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ORIGINAL RESEARCH PAPER

Human hair biochar to remove malachite green dye and bisphenol-A contamination

M. Kamaraj[1,*], P. Kamali[2], R. Kaviya[2], K. Abishek[2], B. Navinkumar[2], T.G. Nithya[3], L.S. Wong[1], J. Aravind[4]

[1] *Life Science Division, Faculty of Health and Life Sciences, INTI International University, Nilai 71800, Malaysia*

[2] *Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology -Ramapuram, Chennai- 600089, Tamil Nadu, India*

[3] *Department of Biochemistry, College of Science and Humanities, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu 603203, India*

[4] *Department of Biotechnology, Dr G.R. Damodaran College of Science, Civil Aerodrome Post, Coimbatore- 641014, Tamil Nadu, India*

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ABSTRACT

BACKGROUND AND OBJECTIVES: Exposure to endocrine-disrupting chemicals and organic dye pollution is associated with an increased risk of toxicity, hazard, and cancer due to their widespread use. Exogenous endocrine disruptors are responsible for interfering with reproduction and development because they can either stimulate or decrease endogenous hormone responses. This work explores the feasibility of human hair biochar as a potential adsorbent for possible solid waste management processes to minimize environmental pollution. Malachite green and bisphenol-A were selected as model pollutants, and the response surface methodology was used to identify the maximal removal of these hazardous substances.

METHODS: Samples of human hair waste are collected and processed. After air drying for 24 hours, it was carbonized in a hot air oven at 200 degrees Celsius for 3 hours to obtain the human hair biochar. The biochar was subjected to various instrumental analyses to ascertain the characteristics of the biochar. Both malachite green and bisphenol-A adsorption experiments are performed in a batch method. Initial pollutant concentration (100 milligrams per liter), the volume of pollutant solution (50 milliliters), temperature (37 degrees Celsius), and agitation speed of orbital shaker (150 rotation per minute) are established as constants in this investigation. Data obtained from an Ultra Violet-Visible spectrophotometer was used to design expert software to calculate adsorption efficiency. Data variables A, B, and C included the potential of hydrogen (3, 6, 9), duration (60, 150, 240 minutes), and adsorbent dose (0.1, 0.3, 0.5 gram per liter) in the Response Surface Methodology experiment.

FINDINGS: The human hair biochar is characterized by analytical methods, and Brunauer, Emmett, and Teller analysis revealed that it has a porous nature and extensive surface area, an amorphous structure, and various functional groups. The efficiency of adsorbent investigated over Malachite green and bisphenol-A in a batch experiment and performance variation of three parameters: A: potential of hydrogen (3, 6, 9), B: duration (60, 150, 240 minutes), and C: Human hair biochar dose (0.1, 0.3, 0.5 gram per liter) were evaluated via box-behnken design. Through analysis of variance and numerical expectation, the optimal potential of hydrogen, duration, and Human hair biochar dose was predicted as 3, 150 minutes, and 0.5 grams per liter, which resulted in a maximum removal of 96 percent for malachite green and 83 percent for bisphenol-A.

CONCLUSION: This study demonstrated the facile heat-assisted development of biochar from human hair waste as a potential candidate for environmental remediation. The topography, structure, surface area, and functional group analysis of human hair biochar were carried out using analytical techniques that reveal the biochar has the potential for adsorbent characteristics. The adsorption efficiency of human hair biochar was demonstrated for malachite green (96 percent) and bisphenol-A (83 percent) response surface methodology under optimal conditions. The results suggested the model's relevance for the sorption of dyes and contaminants. The current study concludes that biochar can be prepared using a less expensive method and can be an alternate option to remove the dyes and other emerging contaminants in the aqueous matrix.

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*Corresponding Author:
Email: *drkamarajm@gmail.com*
Phone: +9197 8950 5023
ORCID: 0000-0002-0111-8524

