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Characterization of agro-waste (*Parthenium hysterophorus*) derived Carbon Dots and to assess their potential as a sustainable adsorbent

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ABSTRACT: Improper disposal of agricultural residues and the proliferation of the invasive weed *Parthenium hysterophorus* pose significant environmental threats. This study investigates the preparation and adsorbent properties of carbon dots (CDs) derived from *Parthenium hysterophorus* shoot biochar (PHS-BC) via bottom-up approach. The CDs were produced by varying PHS-BC dosage, magnetic stirring and centrifugation time, followed by vacuum filtration. Characterization results revealed that the CDs possess a slightly alkaline nature and high electrical conductivity, facilitating the attraction of cationic pollutants. Solid yields ranging from 6.97% to 31.9% were obtained CDs were prepared from more centrifugation time at low PHS-BC dosage and was identified as optimal for preparing CDs with high adsorptive qualities as per the results obtained from proximate analysis. Statistical analysis (one-way ANOVA and post-hoc Tukey tests) confirmed that centrifugation time was the primary determinant of elemental composition ($p < 0.05$), significantly enhancing carbonization. FTIR analysis confirmed that the surface functional groups remained chemically stable for all CDs prepared. The sample B1M4C3, B2M1C3 and B3M4C3 emerged as the superior adsorbents exhibiting highest predicted surface area. This research study demonstrates that while the chemical affinity of CDs is fixed by their precursor, their adsorptive capacity is highly tunable through physical conditions as their preparation time. This study provides a scalable, “green” alternative for contributing to the “Waste-to-Wealth” (WtW) paradigm and aligning with United Nations Sustainable Development Goals 6, 9, 12, and 13.

Key words: Adsorption, Biochar, Carbon Dots, *Parthenium hysterophorus*, Sustainable development goals

Agro-wastes are valuable raw materials and their mismanagement poses severe environmental and sanitary threats. Improper disposal of agro-waste through burning or burying contaminates soil, water and air, with estimates suggesting that 10–50% of agricultural products are discarded annually as waste (Moiceanu *et al.*, 2025). Beyond standard crop residues, the proliferation of the obnoxious weed *Parthenium hysterophorus* exacerbated these challenges. Known for causing severe allergic reactions and ecological imbalance, this invasive species is a biological hazard that requires urgent eradication. However, within the framework of a circular economy, such biomass holds untapped potential for conversion into high-value products, nutraceuticals and nano-materials, which can be done using various thermochemical or biochemical processes. These processes are effective for energy recovery “waste-to-energy” (WtE); however, they are frequently constrained by high operational complexity, significant capital investment and

potential for greenhouse gas emissions (Shah *et al.*, 2023). In comparison, the preparation of adsorbents from agro-waste can range from bulk solids to nano-engineered particles which are regarded as a superior strategy for environmental remediation due to its cost-efficiency, simplicity and scalability. This “waste-to-wealth” (WtW) approach utilizes abundant, carbon-rich precursors to effectively remove environmental pollutants through targeted surface functionalization with higher removal efficiencies (Zikalala *et al.*, 2022). While activated carbon and biochar are widely used adsorbents, they face limitations. Activated carbon production involves expensive chemical activators and high-energy regeneration. Biochar, though excellent for soil, often lacks the fine-tuned surface chemistry required for ultra-trace pollutant removal. A transformative solution lies in the preparation of carbon dots (CDs) from agro-waste using the “bottom-up” approach as it is increasingly favoured due to its superior efficiency, scalability and the

ability to precisely control the final adsorbent's properties. Among various "bottom-up" approaches, pyrolysis stands out as an exceptionally effective method (Kong and Zhou, 2024).

