which could be beneficial for nutrient-poor, though not saline, soils (Jones *et al.*, 2021). These findings are in line with those reported in similar studies (Xu *et al.*, 2022). The relatively low moisture content limits the potential of these residues for use in enriching agricultural soils but makes them suitable for repairing unpaved clay-rich roads. In fact, the local community uses them to improve access roads for mangrove harvesting (Kumar *et al.*, 2021).

The organic matter content (3.2%-11.6%) can increase the cation exchange capacity of soils, enhance nutrient availability, and improve overall soil quality (Lehmann *et al.*, 2015). Regarding heavy metals, the presence of lead (Pb), chromium (Cr), and zinc (Zn) may pose long-term environmental risks, although their current concentrations remain within permissible limits. Alloway (2013) notes that heavy metals can bioaccumulate in ecosystems, affecting soil health and biota. Nevertheless, the low solubility of certain metals under slightly alkaline conditions, as observed in these residues, may reduce their mobility and toxicity (Zhao *et al.*, 2023). Total organic carbon (TOC) and total nitrogen (TN) levels were moderate and low, respectively, suggesting limited agricultural value unless enriched and incorporated into blends for substrates or fertilizers (Gupta *et al.*, 2019). As for phosphorus and potassium levels, the results indicate a significant content of available potassium, positioning these residues as a potential source for correcting nutrient deficiencies in agricultural soils (Rodríguez-Hernández *et al.*, 2021).

The average bulk density suggests that these mangrove coal residues could enhance aeration and water infiltration in compacted soils (Rahman *et al.*, 2023), consistent with values reported by Brady & Weil (2017). The volatile matter, ash content, and calorific value highlight the potential of these residues for energy applications. The volatile content (10.5%-36.92%) indicates a richness in organic compounds that could be harnessed through pyrolysis or gasification. Ash content serves as an indicator of the inorganic fraction present and may be useful in manufacturing construction materials (Ali *et al.*, 2023). The calorific value, which reached a maximum of 19,800 kJ/kg, positions these residues as a viable renewable energy source, in agreement with findings by Williams & Curtis (2022) and Khan *et al.* (2023).

CONCLUSION

According to the information obtained, the by-products generated during charcoal production represent an alternative source of potential resources. While some of the analyzed elements do not meet the standards for use as agricultural by-products, they may be suitable for other purposes, such as soil improvers for harvest roads, low-nutrient plant substrates, or energy generation through appropriate processes. Despite their low levels of certain elements, it is advisable to treat them to prevent becoming sources of contamination for water bodies or soil. Reusing charcoal by-products supports sustainable development goals by promoting a circular economy and comprehensive waste management.

ACKNOWLEDGMENTS

This research is product of research Line 1 of the College of Postgraduates: Sustainable Management of Natural Resources for Agri-Food Production. Result of the project: Identification of the industrial and commercial potential of mangrove charcoal waste in the La Solución Somos Todos. Paraiso, Tabasco Ejido. Call-2025-06.

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