

Environmental applications of agricultural waste-derived biochars for soil improvement and lead adsorption

Aqeela BATOOL ¹, Samreen SHEHZADI ², Dilawar HUSSAIN ^{1, 3}, Riffat HAYAT ⁴, Shumaila ZUBAIR ²

Received January 22, 2026; accepted June 05, 2026
Delo je prispelo 22. januar 2026, sprejeto 5. junij 2026

Environmental applications of agricultural waste-derived biochars for soil improvement and lead adsorption

Abstract: Biochar, a carbon-rich material produced by the pyrolysis of organic waste, has emerged as a low cost and sustainable material for several environmental applications including the enhancement of soil fertility and adsorption of heavy metals. This study evaluated and compared the potential of four plant-based biochars (wheat straw, pine straw, corn cob and parthenium biochars) for environmental applications by analyzing their physicochemical properties. The results showed that of all the analyzed biochars, parthenium biochar was found to be most effective in enhancing soil fertility as it contained the highest total organic carbon (79.50 %) and N contents (2.50 %). Moreover, the concentration of toxic heavy metals was found below safe limits in all the biochars studied in this research which favors their suitability for environmental applications. On the other hand, adsorption studies revealed that the corn cob biochar exhibited the highest lead removal efficiency (98 %) at an adsorbent dose of 2 g l⁻¹. Based on these findings, it is concluded that the agricultural waste-derived biochars can be used as sustainable and effective materials for environmental management, including soil quality enhancement and heavy metal remediation.

Key words: agricultural waste biochar, soil fertility enhancement, environmental remediation, lead adsorption, sustainable soil management, waste valorization

Okoljska uporaba bioogljja, pridobljenega iz kmetijskih odpadkov, za izboljšanje tal in adsorpcijo svinca

Izvleček: Bioogljje, z ogljikom bogat material, proizveden s pirolizo organskih odpadkov, se je izkazal kot poceni in trajnosten material za več okoljskih aplikacij, vključno s povečanjem rodovitnosti tal in adsorpcije težkih kovin. Ta študija je ovrednotila in primerjala potencial štirih rastlinskih bioogljjev [(pšenična slama, borove iglice, koruzni storži in bioogljje iz partenija (invazivna vrsta plevela *Parthenium hysterophorus* L.)) za uporabo v okolju z analizo njihovih fizikalno-kemijskih lastnosti. Rezultati so pokazali, da je bilo partenijevo bioogljje med vsemi analiziranimi bioogljji najbolj učinkovito pri povečevanju rodovitnosti tal, saj je vsebovalo največjo vsebnost skupnega organskega ogljika (79,50 %) in N (2,50 %). Poleg tega je bila koncentracija strupenih težkih kovin v vseh bioogljjih, preučevanih v tej raziskavi, pod varnimi mejami, kar kaže na njihovo primernost za uporabo v okolju. Po drugi strani pa so adsorpcijske študije pokazale, da je bioogljje iz koruznih storžev pokazalo največjo učinkovitost odstranjevanja svinca (98 %) pri odmerku adsorbenta 2 g l⁻¹. Na podlagi teh ugotovitev se sklepa, da se bioogljje, pridobljeno iz kmetijskih odpadkov, lahko uporablja kot trajnostni in učinkoviti materiali za upravljanje okolja, vključno z izboljšanjem kakovosti tal in sanacijo težkih kovin.

Ključne besede: bioogljje iz kmetijskih odpadkov, povečanje rodovitnosti tal, okoljska sanacija, adsorpcija svinca, trajnostno ravnanje s tlemi, valorizacija odpadkov

¹ Pakistan Institute of Engineering and Applied Sciences, Nilore, Islamabad, Pakistan.

² Pakistan Institute of Nuclear Science and Technology, Nilore, Islamabad, Pakistan.

³ Corresponding Author Email & ORCID: Dilawar Hussain, dilawarhussain@pieas.edu.pk, dilawarh16@gmail.com, <https://orcid.org/0009-0008-2156-1276>

⁴ PMAS Arid Agriculture University, Rawalpindi, Pakistan.

1 INTRODUCTION

In the pursuit of sustainable solutions to enhance agricultural productivity, soil degradation, contamination, water scarcity and food security, biochar emerges as a promising solution with various beneficial characteristics. These include its high carbon content, surface area, capacity for carbon sequestration, nutrient leach out mitigation, acidity of soil and also contribution to climate change moderation (Kabir *et al.*, 2023). Biochar is basically an organic carbon rich material produced by thermally decomposing the biomass or organic matter with either little or no oxygen present (B. B. P. Singh *et al.*, 2010). Depletion of soil nutrients and organic content, decline in agricultural production due to uncontrolled use of fertilizers and climate changes caused by anthropogenic activities are rendering the sustainability of tropical regions' agricultural production under great threats. Therefore, it seems inevitably important to use organic alongside inorganic fertilizers to maintain soil health and improve sustainability (Das *et al.*, 2021).

Biochar exhibits good thermal stability, straightforward production process and environmental friendliness, utilizing various feedstock streams, including animal manure, plant biomass, industrial waste, agricultural residues (such as rice husk, corn cob, and wheat straw), and aquatic waste biomass (Zhuo *et al.*, 2023). These feedstocks can be used to produce biochar in a way that transforms such waste into a potentially valuable and useful end product (Ayaz *et al.*, 2021). Applying biochar to the soil is a relatively new and green solution to improve soil fertility. Currently, an increase in carbon dioxide (CO₂) concentration is being observed in the atmosphere worldwide, resulting in higher atmospheric temperatures, in addition to other greenhouse gases. These changes tend to adversely affect soil fertility other than its physical, chemical and biological properties (Niedziński *et al.*, 2023).