The shift toward these sustainable, WtW nano-materials represents a necessary response to the global environmental crisis, contributing directly to the United Nations Sustainable Development Goals (UN-SDGs) (Atchudan *et al.*, 2023). CDs ensure 'Clean Water and Sanitation' (SDG-6) by providing a low-cost, high-efficiency method for removing pollutants and ensuring availability of clean water; 'Industry, Innovation and Infrastructure' (SDG-9) by utilizing agro-waste for preparation of sustainable adsorbents; 'Responsible Consumption and Production' (SDG-12) by repurposing agro-waste biomass that would otherwise be burned and 'Climate Action' (SDG-13) by transforming agro-waste into stable, solid-state CDs effectively sequestering carbon and minimizing the greenhouse gas footprint of waste management.

Keeping this in view, the present study was undertaken with the objectives to explore the influence of varying dosing, stirring and centrifugation conditions on the yield and adsorptive qualities of carbon dots from agro-waste (*Parthenium hysterophorus*); to identify the potential of carbon dots as adsorbents by comprehensively analysing their pH, electrical conductivity (EC), yield, proximate, ultimate analysis, surface functional groups and predicted surface area of carbon dots prepared from agro-waste (*Parthenium hysterophorus*).

MATERIALS AND METHODS

Preparation of Carbon Dots (CDs)

Shoots of *Parthenium hysterophorus* (PHS) was harvested from GBPUA&T, Pantnagar, was surface-sterilized with 70% ethanol, desiccated and pulverized prior to slow pyrolysis at 350°C (10°C/min; 180 min residence time) for biochar (PHS-BC) synthesis (Naudiyal and Srivastava, 2024). CDs were prepared by dispersing PHS-BC in aqueous solution (0.05–0.15 g/10mL) followed by magnetic stirring

(0–45 min), centrifugation at 12,000 rpm (0–20 min) and 0.22 µm vacuum filtration for subsequent characterization (Zhu *et al.*, 2013). The experimental setup and schematic diagram for CDs preparation from PHS-BC is given in Figure 1(a) and 1(b), respectively.

Characterization methods

The pH and electrical conductivity (EC) of the CDs prepared were measured using Hach HQ4300 Portable Multiparameter (Rajkovich *et al.*, 2012). Solid yield (SY) of CDs was expressed as percentage weight of the amount of CDs obtained (W_c) from the weight of the amount of PHS-BC fed (W_b).

$$\text{Solid Yield (SY)} = \frac{W_c}{W_b} \times 100 \quad (1)$$

Moisture content (MC), ash content (AC) and volatile matter (VM) content, was carried out following the protocols established by ASTM International Standards: ASTM 871-82 (2006), ASTM-D 3174-04 (2009) and ASTM-D 3175-07. The fixed carbon (FC) content was calculated by subtracting the MC, AC, and VM content from 100% on a dry basis. The ultimate analysis was done using a CHNS elemental analyser (Model: Vario EL cube). The influence of physical conditions on the elemental carbon content was statistically evaluated using one-way Analysis of Variance (ANOVA) and further significant differences between the experimental groups were further delineated using

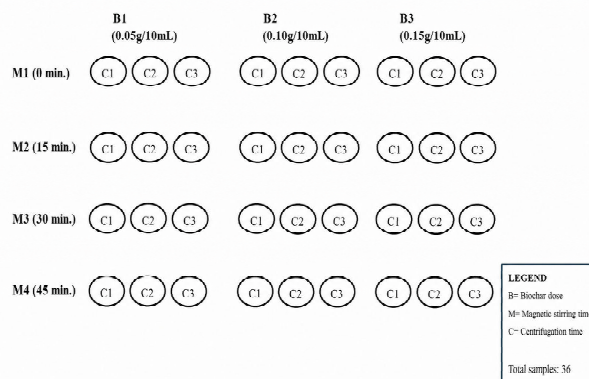


Fig. 1(a): Experimental setup for the preparation of Carbon Dots (CDs) from *Parthenium hysterophorus*-biochar (PHS-BC)