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INTRODUCTION

Human activities are a major contributor to water pollution because of the pollutants in rivers, lakes, and wells. Exposure to endocrine-disrupting chemicals and organic dye pollution is associated with an increased risk of toxicity, hazard, and cancer due to their widespread use in industry (Mathew and Saravanakumar, 2023). The usage of malachite green, an organic chemical, as a dyestuff and, more controversially, as an antibiotic in aquaculture, has caused environmental harm to aquatic creatures by disrupting the food chain in the aquatic ecosystem (Sharma *et al.,* 2023). Exogenous EDCs are responsible for interfering with reproduction and development because they can either stimulate or decrease endogenous hormone responses (Czarny-Krzymińska *et al*., 2023). Even at low doses, bisphenol-A (BPA) can have a deleterious effect on the reproductive system, making it one of the most widely produced EDCs utilized in a wide range of industrial uses around the world every day (Czarny-Krzymińska *et al*., 2023). It is well-documented that malachite green (MG) and BPA may be found in waterways all over the globe. It is crucial to focus on removing these from environmental matrices. There are several methods for cleaning wastewater, and they all have advantages and disadvantages (Kasera *et al.,* 2022). Adsorption is one simple method for treating wastewater that does not require complex machinery or equipment. Biochar is a byproduct of waste biomass pyrolysis and a promising environmentally friendly adsorbent for wastewater treatment (Tan *et al., 2016*). Rapid urbanization and industrialization have resulted in an increase in biowaste that cannot be degraded by natural means and must be disposed of at a cost (Wan *et al.,* 2020). The vast majority of biomass can be used as feedstock for biochar production, as summarized by Xiaorui and Haiping, (2023). Biochar alteration using nitrogen doping has garnered attention in recent years. Not all biomass is created equal; some naturally have a higher N content. Because it is made of keratin protein, human hair has exceptional mechanical qualities and is one of the biological fibers with which we are most familiar. Hair waste may be a good choice for biochar manufacture since it includes more nitrogen, phosphorus, and sulfur than other lignocellulosic wastes (Li and Jiang, 2017). Biochar can be made using many processes, including pyrolysis, hydrothermal carbonation, torrefaction, and microwave-assisted pyrolysis. Recent studies on environmental remediation have concentrated on using biochar and biochar-based adsorbents to remove pollutants from aqueous media (Praveen *et al.,* 2022; Tareq *et al.,* 2019). The features of such materials largely depend on the nature of the feedstock biomass, the conditions under which they are prepared, and the synthesis processes used (Shakoor *et al.,* 2020). The primary elements, such as superficial functional groups, surface charge and area, potential of hydrogen (pH), and porosity, influence the nature of biochar. These characteristics are responsible for the adsorptive performances of biochars (Praveen *et al.,* 2022). As a result, biochar produced significantly contributes to meeting the adsorbent needs, and it is widely regarded as a treatment method that is both efficient and inexpensive (Goswami *et al.,* 2022; Jha *et al.,* 2023). Various adsorbents have been vastly explored for removing hazardous dyes from the environment (Kumar *et al.,* 2023) and emerging contaminants like EDCs (Harsha *et al.,* 2023). Various biochar has also been infinitely reported in literature to remediate environmental pollutants like dyes and EDCs (Cho *et al.,* 2023; Zhang *et al.,* 2023). The global market is constantly looking for new sources of funding, subsidies, and profits, particularly in the rapidly expanding climate market, there is a risk that each will serve to promote and support the other as co-products from biomass. Despite the widespread use of human hair-based adsorbents like hydrochared biochar (Isik *et al.,* 2022; Yabalak and Eliuz, 2023), there has been little work reported on the facile, one-step synthesis of biochar from human hair waste which could be an ideal adsorbent for the dyes and EDCs. The purpose of this study was set to convert the waste in to value added product such as an adsorbent as a potential candidate for environmental remediation. The current study aims to harness a cost-effective method to obtain Human hair biochar and explore the feasibility to remediate dye and bisphenol-A. It is astonishing that there are huge gaps in understanding about biochar that need to be filled before any scientific claims about its benefits can be made; to do this, response surface methodology-based optimization studies are integrated. This study has been carried out in Chennai, TamilNadu, India in 2023.

MATERIALS AND METHODS

The methodology is designed in two major parts: biochar preparation from human hair waste and characterization. The characterized adsorbent is further tested using optimization studies for their pollutant removal efficiency using malachite green dye and bisphenol-A.

Biochar preparation and characterization

Samples of human hair waste are collected from a hair salon in Chennai, Tamil Nadu, India. The gathered human hair as 250 grams (g) was washed three times in tap water and once in distilled water to remove any remaining debris and dust. After air drying for 24 hours (h), it was carbonized in a hot air oven at 200 degree Celsius (°C) for 3 h. To characterize and apply the carbonized sample for the adsorption experiment, it was collected and ground into a fine powder using a mortar and a pestle. To learn about the human hair biochar (HHBC) topographical features, researchers use a scanning electron microscope (SEM) (Thermo scientific Apreo S) study. An energy-dispersive X-ray spectrometer (EDS) is paired with SEM to analyze elemental composition. Brunauer, Emmett, and Teller (BET) method is used to measure the surface area of HHBC and to ascertain the chemical composition and crystal structure of HHBC, X-ray diffraction (XRD) pattern analysis was performed using a BRUKER USA D8 Advance, Davinci. Using a fourier transform infrared (FTIR) spectrometer (SHIMADZU, IRTRACER 100) with a scan range of 400-4000 per centimeter (cm), HHBC pellets analyzed made by combining Potassium bromide (KBr) salt and materials.