Since 2000, human-generated CO₂ emissions have been increasing by slightly above 3 % annually, pushing Earth's ecosystems in the face of swift and permanent climate change. For altering this course, swift and ambitious measures for mitigation are imperative. Numerous studies indicate that cumulative human-caused greenhouse gas (GHG) emissions must stay below a critical upper limit to stabilize the global average surface temperature. All this underscores the necessity for collective efforts to bring future net anthropogenic emissions to zero. Humanity should surpass the threshold for maximum safe cumulative emissions that may have already been reached; even significant reductions in emissions will not suffice to restore the climate within safe limits. Different strategies focused on removing excessive amounts

of CO₂ from the atmosphere would become more crucial than simply dropping emissions by an equivalent amount (Woolf *et al.*, 2010). In response, a recent worldwide effort has established a challenging goal of increasing the amount of organic matter in soil worldwide by 0.4 % per year, which significantly aids in reducing GHG emissions (Minasny *et al.*, 2017). Therefore, given escalating global concerns such as environmental pollution, climate change and soil erosion, utilizing biochar for soil improvement and carbon sequestration emerges as a highly favorable and promising strategy (Tao *et al.*, 2024; Wu *et al.*, 2022). Over the past decade, biochar's unique properties have resulted in its extensive use across multiple fields. Researchers have mainly concentrated on its application in agricultural production, climate change mitigation and environmental pollution minimization (Zhuo *et al.*, 2023).

Recent studies on biochar have highlighted its diverse benefits in agriculture sector and environmental management. Only few studies have systematically compared multiple feedstocks under identical pyrolysis conditions for dual applications in soil fertility improvement and heavy metal removal via adsorption. In this study, conducted at Pakistan Institute of Nuclear Sciences and Technology (PINSTECH), Islamabad - Pakistan, the potential of four different agricultural waste-derived biochars has been compared by analyzing their physico-chemical properties. In conclusion, the most suitable biochars, based on high carbon content, nutritional values and adsorption capacity, have been recommended for soil quality enhancement and environmental remediation.

2 MATERIALS AND METHODS

2.1 BIOCHAR COLLECTION AND CHARACTERIZATION

Four types of agricultural waste materials, corn cob biochar (CCB), pine straw biochar (PSB), Parthenium biochar (PB) – derived from an invasive weed *Parthenium hysterophorus* L. – and wheat straw biochar (WSB) were collected from an agricultural institute, PMAS–Arid Agriculture University Rawalpindi, Pakistan (Figure 1). These samples were pyrolyzed at 450 °C for 1.5 h to produce biochars. After air drying at 105 °C for 24 h, these samples were subjected to physico-chemical analysis (Hoque *et al.*, 2025) it is essential to find sustainable ways to boost crop yields, improve soil health, and address the environmental issues induced by agriculture. The most appropriate approach is to consider sustainable amendments, such as biochar and its derivatives, which

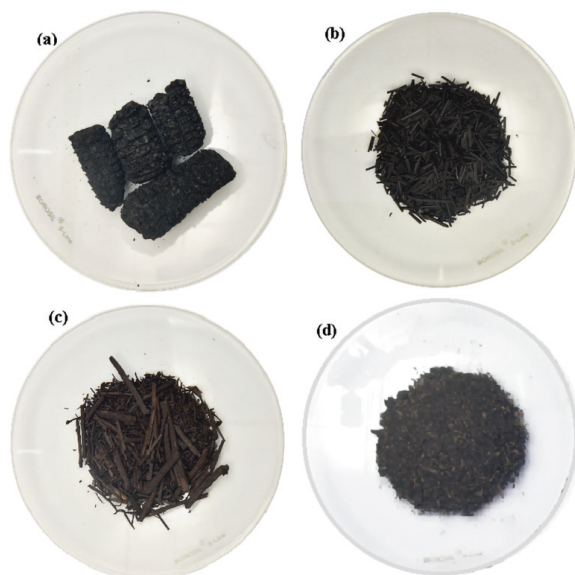


Figure 1: Graphical representation of biochar samples (a) CCB (b) PSB (c) PB (d) WSB.

are vital constituents of soil health due to their affordability, low reactivity, large surface area, and reduced carbon footprint. In this context, biochar and its derivatives in farming systems focus on improving soil structure, nutrient holding capacity, microbial activities, and the perpetuation of soil fertility. Despite its benefits, biochar, if it is used in high concentration, can sometimes become highly toxic, causing soil erosion due to reducing surface area, increasing pH levels, and altering soil properties. This review highlights the production methods and sources of feedstocks, emphasizing their important contribution to the soil's physicochemical and biological properties. Furthermore, it critically evaluates the environmental applications and their impacts, providing data built upon the literature on contaminant removal from soil, economic factors, heavy metal immobilization, carbon sequestration, and climate resilience. This review emphasizes the main challenges and future prospects for biochar use in comparison to modified biochar (MB).

The fine powders (30 mesh size) of these biochar samples were used for analyses such as electrical conductivity (EC), moisture content (MC), pH, heavy metal concentration, total organic carbon (TOC) content, total nitrogen (TN) content, micronutrients (Zn, Mn, Fe, Cu), and macronutrients (P, K, Ca, Mg, and Na). Thermal analysis was carried out in the temperature range of 30–800 °C under oxidative atmosphere at a heating rate of 10 °C min⁻¹.

Elemental analysis of hydrogen, sulphur and oxygen (HSO) was carried out with 140 ml min⁻¹ helium and 250

ml min⁻¹ of oxygen gas for 12 min. The oven and furnace temperatures were held at 65 and 950 °C, respectively.

2.2 PHYSICO-CHEMICAL CHARACTERIZATION

Both the pH and electrical conductivity (EC) of the biochar samples were measured using methods previously described by Singh et al. 2017 (B. Singh et al., 2017). For pH determination each biochar sample was weighed (1.5 g) on an analytical balance, dissolved in 30 ml distilled water and agitated for 1 h at 165 rpm in an orbital shaker. After shaking, the suspension was allowed for 30 min to stand. The pH of biochar samples was recorded using pH meter (HANNAH HI/2211) calibrated with standard buffer solutions of pH 4 and 7. The electrical conductivity of filtered solutions was measured using conductivity meter (Cond 7110 WTW).

