ORIGINAL RESEARCH

Comparative assessment for removal of anionic dye from water by different waste-derived biochar vis a vis reusability of generated sludge

Mayank Singh¹ · Mohd. Ahsan¹ · Versha Pandey¹ · Anupama Singh¹ · Disha Mishra¹ · Neerja Tiwari² · Pooja Singh² · Tanmoy Karak³ · Puja Khare^{1,4,5}

Received: 20 September 2021 / Accepted: 21 January 2022
© The Author(s) 2022

Abstract

In this study, four biochars prepared from different crop residue waste i.e. sugarcane bagasse (SBB), coconut shell (CNB), paddy straw (PDB), and distilled waste of lemongrass (LGB) were evaluated for removal of Remazol Brilliant Blue R from the aqueous system. The RBBR adsorption capacities of biochar were 97–79% for SBB, 99.9–99.47% for CNB, 66.1–48% for PDB, and 78–68% for LGB, dominantly controlled by their aromaticity and mineral content. The Langmuir and Freundlich isotherms and pseudo-second-order kinetic models have described the chemisorption of RBBR on biochar surfaces. The thermodynamic data suggested that adsorption was spontaneous and endothermic. These biochars demonstrated excellent reusability (till four cycles with 50–61% regeneration). The purified water and biochar dye sludge demonstrated no phytotoxicity. The findings obtained in this study may provide supports for the potential of biochars for anionic dye removal from water and utilization of generated sludge for zero waste-producing technologies in the future.

Highlights

- Maximum adsorption capacity of biochars varied from 642 to 893 mg g⁻¹ in 15 min.
- The biochar from coconut shell demonstrated the highest adsorption potential.
- Biochar dye sludge amendment in soil improved the soil quality and plant productivity.

Keywords Biochar · Remazol Brilliant Blue R Dye · Adsorption · Biochar dye sludge

Mayank Singh and Mohd. Ahsan contributed equally to this work

✉ Puja Khare
kharepuja@rediffmail.com

- ¹ Crop Production and Protection, Division, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow 226 015, India
- ² Phytochemistry Division, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow 226 015, India
- ³ Upper Assam Advisory Centre, Tea Research Association, Dikom, Dibrugarh 786101, Assam, India
- ⁴ Academy of Scientific and Innovative Research (AcSIR), Gaziabad, India
- ⁵ Biotechnology Division, Central Institute of Medicinal and Aromatic Plants, Lucknow 226015, India

1 Introduction

Water is a vital resource for the ecosystem as well as for humans. However, the discharge of pollutants in the water body has a toxic effect on the flora and fauna of the environment. Among these contaminants, synthetic dyes are the main source of water pollutants in the textile industry. The reactive dye on release in the water disturbs its physico-chemical properties and deteriorates the quality of the aquatic system (Khamparia and Jaspal 2016). Due to their complex molecular structure, these dyes are resistant to the conventional biological treatment of wastewater (Sonwani et al. 2019). Approximate 10⁵ numbers of different dyes are annually produced for commercial purposes and more than

7×10^5 tonnes of synthetic dyes are marketed to industries (Ahmad et al. 2020). During manufacturing and processing, 12% of synthetic dyes entered into the environment through spillage and or outflow, while approximately 20% of them were released in industrial wastewater (Essawy et al. 2008). Due to their carcinogenicity, mutagenicity and detrimental effect on health, suitable treatment of synthetic dye-rich industrial effluents is necessary with minimum effort and without harming the ecosystem. An anthraquinone-based Remazol Brilliant Blue R dye (RBBR) is widely used in textile industries (Mate and Mishra, 2020). Due to its structural similarity with a polycyclic aromatic hydrocarbon, it is toxic and is extremely harmful to aquatic and vegetative lives (Anita et al. 2020).

Adsorption is considered a promising technique due to its simple design, easy availability, cheapness, and easy operation for the removal of dye from water. There are several adsorbents used for the removal of anionic and cationic dyes from water such as metal oxide-based nanoparticles and graphene (Uddin et al. 2019; Kheirabadi et al. 2019), silica-zeolite (Madan et al. 2019), activated carbon (Naushad et al. 2019), modified bentonite (Huang et al. 2017), cellulose and alginate-based composite (Bhatti et al. 2020) and fly-ash (Alouani et al. 2018). Nowadays, biochar (BC) is considered a good candidate for adsorbent due to its porosity, high surface area, and cost-effectiveness along with several environmental applications (Zhang et al. 2021). Biochars prepared from maple leaf (Choi et al. 2020), tannery sludge (Zhai et al. 2020) and wakame (*Undaria pinnatifida*) (Yao et al. 2020) have been reported for the removal of various anionic dyes from aqueous system. Due to the repulsive nature of the dye with anionic surface functionalities (COOH, OH) of biochars, surface modified biochar such as cationic surfactant modified coffee husk (Kosaiyakanon and Kungsantant 2020) and Cetyltrimethyl ammonium bromide modified magnetic biochar (Wang et al. 2020) were also tried for the removal of anionic dye. However, the modification in the biochar structure required additional cost and usage of chemicals which can put additional load on the environment. The selection of suitably engineered biochar for the effective removal of anionic dye could be a better eco-friendly option for the circular economy. The variable composition and physico-chemical properties of biochar composition according to their feedstock type may lead to different types of interaction between biochar surface and dye and control their effectiveness for dye adsorption (Li et al. 2019). In the present study, the key goal is to assess the valuable biochar prepared from different agro-wastes of sugarcane bagasse, coconut shell, paddy straw, and distilled waste of lemongrass for removal of anionic dye. These feedstocks are easily available as waste material and otherwise burnt leading to environmental hazards. Hence, the study tried to understand the mechanistic aspects of differential adsorption potential

of biochar according to their properties such as aromaticity and mineral contents. In addition to this, this study first time addressed the issue of recycling biochar dye sludge for agricultural purposes as a sustainable and zero waste technology.

2 Materials and methods

The distilled waste of lemongrass was collected from the CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow. Waste of sugarcane bagasse and coconut shells were purchased from the local vendors. The paddy straw was collected from the farmer's field after the harvesting of the paddy. All biomass residues were cut and sieved into 0.211 mm size. Biochars were prepared in a programmed temperature fixed bed reactor and the method is reported elsewhere (Nigam et al. 2019). The biochar was dried and stored in a desiccator, and subsequently used for dye removal trials. The biochars were prepared from different feedstocks named SBB: Sugarcane bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar, and LGB: Lemongrass biochar.

2.1 Chemical characterization

The pH and EC (electrical conductivity) of biochar and soil were measured by pH Meter (model: SevenGoDuoTM SG23) in a water suspension prepared in a 1:10 ratio. Moisture and ash contents of biochar were measured by ASTM (2013) protocol. The organic carbon (OC) in biochar and soil was analyzed by Bray's method (Bray and Kurtz 1945). Elemental analysis in the soil samples was performed using inductively coupled plasma (ICP OES, Perkin Elmer, and Optima 5300 V). A CHN elemental analyzer was used for the carbon, hydrogen, and nitrogen content of biochar. Cation exchange capacity (CEC), water holding capacity (WHC), and bulk density (BD) of soil and biochar were determined by using the methods reported by Jeong et al. (2016). Specific surface areas of prepared BCs were measured using a surface area analyzer (NOVA 2200e, Quantachrome Instrument Corp., and FL) at -196°C by calculating ultra-pure nitrogen gas absorption. Phenolic hydroxyl and COOH groups on biochar surfaces were measured by the titrimetric method. Morphology and functional group analyses of biochar before and after adsorption were done using scanning electron microscopy (SEM) [JEOL (Make), JSM6100 (Model), USA], and Fourier transform infrared (FT-IR) (Perkin Elmer, Spectrum BX). Point of zero charges (pHPZC) of the biochar was done as reported earlier (Chabi et al. 2020).

The ion chromatography (Metrohm 940 Professional IC Vario) was used for the cation and anion analyses of the water using a conductivity detector (Metrohm 940

Professional IC Vario). The mobile phases used for anions and cations were NaCO_3 (3.2 mM) + NaHCO_3 (1.0 mM) and HNO_3 (2.7 mM). The columns used for separations were Metro Sep A Supp 5–250/4.0 for anions and Metro Sep C6-150/4.0 for cations.