RSM Box-Benken design

Both MG and BPA adsorption experiments are performed in a batch method. Initial pollutant concentration (100 milligrams per liter (mg/L), the volume of pollutant solution [50 milliliters (mL)], temperature (37 °C), and agitation speed of orbital shaker: 150 rotation per minute (rpm) are established as constants in this investigation. Design Expert Software used Data from a ultra violet (UV)-visible spectrophotometer (SHIMADZU UV 3600 PLUS) to calculate adsorption efficiency. Data variables A, B, and C included pH (3, 6, 9), duration [60, 150, 240 minutes (min)], and HHBC dose [0.1, 0.3, 0.5 gram per liter (g/L)] in a central composite- Box Behnken design - response surface methodology (BBD-RSM) experiment. 17 experimental runs were conducted, each with its variables and parameters. Analysis of variance (ANOVA) was used to assess the statistical significance of the model and the regression term, and an empirical polynomial equation was used to generate the regression model of the experimental data (Aravind *et al.,* 2016). Design expert software 10.0 is used to forecast experimental data, then compared against actual experimental data (Tables 1 and 2). The optimum conditions predicted in the design were performed in a real-time experiment, and the adsorption efficiency was recorded using a UV-visible spectrophotometer.

RESULTS AND DISCUSSION

The produced HHBC was characterized to study their properties, including morphological, elemental, structural, and functional group analyses. The obtained results of the characterization studies are illustrated in Fig. 1. Due to the release of volatiles and other pyrolysis gases from the human hair waste during treatment at the given temperature, the surface of the HHBC has pores of varying widths (Fig. 1a), as indicated by the SEM study (Yeboah *et al.,* 2020). The SEM images revealed the unequal distribution of the pores, and pore size distributions are observed as meso-pores (1-2 nm) and micro-pores (2-50 nm). The pore volume is observed as 0.117 (cubic centimeter/gram). The organic content in the human hair was cracked, and the C=O and hydrogen-containing functional groups were volatilized to produce the pore structure in the carbon material (Song *et al*., 2021). Fig. 1b displays the EDS analysis of HHBC, which shows that the sample mainly consisted of carbon 46.12 percent (%), nitrogen (19.20%), and oxygen (34.69%). Compared to the EDS analysis of pumpkin peel biochar generated by Bal *et al.* (2021), the pattern is highly congruent. The HHBC's surface area is measured as 10.323 square meter per gram (m^2/g) by the BET method. An amorphous structure due to disordered stacking carbon rings is indicated by a broad diffraction peak in the region 2Θ = 10-30° (Fig. 1c), which is indexed as C (002). Sawdust-based biochar (Hassaan *et al.,* 2023) and biochar made from Palm Kernel shell waste (Yeboah *et al.,* 2020) showed a similar XRD pattern. FTIR analysis (Fig. 1d) shows HHBC has various functional groups. S=O peaks, C=C peaks, and O-H stretches can all be found in the HHBC, with observed maxima at 1028/cm, 1622/

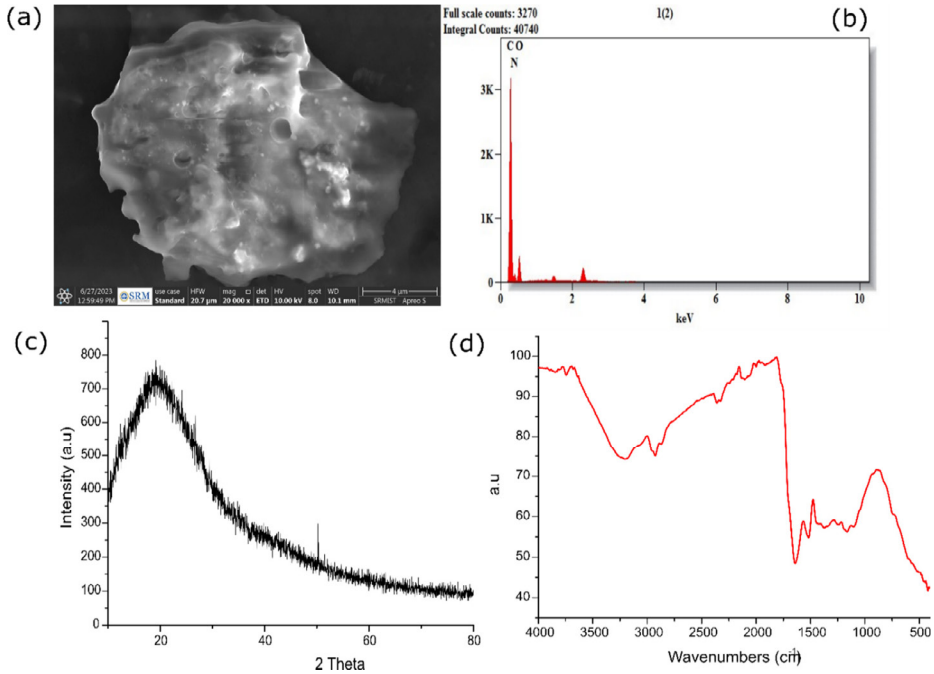

Fig. 1: Characterisation of HHBC: (a) FESEM analysis, (b) EDS analysis, (c) XRD spectrum and (d) FTIR spectrum of HHBC