For moisture content, the fresh air-dried biochar samples were weighed and heated at 70 °C in a heating oven till no change in mass of samples was observed. The moisture content was calculated by using Equation 1.

$$\text{Moisture content (\%)} = \frac{\text{Difference in fresh and oven dried sample mass}}{\text{Oven dried sample mass}} \times 100 \quad \text{Equation 1}$$

Total organic carbon in biochar samples was analyzed using the dichromate digestion technique described by Sajjad et al. 2005 (Azam & Sajjad, 2005). All the biochar samples, each weighed 30 mg, were dissolved in 5 ml of 2 N potassium dichromate and 8 ml of concentrated sulphuric acid in a microwave oven at 60 °C for 1.5 min. After cooling to room temperature, the samples were diluted to 50 ml with distilled water and were filtered. Spectrophotometer (Spectronic +20) was used to quantify the absorbance of the sample at 590 nm. Total organic carbon was measured using Equation 2.

$$C \text{ (mg) in sample} = \frac{5(C \text{ content of standard}) \times \text{Optical density of sample mixture}}{\text{Optical density of standard}} \quad \text{Equation 2}$$

Total nitrogen content in biochar samples was analyzed using the method mentioned by Bremmer et al. (Campbell et al., 2018). 0.2 g of biochar was digested with 3 ml concentrated sulfuric acid (H₂SO₄), copper sulfate, potassium sulfate and selenium at 50–350 °C for 4–5 h. Using distilled water, the digested sample was diluted to 100 ml in a volumetric flask. A 20 ml aliquot of the digest was distilled with 10 ml conc. boric acid and 5 ml of 40 % sodium hydroxide (NaOH) solution. A solution of 0.1 N hydrochloric acid (HCl) was used to titrate the distillate. The nitrogen concentration was determined with 1 ml of 0.1 N HCl, which is the same as 1.4 mg of nitrogen. A blank of the sample was also analyzed for comparison.

Inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Thermo iCAP-6500) was

used to determine the micronutrients (Fe, Zn, Cu, Mn) and macronutrients (N, P, K, Na, Mg, Ca) and toxic heavy metals (Pb, Ni, Cd, Cr) in biochar samples.

X-ray Diffraction pattern of three samples was obtained using high resolution X-ray diffractometer (Proto Manufacturing AXRD Powder Diffraction System, Cu-K α , 35 kV, 30 mA). Diffraction patterns were recorded in 2 θ range of 9–90° following a step size of 0.02° and scan rate of 0.5° min⁻¹. The Fourier Transform Infrared (FTIR) spectroscopy is a chemical analysis technique based on absorption of infrared radiation by molecules. Different functional groups in the molecules absorb infrared radiation corresponding to different wavelengths thus helping in identification of functionalities present in a molecule. The FTIR analysis of two biochar samples having high carbon content (CCB and PB) was carried out before and after lead adsorption to evaluate the adsorption mechanism and the active functional groups involved in adsorption. For the FTIR analysis, the adsorbent dosage of CCB and PB were kept at 2 g l⁻¹ and 1 g l⁻¹, respectively.

3 RESULTS AND DISCUSSION

3.1 PROXIMATE AND ULTIMATE ANALYSIS OF BIOCHARS

The proximate and ultimate analyses of the biochar samples i.e., pH, EC, MC, HSO contents are reported in Table 1. The MC varied between 0.18–2.66 %. The elemental HSO analysis showed the presence of higher hydrogen concentration in PB (5.01 %) followed by CCB (4.39 %) and PSB (4.15 %), respectively. Sulphur was not identified in any of the four biochars. Further results showed the presence of highest oxygen contents in PSB (7.80 %) followed by CCB, PB and WSB, respectively.

According to physico-chemical analysis, the elemental composition of the biochars exhibited notable variations. The results in Table 2 indicated that some bio-

chars were alkaline in nature with pH > 8 such as WSB (pH = 8.95) and PB (pH = 8.24) and showed greater concentration of Ca, K, Mg and Na. Other biochars including PSB and CCB had pH of 6.17 and 6.34, respectively. Biochar with acidic pH possesses the necessary qualities for adsorbing nutrients and improving crop growth (Mujtaba *et al.*, 2021). The electrical conductivity of WSB, PSB, CCB and PB was determined to be 2.57, 0.21, 0.68 and 4.68 mS cm⁻¹, respectively. According to Bouqbis *et al.* (Bouqbis *et al.*, 2017), electrical conductivities higher than 4 mS cm⁻¹ in biochar negatively affect the process of seed germination and lower crop yields with higher sensitivity to salt in a soil solution.

The TOC analyses in Figure 2 showed that PB is a good source of carbon with the highest TOC (79.50 %) followed by CCB, PSB and WSB as shown in Figure 2(a). The organic matter in biochar can stimulate the growth of microbial communities, which in turn leads to increased soil carbon mineralization (Li & Tasnady, 2023).

The results further revealed that PB was a good source of N with 2.50 % TN content, the highest among all the biochar samples in this group as shown in Figure 2(b) and endorsed by reported data in literature (Quratul-Ain *et al.*, 2016). Nitrogen is a major nutrient required by plants in large amounts and it is essential component of chlorophyll, proteins, hormones and nucleic acids. It is also considered a crucial macronutrient for plants and plays a vital role in their metabolic processes, resource allocation and overall growth and development (Fathi, 2022)A. (2022). Hence, its deficiency may adversely affect plant growth.

The C: N ratio is a crucial factor for predicting whether decomposition will result in net mineralization or microbial immobilization. While organic materials with a high C:N ratio (> 30) cause microbial immobilization, those with a low C:N ratio (< 30) encourage nitrogen mineralization (Y. Yang *et al.*, 2024). The results obtained showed that among the four biochars PSB had highest C : N ratio 57.41 followed by WSB, CCB and PB,

Table 1: Proximate and ultimate analysis of different biochars.