2.2 Batch study for dye removal from water

The stock dye solution 50 g L^{-1} was prepared from Remazol dye powder and then diluted into different concentrations (500, 600, 700, 800, and 900 ppm) using deionized water. The maximum absorbance of Remazol effluent was quantified at 616 nm through a UV–Vis spectrophotometer.

Batch adsorption experiments were carried out to examine the effect of pH, contact time, temperature, and dye concentration on adsorption of RBBR by four biochars (weight 0.1 g). The 25 mL of dye concentration was taken from 500 to 900 ppm. Below 500 ppm, 100% adsorption was observed by most of the biochars. The pH value ranged from 3 to 12. The contact time varied from 0.2 to 20 min and the temperature was varied from 30 to 60 °C with 10 °C intervals. The concentrations of dye in the solution after adsorption by biochar were analyzed by spectrophotometer (model: Biotek epoch 2) at λ_{max} 616 nm. The removal efficiency of dye (%) by biochar and equilibrium concentration of dye (q_e in mg g^{-1}) were calculated as follows (Mate and Mishra, 2020):

$$\text{Dye removal efficiency} = \frac{C_o - C_e}{C_o} \times 100 \quad (1)$$

$$q_e = \frac{(C_o - C_e)V}{m} \quad (2)$$

$$qt = \frac{(C_o - C_t)V}{m} \quad (3)$$

where qt denotes the per unit mass of dye adsorbed on biochar at a time (t) and C_t is the dye concentration (mg L^{-1}) after time (t). V (L) and m (g) are the volume of the dye solution and the amount of adsorbent, respectively.

2.2.1 Adsorption isotherms, kinetics, and isotherm

The four most common adsorption isotherm models were used to find the equilibrium adsorption data. These are the Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich models. The experimental data were subjected to various kinetic equations i.e. pseudo-first-order kinetics; pseudo-second-order kinetics, intra-particle diffusion model and Elovich equation for determining the mechanism of adsorption of RBBR dye on biochars. Different thermodynamic parameters such as ΔH (enthalpy change), ΔG (change in

Gibbs free energy), and ΔS (entropy change) were calculated. The details are given in supplementary (SA-I).

2.3 Stimulation of effluent containing dye

The adsorption experiment was also performed in dye spiked wastewater (WW) and agricultural effluent (TW). Wastewater collected from the Kukrail canal, Lucknow. Agricultural effluent was collected from the farm of CSIR-CIMAP. The 500 and 900 ppm concentrations were taken for this study. The same procedure of adsorption as reported in Sect. 2.2 was followed in WW and TW solutions. The pH and EC of WW and TW were taken before and after the dye adsorption. The treated water was used for the phytotoxicity test.

2.4 Recycling test

Regeneration cycles were conducted up to the four-cycle for estimating the potential of resource recovery and reusability of biochars. Desorption of four RBBR laden biochars was done by using a 0.05 M NaOH solution with 15 min of shaking. For this, 50 mL of aqueous anionic dye solution (900 mg L^{-1}) and 0.1 g of each biochar were taken. The centrifugate was used to calculate the amount of desorbed dye. The same process was performed up to four turns.

2.5 Phytotoxicity test in treated water

A germination test was conducted using gram seeds (*Phaseolus mungo*) in control (only distilled water, no dye), dye WW before and after biochar treatment at different dye concentrations. The experiment was performed at four concentrations for four types of biochar SBB, CNB, PDB, and LGB separately in triplicate. The seeds were imbibed by immersing them into 20 ml treatment water in dark at 25 °C for 4 h and then sown on petri dishes with a wetted (with 2 ml treatment water) double layer of filter paper. Each petri dish contained 10 seeds and was kept at 25 °C in the dark in growth cabinets for 5 days, determining the germination rate for every 24 h. A one-millimeter radicle emergence from seed was considered seed germination. The preparation was moistened regularly with distilled water (control) and respective treatments. During the whole experiment, the germinated seedlings were counted every day. After 7 days of germination, the seedlings were harvested to determine the average length, protein (Lowry et al. 1951), and proline contents (Bates et al. 1973).

2.6 Phytotoxicity test in dye biochar sludge

For the germination test in dye biochar sludge, gram seeds (*Phaseolus mungo*) were washed under running water followed by distilled water and soaked for 8 h for imbibition.

10 seeds were sown in each pot (having 500 g soil) for germination and kept at 25 °C in an incubator. During the whole experiment, the germinated seedlings were counted every day for 7 days. The moisture level of the pot was maintained with distilled water. After 7 days, the germination percentage and length of the seeds were taken.

2.7 Statistical analysis

The SPSS software (version 25.0) was used for Tukey's Post Hoc. The Pearson correlation and principal component analysis (PCA) were used for the evaluation of the interrelationship among the variables. Hierarchical Cluster analysis was used for the evaluation of the difference in the biochar adsorption properties.

3 Results and discussion

3.1 Physico-chemical properties of different biochars

The characteristics of all four biochars SBB, CNB, PDB, and LGB are given in Table 1. The pH demonstrated that

all biochars were alkaline. A significant difference was observed among the physico-chemical properties of the four biochars. The biochar produced from sugarcane bagasse (SBB) exhibited higher carbon content than those prepared from other feedstocks. The ash content and electric conductivity of PDB were significantly higher ($p < 0.01$) than those in SBB, CNB, and LGB. The surface area of the SBB was found higher as compared with other biochars. PDB and SBB had the highest and lowest bulk density, respectively. Morphology of biochar as seen in SEM monograph suggested porous surface of all biochars (Fig. 1A). SEM-EDX analysis demonstrated the deposition of mineral particles on biochar surfaces. The PDB biochar showed high content of Al and Si on its surface (SA-II).

The aromaticity and polarity of the biochar are important and can be evaluated by their H/C, O/C, and (O + N)/C atomic ratios to a certain extent. Lower H/C and O/C ratios indicate higher aromaticity, while higher O/C and (O + N)/C indicates higher polarity in biochar structure (Wabel et al. 2013). In the present study, SBB had lower H/C ratios as compared to other biochars suggesting its more aromatic character. In addition, the tentative aromatic frame of each biochar was calculated on the basis of their H/C ratio calculation as given by Xiao et al. (2016).

Table 1 Physico-chemical properties of biochar

	SBB	CNB	PDB	LGB
Moisture	3.2 ± 0.1b	4.2 ± 0.1a	4.0 ± 0.1a	3.4 ± 0.1b
Ash	2.0 ± 0.1d	3.1 ± 0.1c	36 ± 0.2a	8 ± 0.4b
Total acidity (meq/100 g)	1.1 ± 0.3c	1.1 ± 0.2c	2.2 ± 0.4 a	1.43 ± 0.5b
COOH Groups (meq/100 g)	0.56 ± 0.01c	0.51 ± 0.02d	0.71 ± 0.03a	0.60 ± 0.02b
OH Groups (meq/100 g)	0.44 ± 0.02d	0.49 ± 0.01c	1.49 ± 0.03a	0.83 ± 0.02b
pH	8.97 ± 0.25b	9.59 ± 0.21a	9.90 ± 0.35a	8.74 ± 0.35b
pHPZC	7.5 ± 0.11b	8.12 ± 0.21a	6.1 ± 0.09d	6.5 ± 0.12c
EC (μS)	726 ± 12c	111.3 ± 19d	6480 ± 123a	2200 ± 110b
Total C (%)	92.16 ± 0.82a	89.01 ± 0.65b	11.32 ± 0.23d	76.65 ± 0.65c
Total H (%)	3.4 ± 0.11a	2.96 ± 0.22a	1.34 ± 0.21b	3.11 ± 0.15a
Total N (%)	0.6 ± 0.11b	1.1 ± 0.11a	0.6 ± 0.11b	1.3 ± 0.11a
Total O (%)*	3.74 ± 0.11d	6.25 ± 0.08c	40.15 ± 0.14a	16.09 ± 0.19b
H/C	0.31 ± 0.03d	0.40 ± 0.02c	1.20 ± 0.05a	0.49 ± 0.03b
O/C	0.06 ± 0.01d	0.11 ± 0.01c	1.81 ± 0.07a	0.32 ± 0.01b
(O + N)/C	0.09 ± 0.101d	0.13 ± 0.01c	1.84 ± 0.08a	0.34 ± 0.02b
SA (m ² g ⁻¹)	142 ± 7a	76 ± 6c	56 ± 7d	97 ± 8b
Bulk density (g/cm ³)	0.332 ± 0.011c	0.373 ± 0.012c	0.504 ± 0.010a	0.439 ± 0.011b
CEC	37.24 ± 2.1d	40.71 ± 3.4c	123.8 ± 3.6a	77.84 ± 2.9b
Ca (mg/kg)	785 ± 22a	761 ± 17a	599 ± 31b	473 ± 23c
Mg (mg/kg)	133 ± 9b	23 ± 1d	179 ± 6a	76 ± 8c
K (mg/kg)	969 ± 18c	755 ± 65b	1645 ± 71a	1355 ± 39d
Fe (mg/kg)	0.58 ± 1.1a	1.74 ± 0.8b	2.44 ± 0.03d	1.98 ± 0.02c
Mn (mg/kg)	0.24 ± 0.01d	0.42 ± 0.01c	13.6 ± 1.2a	1.3 ± 0.2b
Cu (mg/kg)	0.08 ± 0.01c	0.32 ± 0.01a	0.08 ± 0.01c	0.22 ± 0.02b