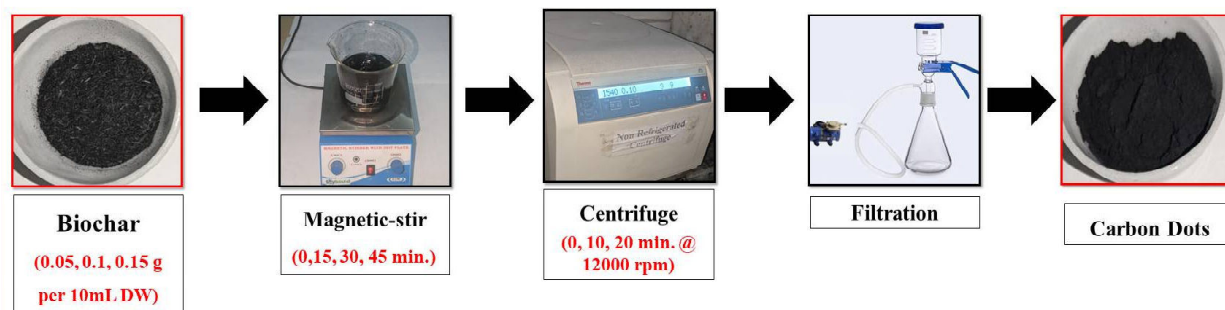


Fig. 1(b): Schematic diagram for the preparation of Carbon Dots (CDs) from *Parthenium hysterophorus*-biochar (PHS-BC)

Tukey's Honestly Significant Difference (HSD) post-hoc analysis. Chemical functional groups of CDs were evaluated by FTIR spectrum analysis. The spectra were recorded in the range of 4000-600 cm^{-1} in transmission mode using FTIR-8400S spectrophotometer manufactured by Shimadzu. BET surface area analyses were conducted by a BELSORP-maxII from Microtrac BEL Corp. The CDs samples were preheated @ 200°C for 12 hours, leak check and vacuum degree values before measurement were found to be 0.0000 Pa/min and 4.6641E-05 Pa, respectively.

RESULTS AND DISCUSSION

Effect of pH and EC of CDs and their adsorbent quality

The preparation of CDs samples have different physical conditions and not chemical conditions,

therefore, pH and EC variation is not notable enough, as shown in Table 1. The average mean pH of the prepared CDs, as shown in Figure 2(a), was found to be slightly alkaline (9.09 ± 0.09). This suggests that the prepared CDs as adsorbents are negatively charged and thus will attract cations (Ozcan *et al*, 2024). The EC of the prepared CDs as shown in Figure 2(b) was found to have an average mean of $3377.58 \pm 3.97 \mu\text{S/cm}$ which was higher than their precursor i.e., PHS-BC ($3158 \mu\text{S/cm}$) this suggests CDs have more stable energy levels, greater heat of adsorption and smaller distances between adsorbate and the adsorbent as compared to their precursors (Naudiyal and Srivastava, 2024).

Effect of solid yield (SY) of CDs and their adsorbent quality

The highest SY was observed in sample B1M1C1 (98.51%) followed by B2M3C1 (97.21%) and