Proximate and Ultimate Elemental Analysis	Unit	Wheat straw biochar (WSB)	Pine straw biochar (PSB)	Corn cob biochar (CCB)	Parthenium biochar (PB)
pH (1:20)		8.95	6.17	6.34	8.24
Electrical conductivity (1:20)	mS cm ⁻¹	2.57	0.21	0.68	4.68
Moisture content	%	1.01	0.81	2.66	2.16
Hydrogen	%	ND	4.15	4.399	5.01
Sulphur	%	ND	ND	ND	ND
Oxygen	%	6.15	7.80	6.64	6.56

*ND = Not detected

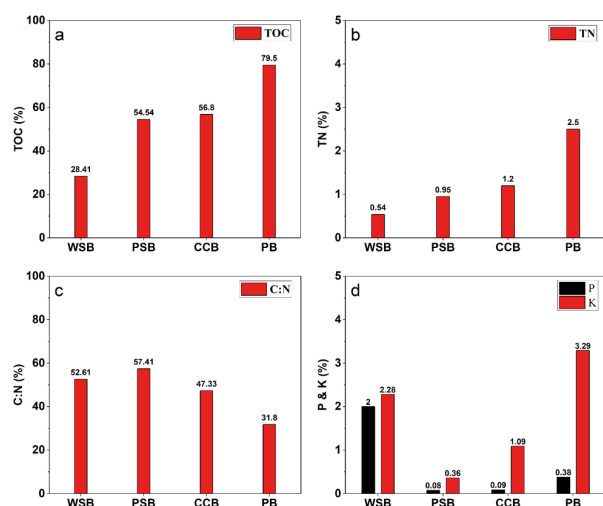


Figure 2: Comparison of nutrients of four different biochar samples (a) Comparison of TOC (b) Comparison of TN (c) Comparison of C: N (d) Comparison of P and K.

respectively, as shown in Figure 2(c). Currently, soil under cultivation in many countries of the world is low in organic matter and essential nutrients that are vital for plant growth, including N, P, K, and Zn (Hamzah Saleem et al., 2022; Jiaying et al., 2022)phosphorus (P).

Macronutrients such as P and K are vital for plant growth. Our results showed that WSB had highest phosphorus content (2.00 %) and the maximum K content were found in PB (3.29 %) (Alfadil et al., 2021; Bian et al., 2018; Muhammad et al., 2017; Qurat-ul-Ain et al., 2016) a pot experiment was conducted with three biochar addition rates of 0% (BA0).

The results of micronutrients and macronutrients analyses are provided in Table 2. Ca, Na and Mg play a vital role in plant development, thus enhancing crop yield and help to activate specific enzyme systems in soil

Table 2: Micronutrients and macronutrients composition of different biochars.

Parameters	Unit	WSB	PSB	CCB	PB
Macronutrients					
Ca	%	8.95	1.12	0.06	3.37
Na	$\mu\text{g g}^{-1}$	5751	10.57	156	321
Mg	$\mu\text{g g}^{-1}$	76.16	27.93	10.41	39.09
Micronutrients					
Zn	$\mu\text{g g}^{-1}$	416	41.94	37.78	75.82
Mn	$\mu\text{g g}^{-1}$	417	30.66	12.03	34.37
Fe	$\mu\text{g g}^{-1}$	3144	370	29.47	835
Cu	$\mu\text{g g}^{-1}$	59.28	4.89	4.38	21.56

which tends to increase the quality of agricultural crops (Guo et al., 2016)involved in many enzyme activities and the structural stabilization of tissues, its importance as a macronutrient ion has been overlooked in recent decades by botanists and agriculturists, who did not regard Mg deficiency (MGD. The highest Ca, Na and Mg contents were found in WSB as 8.95 %, 5751 $\mu\text{g g}^{-1}$ and 76.16 $\mu\text{g g}^{-1}$, respectively.

Micronutrients, known as vitamins and minerals, are essential for both disease prevention and healthy growth. The data showed that the highest concentration of Zn was found in WSB (416 $\mu\text{g g}^{-1}$). The maximum amount of Mn, Cu and Fe contents were recorded in WSB as 417, 59.28 and 3144 $\mu\text{g g}^{-1}$, respectively. The values of macro and micronutrients found in WSB are in good agreement with the data reported in literature (Alfadil et al., 2021; Bian et al., 2018; Muhammad et al., 2017)a pot experiment was conducted with three biochar addition rates of 0% (BA0). These results show the application potential of WSB for mineral nutrient supplementation and alkaline conditioning of the soil to enhance soil nutrient availability. The higher amounts of TN, P, K and TOC, however, make PB a more suitable choice for soil amendment whereas WSB can be used in combination with PB to synergistically enhance soil fertility. Fe plays an important role in metabolic processes in plants such as DNA synthesis, respiration and photosynthesis. Its deficiency in plants can retard plant growth and development. On the other hand, Cu plays a part in several enzymatic processes and is a vital nutrient in the formation of chlorophyll. Our results showed that the highest Cu contents were obtained in PB (21.56 $\mu\text{g g}^{-1}$).

The levels of toxic heavy metals (Pb, As, Cd, Ni, Cr, and Hg) in biochar samples are listed in Table 3. Results revealed that all the toxic heavy metals were found below the safe limits in all the biochar samples. No heavy metals were detected in CCB while only lead was detected in

Table 3: Toxic heavy metals analysis in different biochars.

Toxic Heavy Metals	Unit	WSB	PSB	CCB	PB	*IBI limits
Pb	$\mu\text{g g}^{-1}$	6.94	2.90	ND	4.32	121–300
Cd	$\mu\text{g g}^{-1}$	ND	ND	ND	ND	1.4–39
As	$\mu\text{g g}^{-1}$	3.56	ND	ND	ND	13–100
Ni	$\mu\text{g g}^{-1}$	10.42	ND	ND	1.73	47–420
Cr	$\mu\text{g g}^{-1}$	9.15	ND	ND	1.54	93–1200
Hg	$\mu\text{g g}^{-1}$	ND	ND	ND	ND	1–17

*IBI = International biochar initiative

*IBI Standards provide guidelines for production and use, emphasizing soil health and carbon sequestration

PSB ($2.90 \mu\text{g g}^{-1}$) but found below the safe limits according to IBI guidelines 2013 (Askeland *et al.*, 2019).