*Ash difference basis, CEC cation exchange capacity, PZC point of zero charge, SA surface area

Fig. 1 A SEM images of biochar before and after adsorption of Remazol Brilliant Blue R dye. B FT-IR spectra of biochar before and after adsorption of dye. SBB: Sugarcane bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar, and LGB: Lemongrass biochar

The H/C ratio of SBB (0.31), CNB (0.40), PDB (1.20), and LGB (0.49) suggested probable 5×5 , 4×4 , 1×1 and 3×3 aromatic frame (row $\times$ column) for these biochars respectively. The higher O/C and (O + N)/C of PDB revealed the presence of more polar groups on its surface as compared to other biochars. The number of $-\text{COOH}$ and $-\text{OH}$ groups (Table 1) on the surface of PDB as compared to other biochar is also supported these findings.

FT-IR spectra of the biochar demonstrated the presence of absorption bands for different functional groups present on the surface of biochar (Fig. 1B). Briefly, the peaks from ~ 3412 to 3439 cm^{-1} were associated with the stretching of hydroxyl groups on the biochar surfaces. The presence of sharp bands at $\sim 2916 \text{ cm}^{-1}$ and $\sim 2838 \text{ cm}^{-1}$ demonstrated the asymmetric and symmetric vibrations of aliphatic C–H in alkane and alkene groups. The peak at ~ 1620 – 1636 cm^{-1} was associated with C=O stretching mode of COOH groups present on biochar surface (Li et al. 2016). The band at $\sim 1430 \text{ cm}^{-1}$ was due to C=C stretching vibrations in the aromatic ring or C–H₂ bending (Encinas-Vázquez et al. 2021). The Si–O–Si–O and C–O–C vibrations of functional groups appeared at about 1034 cm^{-1} (Nair et al. 2020). The peaks from 847 to 887 cm^{-1} were due to C=C aromatic ring. Numerous other peaks at 1584 cm^{-1} ($-\text{H}$ stretching of C–O), 1527 cm^{-1} (aromatic C=C), 1383 – 1390 cm^{-1} (C=O stretching in

COOH), and 1117 – 1132 cm^{-1} (C–O stretching and OH deformation of COOH and phenolic groups) were also observed in FT-IR spectra of biochars (Novak et al. 2010).

3.2 Effect of concentration and agitation time on RBRR adsorption

The effect of agitation time and RBRR concentration on adsorption by biochars has been demonstrated in Fig. 2. The adsorption of RBRR on biochars decreased with an increase of dye concentration (SBB: 97–79%; CNB: 99.9–99.47%; PDB: 66.1–48% and LGB: 78–68%). This could be attributed to a reduction in the active site availability and pore diffusion of dye into the bulk of adsorbent (Vyavahare et al. 2018). The maximum adsorption was observed at 20 min shaking time. At a concentration of 900 ppm and 20 min shaking time, CNB (99.79%) demonstrated the higher adsorption capacity for RBRR as compared to other biochars, while PDB (48%) exhibited the lowest adsorption capacity for dye.

3.3 Adsorption isotherms

The Langmuir, Freundlich, Temkin, and D-R models were used for adsorption isotherm analysis (Table 2 and Figs. 3 and 4). Among the four models, the Langmuir model demonstrated better adsorption of RBRR on SBB surface (R^2

Fig. 2 Adsorption of dye on different biochars at different concentrations and time, psuedo first order, psuedo second order, and Intra particle diffusion kinetics for dye adsorption on biochar. SBB: Sugarcane

bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar, and LGB: Lemongrass biochar

0.992–0.999), which suggested that the adsorption behavior of RBBR on SBB was dominated by monolayer surface coverage (homogeneous surface), including chemical and physical adsorption processes. This observation is consistent with previous reports of dye adsorption onto biochar derived from various feedstocks (Lawal et al. 2021; Wang et al. 2021). The Freundlich model could better describe the adsorption of RBBR on CNB (R^2 0.922–0.997), PDB (R^2 0.995–0.966), and LGB (R^2 0.995–0.998). This model described the adsorption of dye to the surface of different affinity sites. It is assumed in the model that a stronger adsorption site is occupied first, then the adsorption capacity of the adsorbent decreases due to enhanced coverage of the adsorption site (Syafiuddin et al. 2018). The theoretical maximum adsorption amount (q_m) calculated by the Langmuir model was highest in CNB (892 mg g^{-1}) and lowest in PDB (641 mg g^{-1}) (Table 2). In the isotherm experiment, RL values ranged between 0.0 and 1.0, which is the indicator of favorable adsorption of RBBR over biochars (Abd-Elhamid et al. 2020). The higher RL values in the initial period (5 to 7 min) were higher in CNB as compared to other biochars suggesting that RBBR had a higher affinity CNB.

The Temkin adsorption isotherm model was chosen to determine the adsorption potentials of the adsorbent for adsorbates. In the present study, the Temkin adsorption potential k_T was highest for SBB and lowest for PDB.

The values of calculated binding energy for these biochars ranged from -2.25 to 18 kJ mol^{-1} . This may be due to the difference in density and distribution of functional groups of biochars. For example, π – π interaction had more binding energy than other interactions. The Temkin isotherm model binding energies were decreased with the time of exposure in all biochars.

The Dubinin-Radushkevich model provides information about the nature of the adsorption process i.e., chemical, physical, or ion exchange (Tatarchuk et al. 2020). In the present investigation, the R^2 values for this model were varied from 0.61 to 0.99 in the biochar taken for the study (Table 2).

In the present study, all biochars had a value of E_s more than 8 kJ/mol except for SBB at 7 and 15 min of agitation. Here, this model suggests that the mechanism of RBBR adsorption on biochar may be chemical and ion exchange (Tatarchuk et al. 2020). The lower R^2 of RBBR adsorption on SBB at 7 and 15 min may have the possibility not to describe the Dubinin-Radushkevich model.