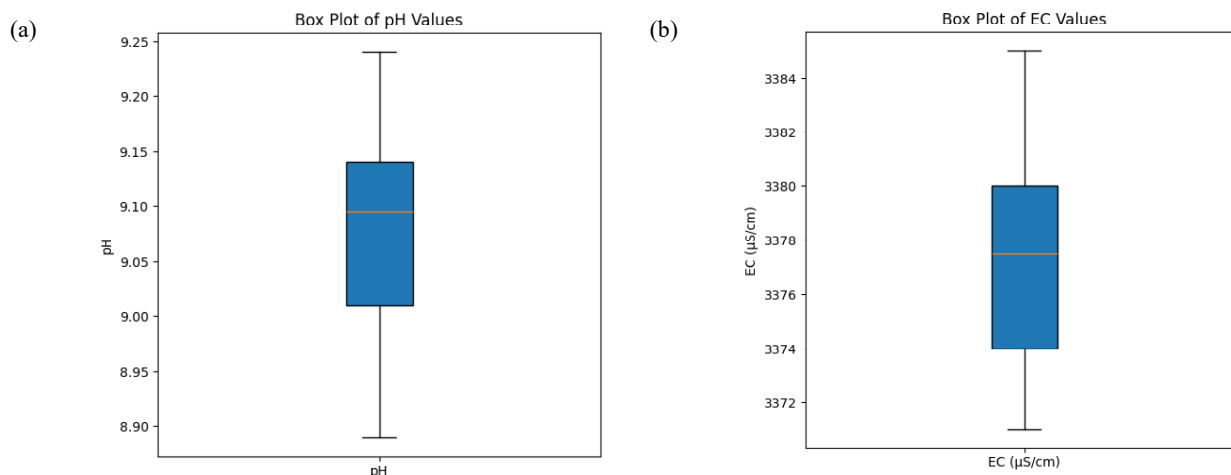


Fig. 2: Average mean of (a) pH, and (b) EC values for all prepared CDs samples

Table 1: Physico-chemical properties, solid yield (SY) and elemental composition of prepared carbon dots (CDs)

S. No.	Sample	pH	EC ($\mu\text{s}/\text{cm}$)	SY (%)	Carbon (%)	Hydrogen (%)	C/N ratio	C/H ratio
1.	B1M1C1	9.14	3380	98.51 [#]	59.66	2.15	14.95	27.75
2.	B1M1C2	9.1	3384	16.66	60.64	2.09	15.43	29.01
3.	B1M1C3	9.14	3380	26.04	61.73	2.02	15.83	30.56
4.	B1M2C1	9.24	3377	88.32	59.96	2.13	15.18	28.15
5.	B1M2C2	9.24	3380	17.18	62.03	2	15.74	31.02
6.	B1M2C3	9.09	3376	13.86	60.45	2.1	15.58	28.79
7.	B1M3C1	9.05	3374	81.74	58.93	2.2	14.77	26.79
8.	B1M3C2	9.1	3374	20.32	62.15	1.99	15.65	31.23
9.	B1M3C3	9.01	3375	17.94	60.76	2.08	15.54	29.21
10.	B1M4C1	8.95	3378	87.06	58.4	2.23	14.71	26.19
11.	B1M4C2	9.1	3371	10.32	62.27	1.99	15.89	31.29
12.	B1M4C3	9.2	3377	17.72	63.28 [#]	1.92 [*]	16.23	32.96 [#]
13.	B2M1C1	8.98	3382	84.64	58.17 [*]	2.25 [#]	14.54 [*]	25.85 [*]
14.	B2M1C2	8.98	3380	25.43	61.13	2.06	15.52	29.67
15.	B2M1C3	9.08	3379	22.31	62.91	1.95	16.17	32.26
16.	B2M2C1	9.15	3385	83.46	59.74	2.15	15.01	27.79
17.	B2M2C2	8.89	3374	16.92	60.68	2.09	15.48	29.03
18.	B2M2C3	9.23	3381	18.93	60.9	2.07	15.62	29.42
19.	B2M3C1	9.11	3371	97.21	60.76	2.08	15.38	29.21
20.	B2M3C2	9.1	3375	13.93	61.47	2.04	15.64	30.13
21.	B2M3C3	9.03	3377	21.68	61.57	2.03	15.79	30.33
22.	B2M4C1	9.05	3380	79.03	59.21	2.18	14.84	27.16
23.	B2M4C2	9.15	3384	17.01	61.96	2.01	15.65	30.83
24.	B2M4C3	9.18	3375	17.37	62.58	1.97	16.01	31.77
25.	B3M1C1	8.99	3374	79.87	59.16	2.19	15.02	27.01
26.	B3M1C2	8.98	3372	21.79	61.75	2.02	15.75	30.57
27.	B3M1C3	9.1	3375	17.71	62.58	1.97	16.17	31.77
28.	B3M2C1	9.1	3380	79.59	58.36	2.24	14.55	26.05
29.	B3M2C2	8.9	3378	11.79	62.16	1.99	15.82	31.24
30.	B3M2C3	9.01	3374	10.39	61.39	2.04	15.82	30.09
31.	B3M3C1	9.06	3372	84.19	61.29	2.05	15.52	29.90
32.	B3M3C2	9.14	3381	9.87	60.67	2.09	15.52	29.03
33.	B3M3C3	9.18	3383	31.90	61.86	2.01	15.86	30.78
34.	B3M4C1	9.05	3378	77.16	59.75	2.15	15.09	27.79
35.	B3M4C2	8.89	3384	6.97 [*]	61.66	2.03	15.65	30.37
36.	B3M4C3	9.04	3373	10.64	63	1.94	16.28 [#]	32.47