3.2 X-RAY DIFFRACTION ANALYSIS

XRD is a versatile and indispensable tool for analysis of crystal structure, phase identification and crystallinity of different samples. Visual presentation of XRD analysis of CCB and PB are given in Figure 3.

3.2.1 Corn cob biochar

Diffractogram of CCB in Figure 3(a) showed broad hump like diffraction peaks corresponding to 2θ angle of 20.63° (100), 26.63° (001), 26.74° (002), 28.35° (200) and 40.32° (220). The peaks at 20.63° and 26.63° corresponded to silicon dioxide (Alsherbeny *et al.*, 2022) atrazine, chlorfenvinphos, chlorpyrifos, cyprodinil, diazinon, dimethoate, diuron, ethion, malathion, and profenofos while the at 26.74° showed the presence of boron nitride. The small peaks at 28.35° and 40.32° correspond to potassium chloride (Pipíška *et al.*, 2022). The diffractogram showed the presence of amorphous carbon in broad range of $2\theta = 16\text{--}30^\circ$ (Fassel & Knfseley, 1974). The compounds found in XRD analysis aid in the elimination of pollutants by bonding with the functionalities present on the pollutant's surface (Alsherbeny *et al.*, 2022) atrazine, chlorfenvinphos, chlorpyrifos, cyprodinil, diazinon, dimethoate, diuron, ethion, malathion, and profenofos.

3.2.2 Parthenium biochar

The XRD spectra of Parthenium biochar (PB) exhibited the presence of Sylvite (KCl) diffraction peaks corresponding to 2θ angle of 28.35° (020), 40.51° (022) and 50.19° (222) as shown in Figure 3(b). The high sylvite contents in PB were indicated by sharp peaks at 28.35° and 40.51° (Ain *et al.*, 2022) produces a lot of non edible biomass that is hazardous to humans. This study provides an insight to its beneficial use by converting

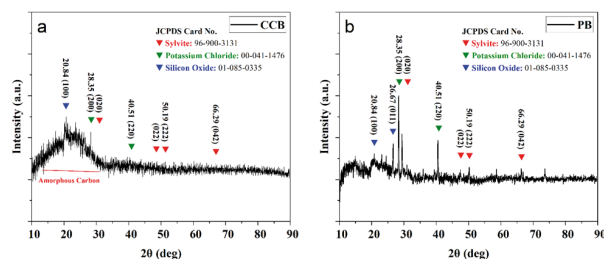


Figure 3: (a) XRD Spectrum of corn cob biochar (b) XRD spectrum of parthenium biochar.

the biomass into value-added materials like compost and biochar and subsequent amendment in soil as fertilizer. The biochar was prepared in a locally fabricated charcolator while the compost was prepared in a rolling tumbler. Two-year field experiment was set up using different combinations of biochar (BC. The results of XRD revealed that PB also have silica (Qurat-ul-Ain *et al.*, 2021) indicated by peaks at 2θ of 20.84° (100) and 26.67° (011).

3.3 THERMOGRAVIMETRIC ANALYSIS

Thermal stability and decomposition behavior of a material can be studied analytically using thermogravimetric analysis (TGA). It involves heating the sample in a controlled environment while measuring its mass changes as a function of temperature or time. Thermogravimetric analysis performs well for sorting out the thermal degradation profile of materials. TGA curves of CCB and PB are shown in Figure 4. Initially, both the biochar samples undergo a similar oxidation process, resulting in a slight increase in mass. The initial increase in mass of CCB at 50°C is due to occurrence of oxidation phenomenon while the decomposition phase at around 120°C was a result of moisture loss (Qurat-ul-Ain *et al.*, 2021) that remained in the sample even after drying. CCB showed lower thermal stability compared to PB. It exhibited an initial mass loss at 257°C , most probably due to degradation of hemicellulose. There was another decomposition step that showed the greatest mass loss in the range of $310\text{--}600^\circ\text{C}$, attributed to the breakdown of cellulose and lignin contents (Padilla *et al.*, 2019).

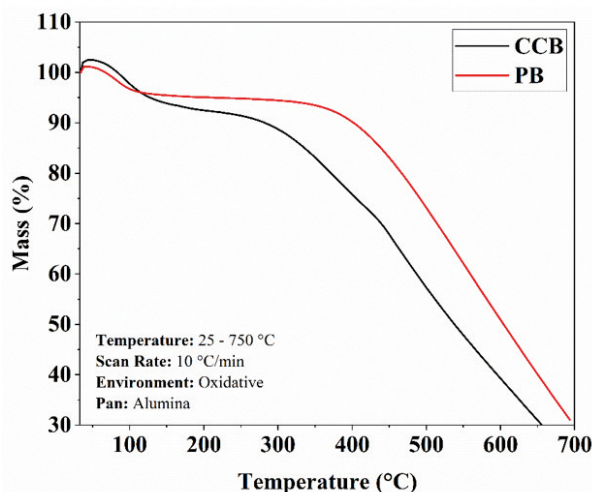


Figure 4: TGA curve of corn cob and parthenium biochar.

TGA results revealed that PB has higher thermal stability compared to CCB. The mass loss due to removal of moisture occurred up to 339 °C, accounting for around 7 % of the total sample mass. There was a significant mass loss in the range of 350–650 °C. The evaluated biochar samples showed thermal stability at elevated temperatures.

3.4 ADSORPTION STUDIES FOR LEAD REMOVAL

3.4.1 Corn cob biochar

The adsorption study of CCB was carried out with 0.5–3 g l⁻¹ of adsorbent dose. The results showed that at 0.5 g l⁻¹ of adsorbent dose, Pb removal was 88.93 % which decreased to 86.16 % at 1 g l⁻¹ adsorbent dose. After increasing the adsorbent dose to 2 g l⁻¹, it showed maximum Pb removal of 98.06 % which decreased to 97.43 % on increasing adsorbent dose to 3 g l⁻¹. The CCB has highly porous structure which has more adsorption capacity for lead removal. Because there were fewer sites available for adsorption, there was a decrease in Pb adsorption. The sharp increase at 2 g l⁻¹ showed the availability of maximum adsorption sites for Pb removal. The trend of Pb removal by CCB is shown in Figure 5(a).