Table 1: BBD design MG and BPA removal by HHBC

Standard order	Run	Factor 1 A: pH	Factor 2 B: Time (min)	Factor 3 C: Dose (g/L)	Response 1 MG degradation (%)	Response 2 BPA degradation (%)
10	1	6	240	0.1	55	43
11	2	6	60	0.5	84	66
2	3	9	60	0.3	72	53
3	4	3	240	0.3	76	74
17	5	6	150	0.3	86	76
7	6	3	150	0.5	96	83
14	7	6	150	0.3	86	76
16	8	6	150	0.3	86	76
4	9	9	240	0.3	69	54
8	10	9	150	0.5	78	67
6	11	9	150	0.1	73	54
12	12	6	240	0.5	84	62
13	13	6	150	0.3	86	76
15	14	6	150	0.3	86	76
9	15	6	60	0.1	69	40
1	16	3	60	0.3	82	74
5	17	3	150	0.1	66	50

cm, and 3268-3500/cm. The findings are consistent with those found in Algal kombucha biochar, as reported by Pathy *et al.* (2022). Compared with the literature, the functional group presence and variation in the material might be due to the variation of synthesis temperature used in this study and the organic character of the human hair. Adsorption of contaminants can be greatly aided by oxygen-containing groups, aromatic/phenolic groups, and hydroxyl and carboxyl groups present on the surface

Table 2: Factors and levels used in the design

Independent factor (unit)	Real values of coded levels		
	−1	0	+1
pH (A)	3	6	9
Duration (B)	60	150	240
HHBC dose (C)	0.1	0.3	0.5

−1, 0, and +1: Factor at a low, medium, and high level

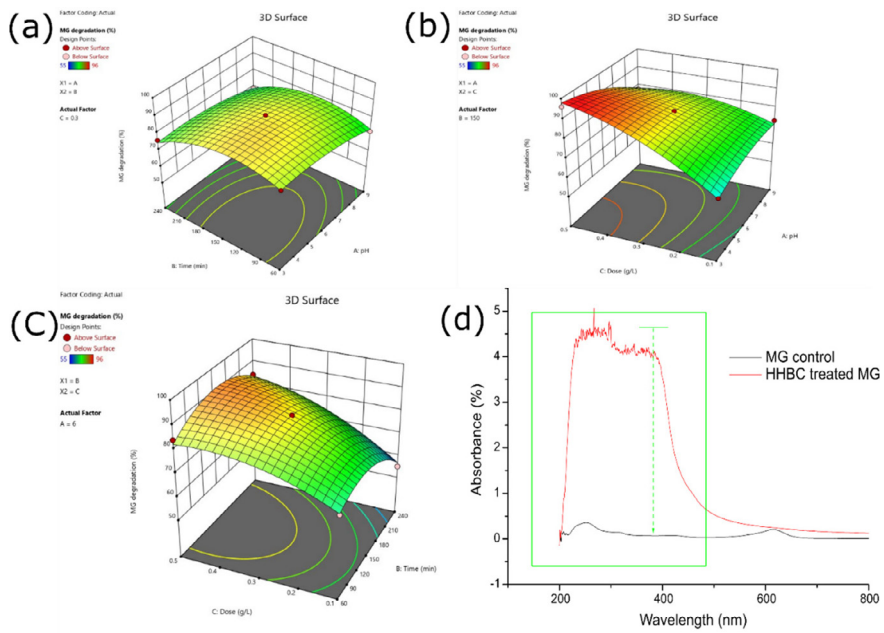

Fig. 2: MG removal optimization by HHBC. Response surface plot (a,b,c) for the interaction of pH, time, and HHBC dose on MG removal efficiency (The color changes from blue to red, indicating the increment of removal rate). (a) plot for pH and time, (b) plot for pH and HHBC dose, and (c) plot for time and HHBC dose. The UV-Vis spectroscopy analysis of actual MG removal experiment on optimum conditions (d)

of biochar (Li and Jiang, 2017). A cationic dye like MG can be bound via anionic carboxylic groups; OH groups may aid in forming coordinating bonds with MG (Omar *et al.*, 2018).

The most important factors for the MG and BPA removal by HHBC were optimized with the help of a Box-Behnken design (BBD). Table 1 shows the design matrix and the results of 17 tests evaluated with the BBD, whereas Table 2 supplied the higher and lower factors. The ANOVA-obtained regression equation describes the relationship between pH, time, HHBC dose, and MG and BPA sorption capacities. Surface plot graphs depict the impact of these variables on the sorption of MG dye (Fig. 2) and BPA (Fig. 3). Adsorption was sensitive to both the nature of the pollutants to be removed and the pH of the solution. It affects not only the adsorbate's speciation but also the degree of ionization and the surface charge of the adsorbent (Pathy *et al.*, 2022). At a pH of 3.0, HHBC has the maximum adsorption capacity for BPA due to the formation of an electron receiver-giver interaction between the two molecules and a strong hydrogen bond (Katibi *et al.*, 2021). Also, similar to the trend described for the removal of another cationic dye (Methylene blue) by Gigantochloa Bamboo-Derived Biochar (Suhaimi *et al.*, 2022), the highest removal of MG was obtained at pH 3 and was found to be lowered by raising the pH. The removal percentage rose linearly with adsorbent dosage (from 0.1 g/L to 0.5 g/L) and contact duration (60-240 mins). At 150 min. MG (96%) and BPA (83%) attained their highest adsorption efficiencies at the HHBC dose value of