[#]highest value, ^{*}lowest value.

B1M2C1 (88.32%). The lowest yield was observed in sample B3M4C2 (6.97%) followed by B3M3C2 (9.87%) and B1M4C2 (10.32%), as shown in Table 1. It was observed that the highest SY percentages were achieved when the centrifugation time was set to 0 minutes (C1). However, the absence of centrifugation in these cases likely resulted in the retention of larger particles within the CDs, thereby suggesting that the overall adsorbent quality of the resulting samples was compromised (Sun *et al.*, 2006). When centrifugation was applied (C2 or C3) during CDs preparation, the SY was found to be between 6.97% and 31.9%, indicating the effective

removal of larger particles and improvement in the overall adsorbent quality of the prepared CDs. Based on the SY, the optimal conditions were identified as a centrifugation time of 10 (C2) or 20 minutes (C3) and a low PHS-BC dose (Zhu *et al.*, 2013). However, no definitive conclusion could be drawn regarding SY and the effect of magnetic stirring time.

Effect of proximate analysis parameters of CDs and their adsorbent quality

The carbon surface captures the pollutants and a higher FC content indicates a larger carbon surface area. Therefore, high FC content is the main factor

in the proximate analysis for adsorbent properties. It is also desirable for an adsorbent to have low AC and low MC. Nevertheless, high VC is not desired as it fill-up the pores of the adsorbent, resulting in a reduction of the surface area and consequential adverse effects on the adsorption properties (Bautista *et al.*, 2025).

The comparative evaluation of all CDs samples for proximate analysis (Figure 3) with the physical conditions reveals clear trends in adsorbent performance. Among the samples, B1M4C3 exhibited the most favourable characteristics, with high FC and low MC, indicating superior structural stability and enhanced adsorption potential. Similarly, samples B2M1C3, B3M4C3, B3M2C3 and B2M4C3 ranked within the top five contenders for adsorption potential on the basis of high FC and low MC, highlighting the critical role of optimized process conditions in maximizing adsorbent

efficiency. Lowest AC is observed in sample B2M3C1 (29.26%) followed by B2M2C2 (29.78%) and B3M1C2 (29.94%). These results correspond with the high FC and low MC as discussed earlier. Low AC was observed mostly in samples where the centrifugation time is kept at 10 minutes (C2). Its lower value indicates superior adsorption of pollutants.

CDs prepared from low dosage (B1) gave the adsorbents like B1M4C3 with higher carbonization (high FC) followed by medium (B2) and high (B3) dosage. The results suggests that lower to medium PHS-BC dosages (B1 and B2), when combined with prolonged magnetic stirring (M4), improve carbon homogeneity and activation, leading to better adsorption properties as per the results of proximate analysis. Furthermore, centrifugation for 20 minutes (C3) was consistently present in all CDs samples having low AC, MC and high FC adsorbents,