3.4.2 Parthenium biochar

The adsorption study of *Parthenium* biochar was carried out with 0.05–3 g l⁻¹ of adsorbent dose. The results showed that at 0.05 g l⁻¹ adsorbent dose the Pb removal was 63.28 %, which increased with increasing the adsorbent dose and at 1 g l⁻¹ adsorbent dose the highest Pb removal (88.46 %) was observed. By increasing the adsorbent dose beyond 2 g l⁻¹, Pb removal efficiency decreased to 86.48 % most probably due to particle agglomeration at higher adsorbent doses (Sandeep, 2020; W. Yang et al., 2023). The trend of Pb removal by PB is shown in Figure 5(b).

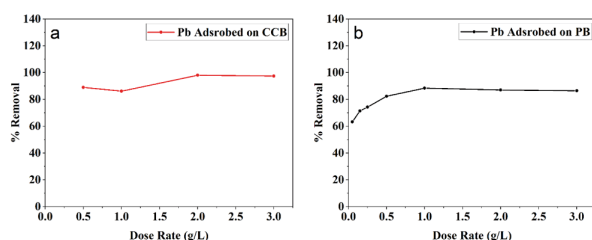


Figure 5: Effect of adsorbent dose of Pb removal (a) From corn cob (b) From parthenium biochar.

3.5 FOURIER TRANSFORM INFRARED SPECTRA

3.5.1 Corn cob biochar

FTIR gives information regarding the chemical bonds and functional groups found in CCB, as well as their influence on lead adsorption. FTIR spectrum of CCB in Figure 6(a) depicts four fundamental band regions. The peak observed at 3272 cm⁻¹ arises from the oxygenated functionalities and adsorption of water from the Pb sample (Qurat-ul-Ain et al., 2021). There should have been characteristics peaks of C-H stretching present at 2830–2980 cm⁻¹, while CCB spectra showed no C-H peaks which may be due to decomposition of -CH₂ groups at higher temperature resulting in lignin demethylation and demethoxylation during pyrolysis (Vuong et al., 2023) 5%, 10%, and 3:3% and 5:5% of the weight of biochar and apatite, the untreated and treated soil were extracted using Tessier's sequence extraction procedure. The five chemical fractions of the Tessier procedure were the exchangeable fraction (F1. It can be seen that the peak at 2360 cm⁻¹ is the characteristic peak of CO₂ (Pipíška et al., 2022) while the band at 1564 cm⁻¹ can be ascribed to aromatic C = C ring vibrations from the lignin structure (Pinky et al., 2023). The peak at 876 cm⁻¹ showed aromatic C-H bend arising from lignin structure (Pinky et al., 2023; Pipíška et al., 2022).

Parthenium biochar

FTIR spectra of PB before and after Pb adsorption is shown in Figure 6(b). The peak observed at 3320 cm⁻¹ before adsorption corresponds to oxygenated functionalities with increased intensity after adsorption of Pb due to accompanying adsorption of water from the Pb sample (Qurat-ul-Ain et al., 2021). The stretching peaks at 2924 and 2858 cm⁻¹ are due to aliphatic CH₂ and CH₃ groups, and phenoxy CH₃ stretching vibrations arising most probably from the lignin structure, respectively (Ain et al., 2022) produces a lot of non edible biomass that is hazardous to humans. This study provides an insight to its beneficial use by converting the biomass into value-add-

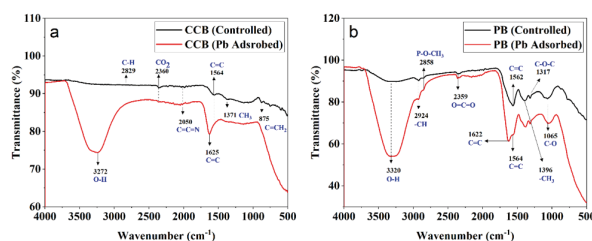


Figure 6: (a) Comparison of corn cob biochar FTIR spectra before and after Pb adsorption (b) Comparison of parthenium biochar FTIR spectra before and after Pb adsorption.

ed materials like compost and biochar and subsequent amendment in soil as fertilizer. The biochar was prepared in a locally fabricated charcolator while the compost was prepared in a rolling tumbler. Two-year field experiment was set up using different combinations of biochar (BC). The characteristic peak at 2359 cm^{-1} showed the presence of CO_2 . Cyclic C=C vibrational bands were observed at 1562 cm^{-1} . After adsorption, peaks shifted at 1564 and 1622 cm^{-1} arise from aromatic C=C deformations in lignin content (Weisz, 2008).

4 CONCLUSIONS

A study was conducted to characterize four biochars, wheat straw biochar (WSB), pine straw biochar (PSB), corn cob biochar (CCB) and parthenium biochar (PB), derived from *Parthenium hysterophorus L.*, with the objective to explore their potential for application in soil amendment and toxic metal removal from water. Higher levels of total organic carbon, total nitrogen, macronutrients, and micronutrients were found in CCB and PB signifying their potential for use as better materials for soil amendment. This finding establishes that these biochars can be used as effective media to mitigate runoff, improve irrigation efficiency, increase soil carbon, and lower agricultural pollution. XRD analysis depicted that the surface elements in CCB were dominated by KCl (Sylvite), boron nitride, SiO_2 and amorphous carbon. TGA studies showed that PB is more thermally stable than CCB. Adsorption studies Pb removal showed that the highest efficiency (98.06 %) for lead removal was recorded in CCB at the adsorbent dose of 2 g l^{-1} . FTIR spectra of biochar confirmed the presence of alkene, alkyl and ether groups in CCB and PB. Based on these results, CCB and PB are recommended as potential biochars for use in soil amendment and for Pb removal in wastewater treatment, respectively.