3.4 Adsorption kinetics

The parameters obtained from different kinetic models for RBBR adsorption on four biochars have been shown in Table 3. The best fit kinetic model is displayed in Fig. 2. The comparison between the models was done according to their

Table 2 Isotherm parameters obtained for four biochars

Model	Langmuir			Freundlich			Temkin		Dubinin-Radushkevich					
	Isotherm parameters	b (Lmg ⁻¹)	Qm (mg g ⁻¹)	R _L	R ²	1/n	K _F (L mg ⁻¹)	R ²	k _T (L g ⁻¹)	Bt (kJ/mol)	R ²	β(mol ² /kJ ²)	E _s (kJ/mol)	R ²
SBB														
5 min		0.1332	434	0.0148–0.0082	0.992	0.369	2.59	0.942	1.44	– 6.77	0.906	0.0012	8.45	0.988
7 min		0.0114	526	0.1493–0.0888	0.991	0.088	16.53	0.904	1.77	– 2.63	0.904	0.020	5.00	0.615
15 min		0.0048	833	0.8076–6999	0.999	0.096	17.18	0.984	1.99	– 2.25	0.922	0.088	2.39	0.812
CNB														
5 min		0.0098	735	0.6707–0.5309	0.797	0.685	2.5	0.922	2.67	– 18.08	0.949	0.0088	7.54	0.995
7 min		0.0084	781	0.4930–0.4173	0.884	0.618	3.6	0.923	2.45	– 16.30	0.936	0.005	10.0	0.927
15 min		0.0024	892	0.4559–0.3177	0.979	0.530	9.44	0.997	2.29	– 14.18	0.981	0.0019	16.22	0.898
PDB														
5 min		2.1151	537	0.0009–0.0005	0.985	0.618	2.55	0.995	0.44	– 6.71	0.990	0.002	15.8	0.951
7 min		2.0537	589	0.0009–0.0005	0.988	0.588	2.93	0.996	0.46	– 6.65	0.992	0.0018	16.7	0.945
15 min		1.24	641	0.0035–0.0005	0.965	0.538	4.49	0.966	0.51	– 6.35	0.861	0.0016	17.7	0.902
LGB														
5 min		– 27.260	474	0.4068–0.4115	0.985	0.588	2.93	0.995	1.45	– 6.98	0.990	0.0065	8.7	0.951
7 min		0.0982	671	0.0199–0.0111	0.988	0.578	2.55	0.996	1.47	– 6.95	0.992	0.0055	9.5	0.945
15 min		0.1347	796	0.0146–0.0081	0.991	0.511	1.99	0.988	1.59	– 6.71	0.994	0.0045	10.5	0.973

Fig. 3 Langmuir and Freundlich isotherm for biochar SBB: Sugarcane bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar, and LGB: Lemongrass biochar

Fig. 4 Temkin and Dubinin-Radushkevich isotherms for biochar SBB: Sugarcane bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar, and LGB: Lemongrass biochar

regression coefficient (R^2) and the agreement between the experimental values of dye adsorption and provided by the model (Δq_e) (Table 3). The RBBR adsorption by SBB was

described equally by pseudo-first-order ($R^2=0.98-0.99$) and pseudo-second-order ($R^2=0.99$). However, lower Δq_e value of pseudo-second-order as compared to pseudo-first-order

Table 3 Kinetics parameters obtained for four biochars

Conc (mg l ⁻¹)	Pseudo First order		Pseudo Second order		Intra particle diffusion		Elovich					
	Q _e (mg g ⁻¹)	K ₁ (min ⁻¹)	R ²	Q _e (mg g ⁻¹)	K ₂ (g mg ⁻¹ min ⁻¹)	R ²	k _{id} (g mg ⁻¹ min ^{-1/2})	C (mg g ⁻¹)	R ²	B (mg g ⁻¹)	α (g mg ⁻¹ min ⁻¹)	R ²
SBB												
500	475	0.0038	0.98	491	2.4 × 10 ⁻⁷	0.99	0.26	17.35	0.26	0.42	2.41	0.45
600	575	0.0038	0.99	591	1.6 × 10 ⁻⁷	0.99	0.52	19.85	0.32	0.27	3.44	0.71
700	675	0.0037	0.99	689	1.2 × 10 ⁻⁷	0.99	0.44	21.98	0.44	0.24	3.43	0.81
800	775	0.0033	0.99	769	1.0 × 10 ⁻⁷	0.99	0.46	23.2	0.46	0.22	3.50	0.85
900	875	0.033	0.99	767	1.0 × 10 ⁻⁷	0.99	0.57	24.48	0.57	0.21	4.74	0.58
ΔQ _e (%)	5.1			2.9								
CNB												
500	439	0.0113	0.352	499	2.28 × 10 ⁻⁷	0.99	0.13	19.18	0.13	1.24	22.15	0.96
600	539	0.0155	0.57	598	1.59 × 10 ⁻⁷	0.99	0.18	22.98	0.16	1.05	22.48	0.94
700	625	0.0156	0.67	696	1.17 × 10 ⁻⁷	0.99	0.16	26.81	0.18	0.93	23.15	0.93
800	699	0.016	0.73	799	0.9 × 10 ⁻⁷	0.99	0.21	30.68	0.18	0.91	26.06	0.97
900	799	0.0125	0.47	899	0.7 × 10 ⁻⁷	0.99	0.18	34.18	0.21	0.70	28.32	0.99
ΔQ _e (%)	6.2			1.0								
PDB												
500	224	0.0055	0.45	328	5.29 × 10 ⁻⁷	0.99	0.09	9.96	0.19	0.77	4.87	0.99
600	310	0.008	0.75	342	4.84 × 10 ⁻⁷	0.99	0.05	11.42	0.25	0.54	5.34	0.98
700	407	0.0025	0.08	369	4.17 × 10 ⁻⁷	0.99	0.15	13.04	0.51	0.42	6.13	0.98
800	513	0.055	0.99	693	1.18 × 10 ⁻⁷	0.88	0.95	14.31	0.55	0.23	6.43	0.97
900	616	0.037	0.88	523	2.08 × 10 ⁻⁷	0.79	1.01	15.36	0.56	0.23	6.72	0.96
ΔQ _e (%)	8.3			2.3								
LGB												
500	295	0.034	0.51	496	2.31 × 10 ⁻⁷	0.98	0.55	10.33	0.66	0.12	0.06	0.95
600	373	0.025	0.4	514	2.15 × 10 ⁻⁷	0.94	0.44	11.58	0.68	0.14	0.18	0.96
700	463	0.018	0.59	524	2.07 × 10 ⁻⁷	0.99	0.47	13.17	0.75	0.18	0.56	0.97
800	577	0.019	0.94	592	1.62 × 10 ⁻⁷	0.99	0.57	14.53	0.97	0.20	0.51	0.97
900	665	0.017	0.76	571	1.74 × 10 ⁻⁷	0.98	0.55	15.61	1.12	0.20	0.57	0.97
ΔQ _e (%)	5.4			1.7								

(Table 3) implied that adsorption of RRBR on SBB followed pseudo-second-order kinetics (Table 3). The adsorption of RRBR on the other three biochars was described only by the pseudo-second order kinetics model (high R^2 values > 0.91). The pseudo-second-order model is based on the assumption that the rate-determining step may be chemical sorption involving valence forces through sharing or exchange of electrons between sorbent and sorbate (Ahmad et al. 2020; Xu et al. 2020). In addition, the high R^2 values in Elovich kinetics in CNB, PDB, and LGB further suggested the suitability and applicability of chemisorption on heterogeneous surfaces. The Elovich kinetics provides information about the initial adsorption rate (α) and surface coverage (β) for adsorption of dye on the adsorbent. The increase in values with an increase in the initial dye concentrations in solution (Table 3) indicated that there was an increase in driving force for mass transfer. It implied that the RRBR molecule reached the biochar surface within a short period and adsorption occurred via more than one mechanism. The higher initial adsorption rate in CNB was corroborated with R_L values and high adsorption of dye on it. The decrease in values of β with increased initial dye concentration demonstrated a reduction in the extension of surface coverage.

The intra-particle diffusion model demonstrates the probability of intra-particle diffusion resistance which affects the adsorption process. In the present study, the plot of q versus $t_{0.5}$ was neither a straight line nor passed through the origin (Fig. 2) suggesting the intraparticle diffusion was not the

only rate-controlling step. The three separate regions for adsorption of dyes implied more than one step involved in the adsorption process. The first sharper section was illustrated to external surface adsorption, demonstrating the availability of acute sites. However, the second and their sections described the gradual adsorption and final equilibrium stage, respectively.