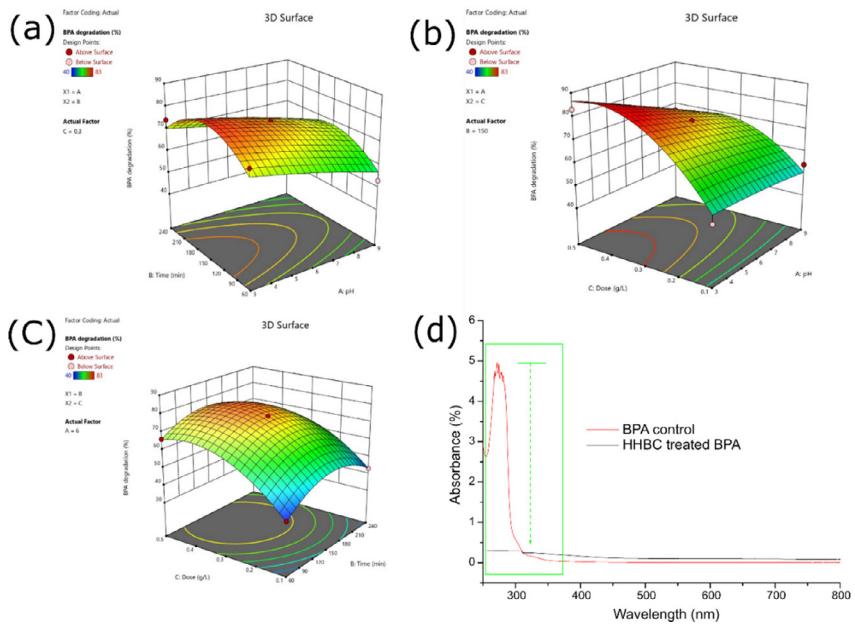

Fig. 3: BPA removal optimization by HHBC. Response surface plot (a, b, c) for the interaction of pH, time, and HHBC dose on BPA removal efficiency (The color changes from blue to red, indicating the increment of removal rate). (a) plot for pH and time, (b) plot for pH and HHBC dose, and (c) plot for time and HHBC dose. The UV-Vis spectroscopy analysis of actual BPA removal experiment on optimum conditions (d)

Table 3: ANOVA for quadratic model of MG and BPA removal by HHBC

Source	Sum of Squares	df	MG			BPA			
			Mean square	F-value	p-value*	Sum of Squares	df	Mean square	F-value	p-value
Model	1610.49	9	178.94	70.57	< 0.0001	2717.78	9	301.98	19.99	0.0003
A-pH	98.00	1	98.00	38.65	0.0004	351.12	1	351.12	23.24	0.0019
B-Time	66.12	1	66.12	26.08	0.0014	4.547E-13	1	4.547E-13	3.010E-14	1.0000
C-Dose	780.13	1	780.13	307.65	< 0.0001	1035.13	1	1035.13	68.52	< 0.0001
AB	2.25	1	2.25	0.8873	0.3776	0.2500	1	0.2500	0.0165	0.9013
AC	156.25	1	156.25	61.62	0.0001	100.00	1	100.00	6.62	0.0369
BC	49.00	1	49.00	19.32	0.0032	12.25	1	12.25	0.8109	0.3978
A^2	37.89	1	37.89	14.94	0.0062	2.37	1	2.37	0.1568	0.7039
B^2	286.58	1	286.58	113.02	< 0.0001	556.84	1	556.84	36.86	0.0005
C^2	95.00	1	95.00	37.46	0.0005	581.32	1	581.32	38.48	0.0004
Residual	17.75	7	2.54			105.75	7	15.11		
Lack of fit	17.75	3	5.92			105.75	3	35.25		
Pure error	0.0000	4	0.0000			0.0000	4	0.0000		

***P-values** less than 0.05 indicate model terms are significant. In this case of dye degradation, A, B, C, AC, BC, A^2, B^2, and C^2 are significant model terms. In the case of BPA removal, A, C, B^2, and C^2 are significant model terms.

0.5 g/L. This is because there will be enough time for the MG and BPA molecules to reach the interior adsorption sites. The high concentrations of the adsorbent dosage were suitable for biosorption of the pollutant because of the abundance of adsorption sites (Aziz *et al.,* 2022). A signal-to-noise ratio of 4 or higher is adequate for precision (Vyavahare *et al.,* 2018).