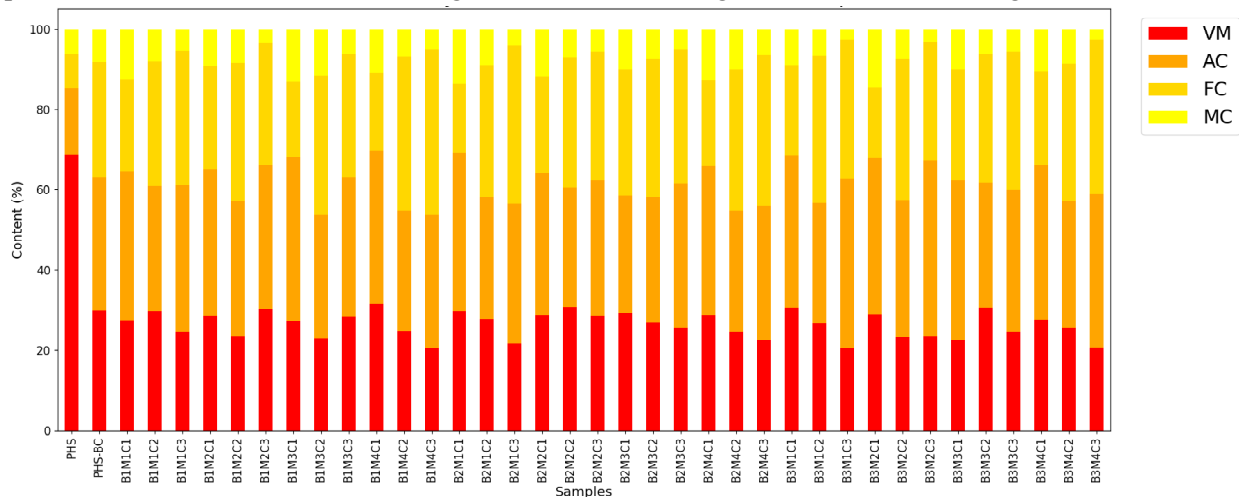


Fig. 3: Proximate analysis for PHS, PHS-BC and all CDs samples

Table 2: One-way Analysis of Variance (ANOVA) and post-hoc Tukey HSD test results for carbon (%) content across physical preparation factors

Element	Factor	F	p-value
Carbon (%)	Biochar dose	0.13	0.88
Carbon (%)	Magnetic stirring time	0.41	0.75
Carbon (%)	Centrifugation time	29.21	0.00

C% across centrifugation						
group1	group2	mean diff	p-adj	lower	upper	reject
C1	C2	2.09	0	1.24	2.95	TRUE
C1	C3	2.47	0	1.61	3.32	TRUE
C2	C3	0.37	0.54	-0.49	1.23	FALSE

underscoring its importance in enhancing their adsorbent properties.

Effect of Ultimate analysis of CDs and their adsorbent qualities

The statistical tool one-way ANOVA applied on the results obtained from ultimate analysis (Table 1) revealed that centrifugation (C) was the only physical parameter that significantly influenced the carbonization composition of the CDs, while PHS-BC dose (B) and stirring time (M) showed no significant effects (all $p > 0.05$), as shown in Table 2.

Post-hoc Tukey analysis revealed that increasing centrifugation time (C1→C3) caused a progressive increase in carbon content and ultimately carbonization, as shown in Table 2, which is associated with higher hydrophobicity and affinity for non-polar organic pollutants (Tan *et al.*, 2015).

Effect of FTIR spectra of CDs and their adsorbent qualities

The FTIR spectra of the CDs samples, as shown in Figure 4 (a-d), provide critical evidence of the surface chemistry about their potential as an

adsorbent of all sample (Ahmad *et al.*, 2014). The presence of specific oxygen-containing and aromatic functional groups which includes (C–C), (C=C), (C–H), hydroxyl (O–H), carbonyl (C=O) and aromatic skeletal (C=C), suggests that these carbon dots (CDs) are well-equipped for environmental remediation, revealing a high degree of spectral congruence. Consequently, the surface functionalization remains unchanged across the different preparation parameters (M1-M4 and C1-C3), suggesting that the CDs inherit their adsorptive qualities directly from the stable chemical framework of their precursor (PHS-BC) without undergoing further chemical modification.