3.5 Thermodynamics studies

The influence of temperature on dye removal and thermodynamics parameters for adsorption of RRBR on four biochar are shown in Fig. 5A and Table 4. The Van't half plot to calculate the thermodynamic parameters is given in Supplementary material (SA-III). The positive ΔH values suggested that the adsorption of anionic dye on these biochars is an endothermic process. This suggests the fast mobility of dye, which favours its penetration and interaction with internal functional groups of biochars due to more collision and increasing the sorption sites at elevated temperatures (Li et al. 2020). This may lead to enhanced adsorption of dye on biochar surfaces at elevated temperatures. The values of ΔH are indicative of physical (ΔH ranged between 2.1 and 20.9 kJ mol^{-1}) and chemisorption (ΔH ranged between 20.9 and 418 kJ mol^{-1}) (Du et al. 2019). In the present case, the ΔH value for all biochars ranged from 37 to 83 kJ mol^{-1} revealing that RRBR dye adsorption took place

Fig. 5 **A** Effect of temperature on removal efficiency of dye by biochars **B** Effect of pH on dye adsorption **C** Adsorption of dye wastewater (WW) and agricultural water (AE). **D** Desorption cycle of four

biochars SBB: Sugarcane bagasse biochar, CNB: Coconut shell biochar; PDB: Paddy biochar and LGB: Lemongrass biochar

Table 4 Thermodynamics parameters obtained for four biochar

Temp (°C)	Kd	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (J/molK)
SBB				
30	3137.50	− 20.28	83.54	− 60.75
40	2083.33	− 19.89		
50	1556.25	− 19.74		
60	1029.17	− 19.21		
CNB				
30	1285.00	− 18.03	70.54	− 33.66
40	689.55	− 17.01		
50	416.57	− 16.20		
60	364.11	− 16.33		
PDB				
30	10.53	− 5.93	37.91	− 32.40
40	9.56	− 5.88		
50	8.82	− 5.85		
60	5.70	− 4.82		
LGB				
30	137.18	− 12.40	43.48	− 12.17
40	92.13	− 11.40		
50	75.40	− 11.25		
60	70.83	− 11.44		

through the chemisorption mechanism. The negative value of ΔS supported the affinity of biochar to RBBR anionic dye and suggested a decrease in randomness at the adsorbent/solution interface during adsorption. Negative Gibbs free energy value indicated that the adsorption process occurred spontaneously (Du et al. 2019).

3.6 The effect of pH solution

The variation of dye adsorption on the biochar surface showed a gradual decline with an increase in pH (Fig. 5B). This may be due to the release of more H^+ ions at acidic pH, which enhanced the electrostatic interaction with positive ions present at the biochar surface. However, at higher pH, the negative surface of the adsorbent does not favour the adsorption of dye due to the electrostatic repulsion and competition between dye anions and excess hydroxyl ions (Sewu et al. 2019). Only, PDB showed dual adsorption maxima at pH 2 and pH 12 (Fig. 5B).

3.7 Removal of dye from different types of water

Two types of water i.e. wastewater (WW) (TDS: 2341 ± 204 mgL^{-1} , Ca: 423 mgL^{-1} , and Mg: 238 mgL^{-1}) and agricultural effluent (AE) (TDS: 1245 ± 92 mgL^{-1} , Ca: 1829 mgL^{-1} , and Mg: 687 mgL^{-1}) were used to examine the dye adsorptive potential of biochar (Fig. 5C). The slightly lower removal efficiency of dye from WW and AE (66–95%) by

biochar was observed as compared with distilled water. It is reported that the increase in ionic strength led to a reduction in the adsorption capacity of biochar (Pormazar and Dalvand 2020).

The preoccupation of biochar active sites with the ions and/or organic molecules present in WW and AE may reduce the availability of binding sites on biochar for dye molecules.

3.8 Relationship between biochar properties and adsorption parameters

In this investigation, hierarchical cluster analysis (HCA) was used to distinguish the biochar according to their properties (carbon, ash, surface area, CEC functional groups, and H/C, O/C, and (O + N)/C atomic ratios of the biochars) (Fig. 6A). The results of HCA displayed two major clusters, one with PDB and the other with SBB, CNB, and LGB. The second cluster was further divided into two groups I with LGB and II with SBB and CNB. Hence, HCA demonstrated that PDB had quite different characteristics than other biochar while SBB and CNB had some similarities in their properties. These differences could be associated with high ash content in PDB and high aromaticity of SBB and CNB. Though other properties such as surface area and functionality may also be responsible for the differences in adsorption capacities of biochar.

HCA was further applied to adsorption parameters deduced from kinetics and isotherms i.e., maximum dye adsorption capacity of biochar (Q_m), equilibrium capacity of dye taken from pseudo-second-order at different concentrations (Q_e), rate of pseudo-second-order reaction of dye adsorption (k_2), Freundlich constant at a different time (KF1, KF2, and KF3), and mean sorption energy at a different time of shaking (E_s) (Fig. 6B). Two major clusters in HCA analysis were observed, one with PDB and the other with SBB, LGB, and CNB. The second cluster was further showed two subclusters, one with CNB and the other with SBB and LGB. It implied that the adsorption of RBBR dye on PDB had a difference in adsorption mechanisms or their different magnitude than other biochars. This can be explained by the PCA and correlation (Fig. 6C and D) results which provide information about the relationship between the biochar properties and adsorption parameters deduced from kinetics and isotherms. The PCA showed three factors with 64%, 21%, and 13% of the variance, respectively (SA-IV). The score plot of these three factors showed the grouping of Q_e , Q_m , KF2, and KF3 with C, H, Ca, pH_{PZC}, and SA of biochars, while R^2 and E_s and KF1 were grouped with the ash, $-COOH$, $-OH$, H/C, O/C and (O + N)/C (Fig. 6C) and SBB and LGB had similarities in RBBR adsorption mechanism i.e., trends in kinetic and isotherm parameters. The correlation analysis also demonstrated similar findings. This suggests that the maximum adsorption capacities of biochar

Fig. 6 **A** Dendrogram from hierarchical cluster analysis using properties of four biochars, **B** Dendrogram from hierarchical cluster analysis using adsorption parameters of RBBR dye on four biochars, **C**

Heatmap of correlation among the biochar properties and adsorption parameters **D** Score plot of principal component analysis

and equilibrium capacities of dye in the present study may be associated with the C, H, Ca, pH/PZC, and SA of biochars. However, the ash, aromaticity, and polarity of the biochars played a dominant role in controlling the rate of dye adsorption on biochars.

3.9 Mechanism of adsorption

The elucidation of the adsorption mechanism of dye on biochar with different surface functionality and attributes is the major challenge. For this, an understanding of dye structure, biochar surface properties, and the interrelationship between the biochar properties and the adsorption parameters deduced from the isotherms and kinetics can provide useful information. The anthraquinone structure and C=O, NH₂, S=O, and NH group of RBBR dye were available for binding with biochar surface functionalities. Similarly, plenty of functional groups (–OH, –CO and –CH) were available on the biochar surface, which may participate during the adsorption of dyes through π - π stacking, hydrogen bond, and van der Waals force, etc. The involvement of various

functional groups in the adsorption of RBBR on biochar surfaces can be inferred by the broadening of the peak at 3455–3449 cm⁻¹ (indicating hydrogen bonding) (Rápó et al. 2020) and 1627 (aromatic C–C), and shifting of the peak at 1034 (Si–O–S and O–C–O) and appearance of a peak at 1385 cm⁻¹ (presence of sulphonate group characteristics of dye) (Sathishkumar et al. 2020) in the FT-IR spectra of biochar after dye adsorption (SA-III). The adsorption isotherms and kinetics studies supported the FT-IR results which demonstrated the monolayer (SBB) and multi-layer adsorption chemical adsorption (CNB, LGB, and PDB). The porous and vertical channel observed in SEM images of biochar suggested that pore filling could be another contributor to dye adsorption (Nartey and Zhao 2014).