The adjusted R^2 of 0.9751 agrees well with the expected R^2 of 0.8256 from the ANOVA, with the difference between the two being less than 0.2. The F values were high, and the *p*-values <0.05, proving

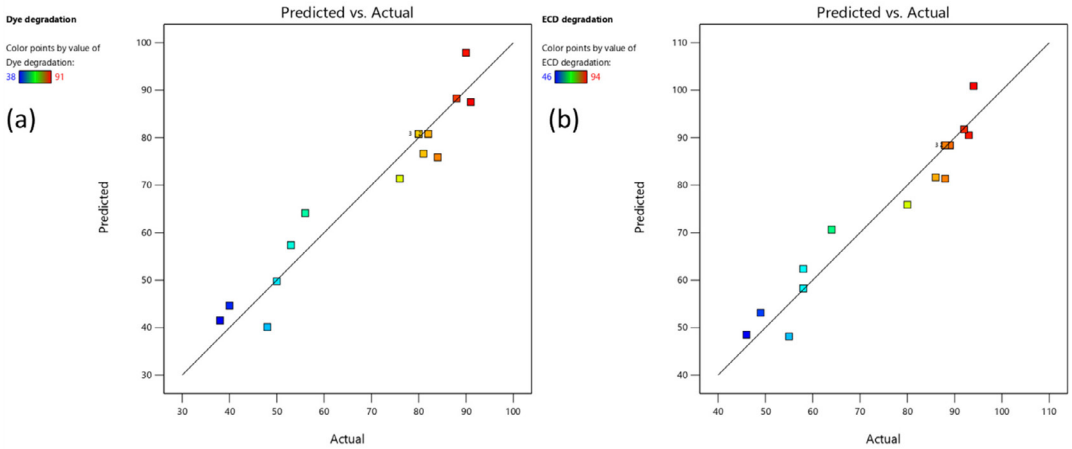

Fig. 4: Actual versus predicted values for malachite green dye (a) and bisphenol-A (b) removal using HHBC

Table 4: Comparative study of malachite green and bisphenol-A removal by selective biochar

Pollutant	Biochar	Effectiveness (%)	Sources
Malachite green	Palm leaves biochar	88	Hammud *et al.*, 2023
	Calcium-functionalized Magnetic Biochar	71.21	Wang *et al.*, 2022
	$KMnO_4$-Modified Biochar	99.17	Deng *et al.*, 2022
	Corn straw biochar	17.8	Eltaweil *et al.*, 2020
	Metal doped biochar	99	Huang *et al.*, 2021
Bisphenol A	Alkali-modified biochar	75	Tang *et al.*, 2022
	Bamboo-derived metal dopped	96	Talukdar *et al.*, 2020
	Metal doped biochar	97	Xu *et al.*, 2020
	Sludge biochar	98	Diao *et al.*, 2020
	Metal doped biochar	100	Jung *et al.*, 2019
Malachite green, bisphenol A	Human hair biochar	96, 83	Current work

the relevance of the mathematical model (Aziz *et al.*, 2022). According to the results of the ANOVA test (Table 3), the relevance of the model for the sorption of MG and BPA on HHBC was determined to be within the range of experimental factors. The results show that the created model is accurate and reliable, with projected elimination of MG and BPA by the HHBC adsorbents of 97.88% and 86.50%, similar to the actual values of 96% and 83%, using Eq. 1. (Aravind *et al.*, 2016).

$$\text{Dye degradation} = +80.80 +1.87A +7.75B +21.13C +1.50AB +2.25AC +5.50BC -4.53A^2 -7.78B^2 -9.52C^2 \quad (1)$$

It is evident from the polynomial quadratic equation (Eq. 1) the positive interaction and correlation of pH (A), time (B), dosage (C), the interaction of pH, with dosage (AC), interaction of time with dosage (BC) on the dye degradation, while pH^2 (A^2), $time^2$ (B^2), $dosage^2$ (C^2) negatively correlated on the dye degradation. Vyavahare *et al.* (2018), in their study of biochar's capability to degrade malachite green, found that the pH, dye concentration, temperature, and dosage levels positively impacted the overall dye degradation. Similar encouraging results were reported by Makhado *et al.* (2022), wherein the dosage and contact time had more impact on the degradation of malachite green, using Eq. 2 (Aravind *et al.*, 2016).

$$\text{BPA degradation} = +88.40 -2.12A +7.50B +18.88C +2.00AB +2.75AC +5.00BC -5.83A^2 -8.58B^2 -10.32C^2 \quad (2)$$

While evaluating the BPA degradation, from the

quadratic equation 2 (Eq. 2), dosage (B), time (C), pH with dosage (AC), pH with time (AB), and time with dosage (BC) had positive impact and correlation on BPA removal. The pH (A), pH^2 (A^2), $time^2$ (B^2), and $dosage^2$ (C^2) negatively correlated with the BPA degradation. Chen and Yu (2020) found that pH and dosage positively impacted BPA removal. Zdarta *et al.* (2020) found that pH, time, and temperature positively impacted BPA removal.