Data Availability Statement

The underlying raw and processed datasets supporting the findings of this study – including total organic content, total carbon content, phosphorus (P) and potassium (K) content, lead (Pb) adsorption kinetics and isotherms, X-ray diffractograms, FTIR spectra, and TGA thermograms – are publicly available in the Zenodo repository at <https://doi.org/10.5281/zenodo.20592622> (Batoool *et al.*, 2026). All other supporting datasets are reported within the text.

5 REFERENCES

Ain, Q. ul, Shafiq, M., Nazir, A., & Bareen, F. e. (2022). Fertilizer perspective of biochar and compost derived from biomass

- of *Parthenium hysterophorus* in the rice wheat system in Punjab, Pakistan. *Journal of Plant Nutrition*, 46(10), 2434–2450. <https://doi.org/10.1080/01904167.2022.2155555>
- Alfadil, A. A., Xia, J., Shaghaleh, H., Alhaj Hamoud, Y., Ibrahim, J. N., Hamad, A. A. A., Fahad Rahim, S., Sheteiwy, M. S., & Wu, T. (2021). Wheat straw biochar application improves the morphological, physiological, and yield attributes of maize and the physicochemical properties of soil under deficit irrigation and salinity stress. *Journal of Plant Nutrition*, 44(16), 2399–2420. <https://doi.org/10.1080/01904167.2021.1918156>
- Alsherbeny, S., Jamil, T. S., El-Sawi, S. A. M., & Eissa, F. I. (2022). Low-cost corn cob biochar for pesticides removal from water. *Egyptian Journal of Chemistry*, 65(2), 639–650. <https://doi.org/10.21608/EJCHEM.2021.101806.4728>
- Askeland, M., Clarke, B., & Paz-Ferreiro, J. (2019). Comparative characterization of biochars produced at three selected pyrolysis temperatures from common woody and herbaceous waste streams. *PeerJ*, 7, e6784. <https://doi.org/10.7717/peerj.6784>
- Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar role in the sustainability of agriculture and environment. *Sustainability*, 13(3), 1330.
- Azam, F., & Sajjad, M. H. (2005). Colorimetric determination of organic carbon in soils by dichromate digestion in a microwave oven. *Pakistan Journal of Biological Sciences*, 8(4), 596–598. <https://doi.org/10.3923/pjbs.2005.596.598>
- Batoool, A., Shehzadi, S., Hussain, D., Hayat, R., & Zubair, S. (2026). *Raw and processed dataset for agricultural waste-derived biochars characterization and lead (Pb) adsorption*. Zenodo. <https://doi.org/10.5281/zenodo.20592622>
- Bian, R., Li, L., Shi, W., Ma, B., Joseph, S., Li, L., Liu, X., Zheng, J., Zhang, X., Cheng, K., & Pan, G. (2018). Pyrolysis of contaminated wheat straw to stabilize toxic metals in biochar but recycle the extract for agricultural use. *Biomass and Bioenergy*, 118(August), 32–39. <https://doi.org/10.1016/j.biombioe.2018.08.003>
- Bouqbis, L., Daoud, S., Koyro, H. W., Kammann, C. I., Ainhout, F. Z., & Harrouni, M. C. (2017). Phytotoxic effects of argan shell biochar on salad and barley germination. *Agriculture and Natural Resources*, 51(4), 247–252. <https://doi.org/10.1016/j.anres.2017.04.001>
- Campbell, G. S., Jackson, R. D., Mortland, M. M., Nielsen, D. R., & Klute, A. (2018). Methods of soil analysis. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*, 5, 1–1188. <https://doi.org/10.2136/sssabookser5.1.2ed>
- Das, S., Mohanty, S., Sahu, G., Rana, M., & Pilli, K. (2021). Biochar: A sustainable approach for improving soil health and environment. *Soil Erosion - Current Challenges and Future Perspectives in a Changing World*. <https://doi.org/10.5772/intechopen.97136>
- Fassel, V. A., & Knfseley, R. N. (1974). Inductively coupled plasma: Optical emission spectroscopy. *Analytical Chemistry*, 46(13), 1110A–1120A. <https://doi.org/10.1021/ac60349a023>
- Fathi, A. (2022). Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review. *Agrosist*, 28(October), 1–8. <https://doi.org/10.5281/ZENODO.7438164>
- Guo, W., Nazim, H., Liang, Z., & Yang, D. (2016). Magnesium