Effect of BET predicted surface area of CDs and their adsorbent properties

Although surface functional groups on all CDs samples remain constant, there was variation in predicted surface area of all CDs samples (Figure 5). While the functional groups provide the “affinity” for pollutants, the surface area provides the “capacity.” A higher BET predicted surface area indicates a greater density of these pre-existing active sites per unit mass. The highest predicted

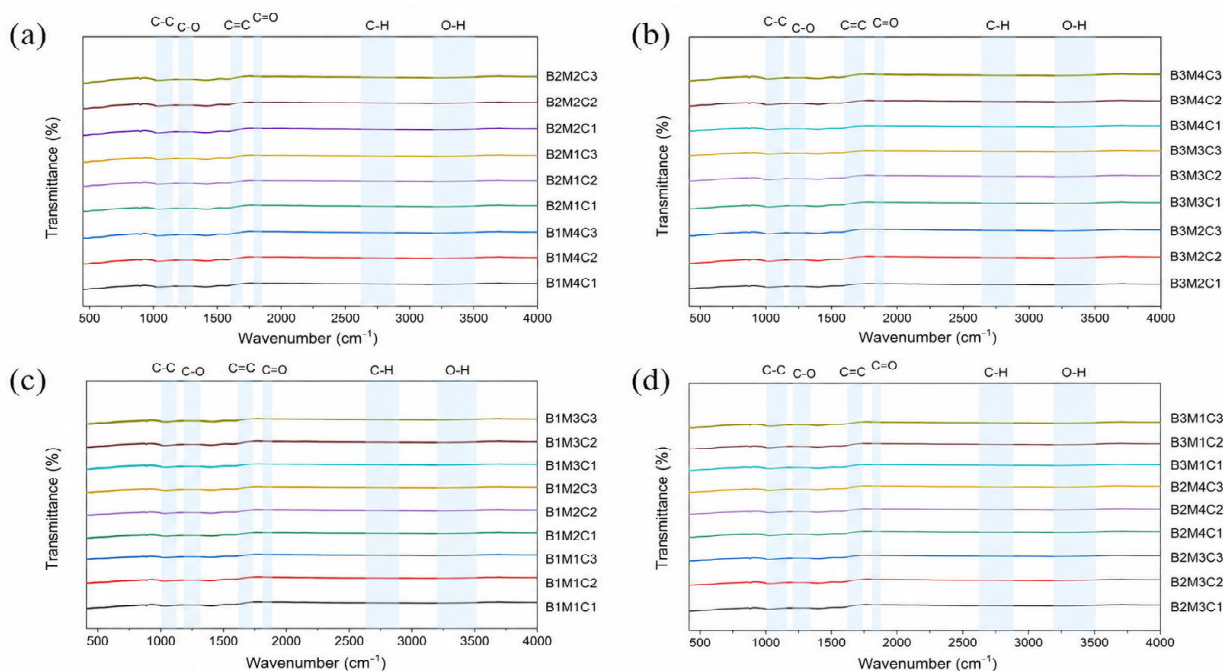


Fig. 4: FTIR spectra for all the prepared CDs samples

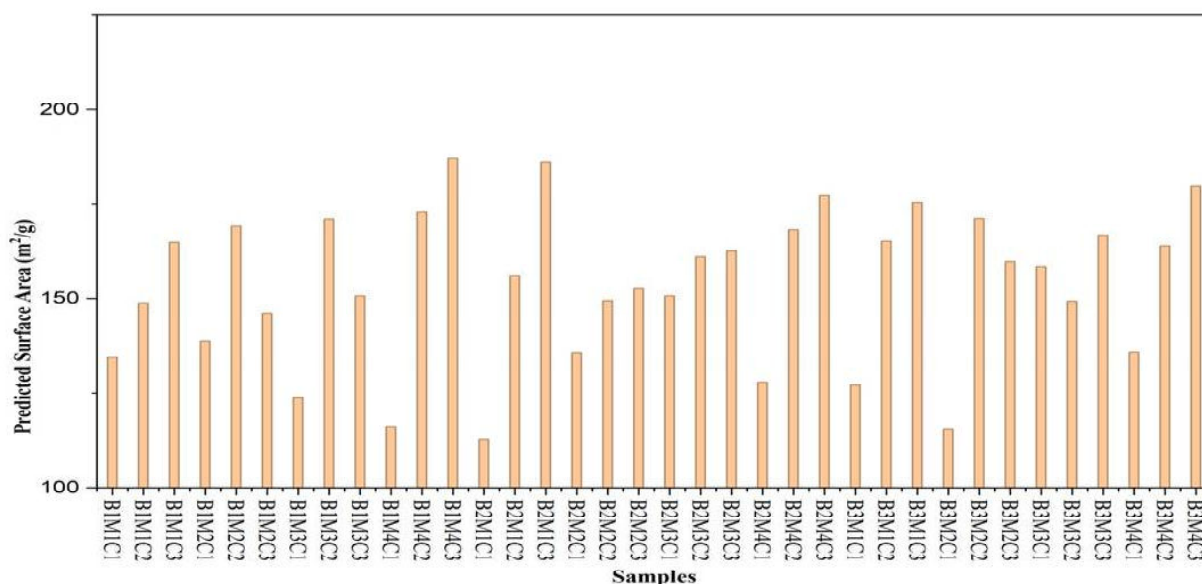


Fig. 5: BET analysis for all the prepared CDs samples

surface area is found on sample B1M4C3 (187.10 m²/g) followed by B2M1C3 (186.08 m²/g), B3M4C3 (179.64 m²/g) and B2M4C3 (177.36 m²/g) (Kuyucu, 2025).

Selection of potential adsorbent and their adsorbitive efficacy for environmental remediation

Based on the integration of BET surface area, fixed carbon content and yield, the following three samples were identified as the superior adsorbents for environmental remediation: B1M4C3 (0.05 g biochar, 45 min stirring, 20 min centrifugation) was identified as the flagship adsorbent as it exhibited the highest BET surface area (187.10 m²/g) and the maximum FC content (41.30%) observed in the study. Following closely were B2M1C3 (186.08 m²/g) and B3M4C3 (179.64 m²/g and FC content of 63%). These variants represent the optimal balance of physical and chemical refinement. The centrifugation step refined the carbon composition, increasing carbon content to 63.28% in B1M4C3 and fostering a more condensed, hydrophobic core suitable for the sequestration of non-polar pollutants.

CONCLUSION

The present study successfully demonstrated the

transformation of the obnoxious weed *Parthenium hysterophorus* into functionalized CDs through a combination of slow pyrolysis and physical exfoliation. By systematically varying the biochar dosage, stirring time, and centrifugation duration, the research established a clear relationship between processing parameters and the physico-chemical properties of the resulting adsorbents. The preparation method successfully preserves the potent functional groups of the precursor (PHS-BC) while optimizing the physical interface required for maximum pollutant removal. The identification of the superior adsorbents highlights that precise control over centrifugation and dosage is essential for maximizing the structural stability and active site density of nano-scale CDs. This dual-efficiency makes them ideal candidates for low-cost, sustainable environmental remediation as adsorbents aligned with global circular economy goals. In conclusion, this research provides a viable blueprint for achieving UN-SDGs by converting agricultural liabilities into valuable environmental assets. Future work should focus on testing the adsorption kinetics of these optimized CDs against specific heavy metals and complex industrial effluents to further validate their commercial potential in large-scale water

treatment systems.

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