3D response curve was plotted using design-expert 13 to understand the interaction between the variables used and response dye degradation and BPA removal; the interaction of pH with time (A vs. B) on the response is shown in Fig. 2a, the interaction between time and dosage (B vs C) in Fig. 2b and interaction of time with pH (C vs A) in Fig. 2c. At lower pH with increasing dosage had a compelling impact on the outcome dye degradation; and at elevated level of time and dosage had maximal dye degradation, optimal time and dosage with low pH has maximal dye degradation. An independent run confirmed the optimal values of the variables A, B, and C to be 4 (pH), 192 min. (time), and 0.45 g/L (HHBC dosage) for maximal dye degradation. The counterplots were elliptical by raising ridge or mound, the desired output to arrive at the optimal response. In their work, Vyavahare *et al.* (2018) achieved optimal MG degradation with a pH of 6 and a time duration of 60 min.; they evaluated temperature and dye concentration as other variables to optimize. Moustafa, (2023) achieved 94.5% MG degradation using a low-cost adsorbent after optimizing the process parameters, where the optimum pH was 5.5, the adsorbent dosage was 0.7 g/L, and the contact time was 40h. In the case of BPA removal, an independent run confirmed the optimal values to be pH (4.5), 180 min. (time), and 0.5g/L (HHBC dosage) for optimal BPA removal. Chen and Yu, (2020) found their optimum values of pH 4.9 and dosage 3 g/L to obtain 59.54% of BPA degradation. In another study, the RSM optimization fetched the optimum conditions as pH 4.3, dosage 2 g/L, and time of 244 min., an adsorption maximal of 177.78 mg/g was achieved (Zhang *et al.,* 2020). Tang *et al.* (2022) used alkali-modified wheat straw-based biochar for the removal of bisphenol-A; they achieved 95% removal performed in 9 hours, at an optimum pH of 8, rpm of 180 and at a room temperature of 27 °C. Diao *et al.* (2022) utilized ultrasound-enhanced sludge biochar to remediate bisphenol-A; they achieved 98% degradation under 80 min., with optimum conditions of 3 pH, at room temperature, with an initial BPA load of 20 mg/L and for a biochar dosage of 2 g/L. Huang *et al.* (2021) effectively degraded 98.9% of MG with the aid of copper-iron-eucalyptus sawdust-biochar composite at an adsorbent dosage of 0.2 g/L, 4.8 pH, room temperature, and the feat was achieved under 90 min. Pathy *et al.* (2022) successfully used SCOBY biochar- composite to remove 98% of MG under 120 min., for an initial concentration of 100 mg/L, 4 pH, room temperature, and biochar dosage of 100 mg/g. UV-visible spectroscopy full spectral analysis showed evidence of nearly complete removal of MG (Fig. 2d) and BPA (Fig. 3d) by HHBC for the actual experiment performed at the optimum removal conditions (HHBC-0.5 g/L, pollutant-100 mg/L, 37 °C, 150 rpm, pH 3, 150 mins). The obtained spectrum's pattern is consistent with our prior research on the almond tree leaves adsorbent-mediated removal of dyes (Kamaraj *et al.,* 2022), which exhibited maximum removal. The comparative efficiency of diverse biochar on the removal of MG and BPA is provided in Table 4, which shows that the current research study has significant improvement over a few biochar and has the maximum potential like other biochar compared in Table 4. Removing pollutants, including dye and EDCs, from wastewater by utilizing natural and modified biochar involves many mechanisms, including but not limited to electrostatic attraction and attraction, surface complexation precipitation, ion exchange, cation–π interactions, etc. The synthesis and modification of biochar both support an excellent adsorption capacity for removing dyes; this is because the characteristics of biochar are tuned from the production stage onward and are connected with specific adsorption mechanisms (Amalina *et al.,* 2023). In the meantime, a framework for artificial neural networking and machine learning is recommended to simulate the efficacy of biochar in removing pollutants from wastewater, as Goswami *et al.* (2022) suggested. The biosorption models are recommended for utilization to understand the biochar's capability to function as a biosorbent for the utilization of diverse pollutant removal approaches. Fig. 4a and Fig. 4b depict the actual versus predicted values of MG degradation and bisphenol-A removal. An independent validation run

was conducted to ascertain the biochar's optimal performance. A maximal removal of 96% (MG) and 83% (bisphenol A) was achieved for a pH of 5.5, dosage of 0.7 g/L, and contact time of 40 min.

CONCLUSION

The industrial revolution that occurred in the 20th century was responsible for the development of a great deal of anthropogenic chemical pollutants. Among several methods and materials used to remove pollutants, biochar, a solid residue formed from the carbonization of naturally accessible biomass, has captured the attention of researchers. A variety of physicochemical features supports this ability. This work established that the heat-assisted fabrication of biochar from human hair waste is a cost-effective approach to harnessing biochar for handling pollution. The characterization of HHBC performed by instrumental analysis exposed that HHBC has the potential of a promising adsorbent. The adsorption competence of HHBA was revealed for MG (96%) and BPA (83%) using BBD in the RSM method under optimal conditions of pH 5.5, adsorbent dosage 0.7 g/L, and contact time of 40 h. The ANOVA test results suggested the model's significance for the sorption of MG and BPA. The presented study determined that the biochar can be made from human hair waste at 250 °C / 3 h and used as a valuable option to eliminate the dyes and EDCs contained in the wastewater. A new and simplified production process of hair waste-based biochar is opened, and further studies are recommended to improve the production possibilities of HHBC. Taking into consideration the precise chemistry of polluted media and the nature of HHBC used in this study, research is needed to expand further on diverse pollutants, such as heavy metals, organic pollutants, nutrients, oxyanions, hazardous gases, etc., to know the actual efficiency of HHBC in the real-time pollutant removal process. There is additional discussion regarding the functional enhancement of biochar as an adsorbent by the process of further chemical functionalization or manufacturing of biochar composite, with a particular emphasis on these pollutants also highly recommended. The future research prospects of HHBC on the recommended aspects are necessary to overcome the challenges associated with HHBC-mediated removal of pollutants from diverse real wastewater sources.