The mineral present on the biochar surface could also contribute to the binding of dye molecules through ion exchange processes. The displacement of mineral ions of biochar after exposure to its mineral structure with the aqueous solution was also reported for the adsorption of anionic dyes particularly for mineral-rich biochar (Ravenni et al. 2020; Fan et al. 2017). In the present investigation,

the release of K^+ , Na^+ , Ca^{2+} , and Mg^{2+} cations and anions NO_3^- , PO_4^{2-} and SO_4^{2-} (cation to anion ratio) from biochar in an aqueous solution (SA-V) suggested the possibility of anion-exchange which can facilitate the interaction of sulfonic groups ($-SO_3^-$) of dye with cations present on the biochar surface. The reduction in Ca^{2+} and Mg^{2+} ion concentrations in the solution after dye adsorption implied the occurrence of ion exchange processes in all biochars (Pormazar and Dalvand 2020). The formation of ternary complexes by metal-bridging in mineral-rich biochars can ease the sorption dyes on the biochar surface in the presence of Ca^{2+} (Tan et al. 2020). The positive and significant correlation of Ca^{2+} concentration of biochar with Qm also implied the possibility of metal-bridging or cation π interaction. The higher reduction in Ca^{2+} and Mg^{2+} in solution during anionic dye adsorption by PDB as compared to that by other biochars indicates the higher ion exchange processes in PDB. The π - π interactions of the aromatic molecule are associated with the strong hydrophobicity of biochar (Du et al. 2019). CNB, SBB, and LGB due to higher aromaticity as compared to PDB had more possibility for the π - π interactions. The higher aromatic frame (5×5) of SBB may lead to the dominance of π - π interactions with dye and showed the monolayer adsorption. The negatively charged surfaces (higher content of CEC, COOH, and OH groups) of PDB might prevent π - π interactions due to the electron density at the π band of the carbon (Qui et al. 2009). This could be also the reason for the lower dye adoption by PDB as compared to other biochars. The association of maximum adsorption capacities of biochar and equilibrium capacities of dye with the C, H, and SA in PCA was also corroborating these findings. Hence, the tentative mechanism of RBBR based on biochar properties was illustrated and depicted in (Fig. 7).

Previously various materials were used for RBBR adsorption using adsorbents like chitosan-tripolyphosphate/kaolin clay, macroporous polystyrene resin (Amberlyst A21), leaf powder and lime peel powder, coffee husk based activated carbon, and bone (Table 5). The adsorption capacities of biochars used in the present study were higher than those of other adsorbents (9.6 – 208 mg g^{-1}) except chitosan-tripolyphosphate/kaolin clay (687 mg g^{-1}) used for RBBR removal (Jawad and Abdulhameed 2020). These biochars were prepared from discarded waste materials, hence they can be considered as more efficient and cost-effective adsorbent than chitosan-tripolyphosphate/kaolin clay. In addition, biochar prepared from *U. reticulata* can be adsorbed other similar to RBBR like Remazol Black B, Remazol Brilliant Orange 3R, Remazol Brilliant Violet 5R from aqueous solution with between 173.22 mg/g and 186.32 mg/g adsorption (Gokulan et al. 2020). Hence biochars taken for the study could also be capable to remove these dyes, however, further study is needed for quantification of exact concentration.

3.10 Evaluation of phytotoxicity of the filtered water

The phytotoxicity test demonstrated a good germination percentage (100%) of gram seeds in treated and untreated water (SA-VI). The length of plantlets grown in treated water by SBB (5.63 cm) and CNB (4.59 cm) was almost equal to the control (5.64 cm). However, the elongation of plantlets in untreated water (3.28 cm) was significantly reduced as compared to the control. The higher protein content in seeds germinated in treated water (0.24 – 0.29 mg g^{-1}) as compared to the untreated water (0.18 mg g^{-1}) was observed (SA-VI). The seeds germinated in untreated water had elevated levels of proline ($2.35 \mu\text{mol min}^{-1} \text{ g}^{-1} \text{ FW}$) as compared with that

Fig. 7 Tentative mechanism of RBBR adsorption on biochar

Table 5 The adsorption capacity of other adsorbent for Remazol Brilliant Blue R dye

Different types of adsorbent	Adsorption (mg g ⁻¹)	References
Chitosan-tripolyphosphate/kaolin clay	687.2	Jawad and Abdulhameed (2020)
Macroporous polystyrene resin (Amberlyst A21)	208.33	Ozturk and Silah (2020)
<i>Turbinariaconoides</i> Biochar	85.3	Vijayaraghavan and Ashokkumar (2019)
Bone char from bovine bone	20.6	Bedin et al. (2017)
Pineapple (<i>Ananascomosus</i>) leaf powder and lime (<i>Citrus auran-tifolia</i>) peel powder	9.58	Rahmat et al. (2016)
Snail shell powder	416.66	Ala'a and Al-Da'Amy (2020)
Coffee husk based activated carbon(RBO3R)	66.76	Ahmad and Rahman (2011)
Hydrolyzed rice straw biochar(Brilliant Green, BG)	111.11	Saif Ur Rehman et al. (2016)
Green algae <i>Scenedesmusquadricauda</i>	68 and 95.2	Ergene et al. (2009)
Water hyacinth	83.33	Kulkarni et al. (2018)
Sugar cane baggase biochar (SBB)	833	Present study
Coconut shell biochar (CNB)	892	Present study
Paddy waste biochar (PDB)	641	Present study
Lemongrass distilled waste biochar (LGB)	796	Present study

in the control (0.90 $\mu\text{mol min}^{-1} \text{g}^{-1}$ FW) and treated water (0.93–1.34 $\mu\text{mol min}^{-1} \text{g}^{-1}$ FW). The slight phytotoxicity and elevated proline levels in the plants under dye water treatment could be due to the presence of polyaromatic rings of dye molecules or utilization of all minerals during germination or excess presence of minerals in the wastewater (Varjani et al. 2020). On the other hand, excellent germination without toxicity in seeds grown in treated water may be related to reduced toxicity as well as the release of nutrients from biochar during the process of dye adsorption.

3.11 Reusability

In any adsorption process, the regeneration of the adsorbent is an important factor for cost economic and environmentally viable technology. The regenerative capacity of each biochar is demonstrated in Fig. 5D. Biochars demonstrated 76–85% desorption efficiency in the first cycle, which suggested suitability for reusing these biochars. After four cycles, the desorption capacities of biochars for RRBR dye reduced by 50–61% due to non-recovery of dye and that remains attached on the adsorbent surface. The high electrostatic repulsion between the negative charge of biochar and dye may favour the desorption of dye anions (Yu et al. 2021). The difference in desorption capacities of biochars was likely due to their different surface functionalities leading to different interactions on biochar surfaces.

3.12 Use of the dye biochar sludge for agricultural purposes

The biochar amendments in the soil enhanced the stable C in soil, biological health of the soils, and the nutrient use

efficiency of the plants which in turn increased the plant growth or soil fertility (Liu et al. 2020). Similar to other organic sludge (Markowicz et al. 2020), dye biochar sludge can be used for soil quality improvements. This is a good way toward a circular and zero-waste economy for the textile industry. No phytotoxicity i.e., 100% of germination of gram seeds in all treatments suggested its suitability for soil amendment (SA-VII). The elongation pattern of seeds germinated in the biochar dye sludge amendments was also comparable with biochar treatments. Maximum growth in gram seeds was observed in the SBB treatments and a minimum was found in LGB treatments. The nutrient release and improved soil conditions by biochar may be the reason for the enhanced germination (Das et al. 2020). The slight biotoxicity in dye-biochar sludge could be due to less mineralization of dye and interaction of seeds with the dye molecule.

4 Conclusions

The biochars prepared from four different biomass residues were evaluated for removal of anionic dye Remazol Brilliant Blue R from the aqueous system. The performance of biochar for removal of anionic dye was coconut shell biochar (99.47–99.99%) > sugarcane baggage biochar (79–97%) > distilled waste of lemongrass biochar (68–78%) > paddy biochar (66.1–48%). Their aromaticity, hydrophobicity, and mineral matter content could be the reason for the difference in their adsorption behavior. The adsorption isotherm followed the Langmuir (SBB) and Freundlich models and the kinetics fit the pseudo-second order kinetic model. The SEM, FT-IR, and ion chromatographic analyses confirmed that the RRBR adsorption on

these biochars was mainly due to chemisorption and electrostatic interactions. All biochars can be recycled for up to four cycles. The water after dye adsorption demonstrated no phytotoxicity in the germination test. The use of biochar dye sludge as a soil fertility enhancer demonstrated a circulatory system, which can not only prevent waste generation but can also generate a system for improving crop production without the application of additional inputs. However, further research should be carried out with the number of biochars and the economic feasibility and interference of other pollutants.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42773-022-00140-7>.