- deficiency in plants: An urgent problem. *Crop Journal*, 4(2), 83–91. <https://doi.org/10.1016/j.cj.2015.11.003>
- Hamzah Saleem, M., Usman, K., Rizwan, M., Al Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science*, 13. <https://doi.org/10.3389/fpls.2022.1033092>
- Hoque, M. M., Saha, B. K., Scopa, A., & Drosos, M. (2025). Biochar in agriculture: A review on sources, production, and composites related to soil fertility, crop productivity, and environmental sustainability. *C-Journal of Carbon Research*, 11(3), 1–18. <https://doi.org/10.3390/c11030050>
- Jiaying, M., Tingting, C., Jie, L., Weimeng, F., Baohua, F., Guangyan, L., Hubo, L., Juncai, L., Zhihai, W., Longxing, T., & Guanfu, F. (2022). Functions of nitrogen, phosphorus and potassium in energy status and their influences on rice growth and development. *Rice Science*, 29(2), 166–178. <https://doi.org/10.1016/j.rsci.2022.01.005>
- Kabir, E., Kim, K. H., & Kwon, E. E. (2023). Biochar as a tool for the improvement of soil and environment. *Frontiers in Environmental Science*, 11, 1324533. <https://doi.org/10.3389/fenvs.2023.1324533>
- Li, S., & Tasnady, D. (2023). Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspectives. *C++ Conference*. <https://doi.org/10.3390/c9030067>
- Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z. S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., ... Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, 292, 59–86. <https://doi.org/10.1016/j.geoderma.2017.01.002>
- Muhammad, N., Aziz, R., Brookes, P. C., & Xu, J. (2017). Impact of wheat straw biochar on yield of rice and some properties of Psammaquent and Plinthudult. *Journal of Soil Science and Plant Nutrition*, 17(3), 808–823. <https://doi.org/10.4067/S0718-95162017000300019>
- Mujtaba, G., Hayat, R., Hussain, Q., & Ahmed, M. (2021). Physio-chemical characterization of biochar, compost and co-composted biochar derived from green waste. *Sustainability*, 13(9), 4628.
- Niedziński, T., Łabętowicz, J., Stępień, W., & Pęczek, T. (2023). Analysis of the use of biochar from organic waste pyrolysis in agriculture and environmental protection. *Journal of Ecological Engineering*. <https://doi.org/10.12911/22998993/159347>
- Padilla, E. R. D., Nakashima, G. T., Hansted, A. L. S., Santos, L. R. O., De Barros, J. L., De Conti, A. C., & Yamaji, F. M. (2019). Thermogravimetric and FTIR analyzes of corn cob pyrolysis. *Quimica Nova*, 42(5), 566–569. <https://doi.org/10.21577/0100-4042.20170360>
- Pinky, N. S., Mobarak, M. Bin, Mustafi, S., Rahman, M. Z., Nahar, A., Saha, T., & Bahadur, N. M. (2023). Facile preparation of micro-porous biochar from Bangladeshi sprouted agricultural waste (corn cob) via in-house built heating chamber for cationic dye removal. *Arabian Journal of Chemistry*, 16(9), 105080.
- Pipíška, M., Krajčíková, E. K., Hvostik, M., Frišták, V., Ďuriška, L., Černíková, I., Kaňuchová, M., Conte, P., & Soja, G. (2022). Biochar from wood chips and corn cobs for adsorption of thioflavin T and erythrosine B. *Materials*, 15(4), 1492. <https://doi.org/10.3390/ma15041492>
- Qurat-ul-Ain, Firdaus-e-Bareen, & Shafiq, M. (2016). Management of the *Parthenium hysterophorus* through biochar formation and its application to rice-wheat cultivation in Pakistan. *Agriculture, Ecosystems and Environment*, 235, 265–276. <https://doi.org/10.1016/j.agee.2016.10.027>
- Qurat-ul-Ain, Shafiq, M., Capareda, S. C., & Firdaus-e-Bareen. (2021). Effect of different temperatures on the properties of pyrolysis products of *Parthenium hysterophorus*. *Journal of Saudi Chemical Society*, 25(3), 101197. <https://doi.org/10.1016/j.jscs.2021.101197>
- Sandeep, P. K. K. (2020). Evaluation of lead (Pb(II)) removal potential of biochar in a fixed-bed continuous flow adsorption system. *Journal of Health & Pollution*, 10(28), 1–15.
- Singh, B. B. P., Singh, B. B. P., Singh, B. B. P., Singh, B. B. P., Singh, B. B. P., Cowie, A., Cowie, A., A. B. S., B. B. P. S., & C, A. L. C. (2010). Characterisation and evaluation of biochars for their application as a soil amendment. *Soil Research*, 516–525. <https://doi.org/10.1071/sr10058>
- Singh, B., Shen, Q., Arbestain, M. C., Dolk, M. M., & Camps-Arbestain, M. (2017). Chapter 3. Biochar pH, electrical conductivity and liming potential biochar ageing effects on N and P dynamics: Mechanisms and controlling factors view project soils in the global agenda-ITPS-GSP?FAO View project 3 Biochar pH, electrical conductivity and li. *Biochar: A Guide to Analytical Methods*, March, 23–38. <https://www.researchgate.net/publication/319206365>
- Tao, Y., Feng, W., He, Z., Wang, B., Yang, F., Nafsun, A. I., & Zhang, Y. (2024). Utilization of cotton byproduct-derived biochar: a review on soil remediation and carbon sequestration. *Environmental Sciences Europe*, 36(1), 79.
- Vuong, T. X., Stephen, J., Nguyen, T. T. T., Cao, V., & Pham, D. T. N. (2023). Insight into the speciation of heavy metals in the contaminated soil incubated with corn cob-derived biochar and apatite. *Molecules*, 28(5), 1–23. <https://doi.org/10.3390/molecules28052225>
- Weisz, K. (2008). Ultraviolet Spectroscopy. *Nucleic Acids from a to z: A Concise Encyclopedia*, 322. <https://doi.org/10.1520/stp37187s>
- Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(5), 56. <https://doi.org/10.1038/ncomms1053>
- Wu, F., Li, F., Zhao, X., Bolan, N. S., Fu, P., Lam, S. S., Mašek, O., Ong, H. C., Pan, B., Qiu, X., Rinklebe, J., Tsang, D. C. W., Van Zwieten, L., Vithanage, M., Wang, S., Xing, B., Zhang, G., & Wang, H. (2022). Meet the challenges in the “Carbon Age.” *Carbon Research*, 1(1). <https://doi.org/10.1007/s44246-022-00001-9>
- Yang, W., Lu, C., Liang, B., Yin, C., Lei, G., Wang, B., Zhou, X., Zhen, J., Quan, S., & Jing, Y. (2023). Removal of Pb(II) from aqueous solution and adsorption kinetics of corn stalk biochar. *Separations*, 10(8). <https://doi.org/10.3390/separations10080438>
- Yang, Y., Ahmed, W., Ye, C., Yang, L., Wu, L., Dai, Z., Khan, K. A., Hu, X., Zhu, X., & Zhao, Z. (2024). Exploring the effect

of different application rates of biochar on the accumulation of nutrients and growth of flue-cured tobacco (*Nicotiana tabacum*). *Frontiers in Plant Science*, 15, 1225031. <https://doi.org/10.3389/fpls.2024.1225031>

Zhuo, Q., Liang, Y., Hu, Y., Shi, M., Zhao, C., & Zhang, S. (2023). Applications of biochar in medical and related environmental fields: current status and future perspectives. *Carbon Research*, 2(1), 32.