AUTHOR CONTRIBUTIONS

M. Kamaraj was instrumental in the study's conception, design, and writing. P. Kamali was responsible for the methodology and experiment. R. Kaviya was responsible for the methodology, collecting data, and curating the results. B Navinkumar performed the experiments. K. Abishek compiled the data and prepared the manuscript. T.G. Nithya reviewed and edited the manuscript and performed data analysis and interpretations for specific experiments. L.S. Wong reviewed and edited the manuscript. J. Aravind designed the optimization experiments and performed the data analysis and interpretation.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the authors observed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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ABBREVIATIONS

%	Percent
°C	Degree Celsius
ANOVA	Analysis of Variance
BBD	Box Behnken design
BET	Brunauer, Emmett, and Teller
BPA	Bisphenol-A
CCD	Central composite design
/cm	Per centimetre
EDCs	Exposure to endocrine-disrupting chemicals
EDS	Energy-dispersive X-ray spectrometer
Eq.	Equation
Fig.	Figure
FTIR	Fourier Transform Infrared
g	Gram
g/L	Gram per litre
h	Hour
HHBC	Human hair biochar
KBr	Pottasium bromide
m^2/g	Square meter per gram
MG	Malachite green
mg/g	Milligram per gram
mg/L	Milligram per litre
mL	Millilitre
pH	Potential of hydrogen
R^2	R-squared
rpm	Rotation per minute
RSM	Response surface methodology
SEM	Scanning electron microscope
UV	ultra violet
XRD	X-ray diffraction

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AUTHOR (S) BIOSKETCHES

Kamaraj, M., Ph.D., Associate Professor, Life Science Division, Faculty of Health and Life Sciences, INTI International University, Nilai 71800, Malaysia
- Email: *drkamarajm@gmail.com*
- ORCID: 0000-0002-0111-8524
- Web of Science ResearcherID: AAP-1422-2020
- Scopus Author ID: 55645159500
- Homepage: https://newinti.edu.my/academic-programmes/biotechnology-life-sciences/

Kamali, P., B.Sc. Student, Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology -Ramapuram, Chennai- 600089, Tamil Nadu, India.
- Email: *kamalipadmanaban6@gmail.com*
- ORCID: 0009-0003-4564-7721
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://fsh.srmrmp.edu.in/department-of-biotechnology/

Kaviya, R., B.Sc. Student, Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology -Ramapuram, Chennai- 600089, Tamil Nadu, India.
- Email: *kavs1202@gmail.com*
- ORCID: 0009-0001-0732-5647
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://fsh.srmrmp.edu.in/department-of-biotechnology/

Abishek, K., B.Sc. student, Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology -Ramapuram, Chennai- 600089, Tamil Nadu, India.
- Email: *abiabi8821@gmail.com*
- ORCID: 0009-0005-2208-3745
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://fsh.srmrmp.edu.in/department-of-biotechnology/

Navinkumar, B., B.Sc. Student, Department of Biotechnology, Faculty of Science and Humanities, SRM Institute of Science and Technology -Ramapuram, Chennai- 600089, Tamil Nadu, India.
- Email: navinkumar03355@gmail.com
- ORCID: 0009-0001-0574-0791
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://fsh.srmrmp.edu.in/department-of-biotechnology/

Nithya, T.G., Professor, Department of Biochemistry, College of Science and Humanities, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu 603203, India.
- Email: *nithyag@srmist.edu.in*
- ORCID: 0000-0002-6210-2606
- Web of Science ResearcherID: L-7308-2018
- Scopus Author ID: 55193514300
- Homepage: https://www.srmist.edu.in/faculty/dr-nithya-t-g-2/

Ling Shing Wong., Professor, Life Science Division, Faculty of Health and Life Sciences, INTI International University, Nilai 71800, Malaysia
- Email: *lingshing.wong@newinti.edu.my*
- ORCID: 0000-0002-5869-0804
- Web of Science ResearcherID: NA
- Scopus Author ID: 55819849800
- Homepage: https://newinti.edu.my/campuses/inti-international-university/

Aravind, J., Ph.D., Professor, Department of Biotechnology, Dr G.R. Damodaran College of Science, Avinashi Road, Civil Aerodrome Post, Coimbatore- 641014, Tamil Nadu, India.
- Email: *j.aravind@grd.edu.in*
- ORCID: 0000-0001-9699-2312
- Web of Science ResearcherID: O-9296-2015
- Scopus Author ID: 23569355700
- Homepage: https://www.grd.org/grdcs/bio-technology/

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