Acknowledgements The authors are thankful to the Director, Central Institute of Medicinal and Aromatic Plants, Lucknow, India for constant supports and encouragement. The authors also acknowledge the financial support by the Department of Biotechnology (DBT), New Delhi (BT/PR24706/NER/95/822/2017) under the twinning program.

Author contributions MS Investigation, Formal analysis, Data interpretation. MA Methodology, Formal analysis. VP Methodology, Editing. AS Methodology, Formal analysis. DM Methodology, Formal analysis. NT Methodology, Formal analysis. PS Methodology, Formal analysis. TK Editing, fund raising. PK Conceptualization, Writing—Review and Editing, fund raising. All authors read and approved the final manuscript.

Availability of data and materials The manuscript has provided all the associated data.

Code availability Not applicable.

Declarations

Conflict of interest I Dr. Puja Khare, on the behalf of all authors declare that the authors have no known competing financial interests, personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval Not applicable.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Abd-Elhamid A, Emran M, El-Sadek M, El-Shanshory AA, Soliman HM, Akl M, Rashad M (2020) Enhanced removal of cationic dye by eco-friendly activated biochar derived from rice straw. *Appl Water Sci* 10(1):1–11. <https://doi.org/10.1007/s13201-019-1128-0>
- Ahmad MA, Rahman NK (2011) Equilibrium, kinetics and thermodynamic of Remazol Brilliant Orange 3R dye adsorption on coffee husk-based activated carbon. *Chem Eng J* 170(1):154–161. <https://doi.org/10.1016/j.cej.2011.03.045>
- Ahmad A, Khan N, Giri BS, Chowdhary P, Chaturvedi P (2020) Removal of methylene blue dye using rice husk, cow dung and sludge biochar: characterization, application, and kinetic studies. *Bioresour Technol*. <https://doi.org/10.1016/j.biortech.2020.123202>
- Ala'a H, Al-Da'Amy MA (2020) Equilibrium and Thermodynamic studies of Adsorption of Remazol Brilliant Blue dye on snail shell powder. *IOP Conf Ser Mat Sci Eng IOP Pub* 871:012036
- Alouani MEL, Alehyen S, Achouri MEL, Taibi M (2018) Removal of cationic dye—methylene blue—from aqueous solution by adsorption on fly ash—based geopolymer. *J Mater Environ Sci* 9(1):32–46. <https://doi.org/10.26872/jmes.2018.9.1.5>
- Al-Wabel MI, Al-Omran A, El-Naggar AH, Nadeem M, Usman AR (2013) Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from *Conocarpus* wastes. *Bioresour Technol* 131:374–379. <https://doi.org/10.1016/j.biortech.2012.12.165>
- Anita SH, Ardiati FC, Oktaviani M, Sari FP, Nurhayat OD, Ramadhan KP, Yanto DHY (2020) Immobilization of laccase from *Trametes hirsuta* EDN 082 in light expanded clay aggregate for decolorization of Remazol Brilliant Blue R dye. *Bioresour Technol Rep*. <https://doi.org/10.1016/j.biteb.2020.100602>
- Bates LS, Waldren RP, Teare I (1973) Rapid determination of free proline for water-stress studies. *Plant Soil* 39:205–207. <https://doi.org/10.1007/BF00018060>
- Bedin KC, de Azevedo SP, Leandro PK, Cazetta AL, Almeida VC (2017) Bone char prepared by CO₂ atmosphere: preparation optimization and adsorption studies of Remazol Brilliant Blue. *J Clean Prod* 161:288–298. <https://doi.org/10.1016/j.jclepro.2017.05.093>
- Bhatti HN, Safa Y, Yakout SM, Shair OH, Iqbal M, Nazir A (2020) Efficient removal of dyes using carboxymethyl cellulose/alginate/polyvinyl alcohol/rice husk composite: adsorption/desorption, kinetics and recycling studies. *Int J Biol Macromol* 150:861–870. <https://doi.org/10.1016/j.ijbiomac.2020.02.093>
- Bray RH, Kurtz L (1945) Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci* 59(1):39–46
- Chabi N, Baghdadi M, Sani AH, Golzary A, Hosseinzadeh M (2020) Removal of tetracycline with Aluminum Boride Carbide and boehmite particles decorated biochar derived from algae. *Bioresour Technol*. <https://doi.org/10.1016/j.biortech.2020.123950>
- Choi YK, Gurav R, Kim HJ, Yang YH, Bhatia SK (2020) Evaluation for simultaneous removal of anionic and cationic dyes onto maple leaf-derived biochar using response surface methodology. *Appl Sci* 10:2982. <https://doi.org/10.3390/app10092982>
- Das SK, Ghosh GK, Avasthe R (2020) Ecotoxicological responses of weed biochar on seed germination and seedling growth in acidic soil. *Environ Technol Innov* 20:101074. <https://doi.org/10.1016/j.eti.2020.101074>
- Du J, Bao J, Hassan MA, Irshad S, Talib MA (2019) Multi-functional biochar novel surface chemistry for efficient capture of anionic Congo red dye: behavior and mechanism. *Arab J Sci Eng* 44(12):10127–10139. <https://doi.org/10.1007/s13369-019-04194-x>

- Encinas-Vázquez A, Quezada-Renteria JA, Cervantes FJ, Pérez-Rábago CA, Molina-Freaner FE, Pat-Espadas AM, Estrada CA (2021) Unraveling the mechanisms of lead adsorption and ageing process on high-temperature biochar. *J Chem Technol Biotechnol* 96:775–784. <https://doi.org/10.1002/jctb.6591>
- Ergene A, Ada K, Tan S, Katircioğlu H (2009) Removal of Remazol Brilliant Blue R dye from aqueous solutions by adsorption onto immobilized *Scenedesmus quadricauda*: equilibrium and kinetic modeling studies. *Desalination* 249(3):1308–1314. <https://doi.org/10.1016/j.desal.2009.06.027>
- Essawy AA, Ali AEH, Abdel-Mottaleb MSA (2008) Application of novel copolymer-TiO₂ membranes for some textile dyes adsorptive removal from aqueous solution and photocatalytic decolorization. *J Hazard Mater* 157(2–3):547–552. <https://doi.org/10.1016/j.jhazmat.2008.01.072>
- Gokulan R, Prabhu GG, Avinash A, Jegan J (2020) Experimental and chemometric analysis of bioremediation of remazol dyes using biochar derived from green seaweeds. *Desalin Water Treat* 184:340–353. <https://doi.org/10.5004/dwt.2020.25339>
- Huang Z, Li Y, Chen W, Shi J, Zhang N, Wang X, Zhang Y (2017) Modified bentonite adsorption of organic pollutants of dye wastewater. *Mater Chem Phys* 202:266–276. <https://doi.org/10.1016/j.matchemphys.2017.09.028>
- Jawad AH, Abdulhameed AS (2020) Facile synthesis of crosslinked chitosan-tripolyphosphate/kaolin clay composite for decolorization and COD reduction of remazol brilliant blue R dye: optimization by using response surface methodology. *Colloid Surf A-Physicochem Eng Asp* 605:125329. <https://doi.org/10.1016/j.colsurfa.2020.125329>
- Jeong C, Dodla SK, Wang JJ (2016) Fundamental and molecular composition characteristics of biochars produced from sugarcane and rice crop residues and by-products. *Chemosphere* 142:4–13. <https://doi.org/10.1016/j.chemosphere.2015.05.084>
- Khamparia S, Jaspal D (2016) Investigation of adsorption of Rhodamine B onto a natural adsorbent *Argemone mexicana*. *J Environ Manag* 183:786–793. <https://doi.org/10.1016/j.jenvman.2016.09.036>
- Kheirabadi M, Samadi M, Asadian E, Zhou Y, Dong C, Zhang J, Moshfegh AZ (2019) Well-designed Ag/ZnO/3D graphene structure for dye removal: adsorption, photocatalysis and physical separation capabilities. *J Colloid Interface Sci* 537:66–78. <https://doi.org/10.1016/j.jcis.2018.10.102>
- Kosaiyakanon C, Kungsanant S (2020) Adsorption of reactive dyes from wastewater using cationic surfactant-modified coffee husk biochar. *Environ Nat Resour J* 18:21–32. <https://doi.org/10.32526/ennrj.18.1.2020.03>
- Kulkarni MR, Bhagyalakshmi C, Anand D, Herle RN (2018) Removal of remazol brilliant blue dye from aqueous solutions using water hyacinth root powder. *Desalination Water Treat* 122:331–338. <https://doi.org/10.5004/dwt.2018.23037>
- Lawal AA et al (2021) Adsorption mechanism and effectiveness of phenol and tannic acid removal by biochar produced from oil palm frond using steam pyrolysis. *Environ Pollut* 269:116197. <https://doi.org/10.1016/j.envpol.2020.116197>
- Li B, Guo Y, Iqbal A, Dong Y, Li W, Liu W, Qin W, Wang Y (2016) Insight into excitation-related luminescence properties of carbon dots: synergistic effect from photoluminescence centers in the carbon core and on the surface. *RSC Adv* 6:107263–107269. <https://doi.org/10.1039/C6RA20562C>
- Li W, Mu B, Yang Y (2019) Feasibility of industrial-scale treatment of dye wastewater via bio-adsorption technology. *Bioresour Technol* 277:157–170. <https://doi.org/10.1016/j.biortech.2019.01.002>
- Li Z et al (2020) Adsorption of hazardous dyes on functionalized multiwalled carbon nanotubes in single and binary systems: experimental study and physicochemical interpretation of the adsorption mechanism. *Chem Eng J* 389:124467. <https://doi.org/10.1016/j.cej.2020.124467>
- Liu J, Ding Y, Ji Y, Gao G, Wang Y (2020) Effect of maize straw biochar on bacterial communities in agricultural soil. *Bull Environ Contam Toxicol* 104(3):333–338
- Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (1951) Protein measurement with the Folin phenol reagent. *J Biol Chem* 193(1):265–275
- Madan S, Shaw R, Tiwari S, Tiwari SK (2019) Adsorption dynamics of Congo red dye removal using ZnO functionalized high silica zeolitic particles. *Appl Surf Sci* 487:907–917. <https://doi.org/10.1016/j.apsusc.2019.04.273>
- Markowicz A, Bondarczuk K, Cycoń M, Sułowicz S (2021) Land application of sewage sludge: response of soil microbial communities and potential spread of antibiotic resistance. *Environ Pollut* 271:116317. <https://doi.org/10.1016/j.envpol.2020.116317>
- Mate CJ, Mishra S (2020) Synthesis of borax cross-linked Jhingan gum hydrogel for remediation of Remazol Brilliant Blue R (RBBR) dye from water: adsorption isotherm, kinetic, thermodynamic and biodegradation studies. *Int J Biol Macromol* 151:677–690. <https://doi.org/10.1016/j.ijbiomac.2020.02.192>
- Nair RR, Mondal MM, Weichgrebe D (2020) Biochar from co-pyrolysis of urban organic wastes—investigation of carbon sink potential using ATR-FTIR and TGA. *Biomass Convers Biorefin*. <https://doi.org/10.1007/s13399-020-01000-9>
- Nartey OD, Zhao B (2014) Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: an overview. *Adv Mater Sci Eng*. <https://doi.org/10.1155/2014/715398>
- Naushad M, Alqadami AA, AlOthman ZA, Alsohaimi IH, Algamdi MS, Aldawsari AM (2019) Adsorption kinetics, isotherm and reusability studies for the removal of cationic dye from aqueous medium using arginine modified activated carbon. *J Mol Liq* 293:111442. <https://doi.org/10.1016/j.molliq.2019.111442>
- Nigam N, Khare P, Yadav V, Mishra D, Jain S, Karak T, Panja S, Tandon S (2019) Biochar-mediated sequestration of Pb and Cd leads to enhanced productivity in *Mentha arvensis*. *Ecotoxicol Environ Saf* 172:411–422. <https://doi.org/10.1016/j.ecoenv.2019.02.006>
- Novak JM, Busscher WJ, Watts DW, Laird DA, Ahmedna MA, Nian-dou MA (2010) Short-term CO₂ mineralization after additions of biochar and switchgrass to a Typic Kandiodult. *Geoderma* 154(3–4):281–288. <https://doi.org/10.1016/j.geoderma.2009.10.014>
- Ozturk G, Silah H (2020) Adsorptive Removal of Remazol Brilliant Blue R from water by using a macroporous polystyrene resin: isotherm and kinetic studies. *Environ Process* 7(2):479–492. <https://doi.org/10.1007/s40710-020-00429-4>
- Pormazar SM, Dalvand A (2020) Adsorption of Direct Red 23 dye from aqueous solution by means of modified montmorillonite nanoclay as a superadsorbent: mechanism, kinetic and isotherm studies. *Korean J Chem Eng* 37:2192–2201. <https://doi.org/10.1007/s11814-020-0629-8>
- Qiu Y, Zheng Z, Zhou Z, Sheng GD (2009) Effectiveness and mechanisms of dye adsorption on a straw-based biochar. *Bioresour Technol* 100(21):5348–5351. <https://doi.org/10.1016/j.biortech.2009.05.054>
- Rahmat NA, Ali AA, Hussain N, Muhamad MS, Kristanti RA, Hadibarata T (2016) Removal of Remazol Brilliant Blue R from aqueous solution by adsorption using pineapple leaf powder and lime peel powder. *Water Air Soil Pollut* 227(4):105. <https://doi.org/10.1007/s11270-016-2807-1>
- Rápó E, Aradi LE, Szabó Á, Posta K, Szép R, Tonk S (2020) Adsorption of remazol brilliant violet-5R textile dye from aqueous solutions by using eggshell waste biosorbent. *Sci Rep* 10:1–12. <https://doi.org/10.1038/s41598-020-65334-0>

- Ravenni G, Cafaggi G, Sárossy Z, Nielsen KR, Ahrenfeldt J, Henriksen U (2020) Waste chars from wood gasification and wastewater sludge pyrolysis compared to commercial activated carbon for the removal of cationic and anionic dyes from aqueous solution. *Bioresour Technol Rep.* <https://doi.org/10.1016/j.biteb.2020.100421>
- Saif Ur Rehman M, Kim I, Rashid N, Adeel Umer M, Sajid M, Han JI (2016) Adsorption of brilliant green dye on biochar prepared from lignocellulosic bioethanol plant waste. *Clean: Soil, Air, Water* 44(1):55–62. <https://doi.org/10.1002/clen.201300954>
- Sathishkumar K, Li Y, Sanganyado E (2020) Electrochemical behavior of biochar and its effects on microbial nitrate reduction: role of extracellular polymeric substances in extracellular electron transfer. *Chem Eng J.* <https://doi.org/10.1016/j.cej.2020.125077>
- Sewu DD, Jung H, Kim SS, Lee DS, Woo SH (2019) Decolorization of cationic and anionic dye-laden wastewater by steam-activated biochar produced at an industrial-scale from spent mushroom substrate. *Bioresour Technol* 277:77–86. <https://doi.org/10.1016/j.biortech.2019.01.034>
- Sonwani RK, Giri BS, Singh RS, Rai BN (2019) Studies on optimization of naphthalene biodegradation using surface response methodology: kinetic study and performance evaluation of a pilot scale integrated aerobic treatment plant. *Process Saf Environ* 132:240–248. <https://doi.org/10.1016/j.psep.2019.10.004>
- Syafiuddin A, Salmiati S, Jonbi J, Fulazzaky MA (2018) Application of the kinetic and isotherm models for better understanding of the behaviours of silver nanoparticles adsorption onto different adsorbents. *J Environ Manage* 218:59–70. <https://doi.org/10.1016/j.jenvman.2018.03.066>
- Tan X, Zhu S, Show PL, Qi H, Ho SH (2020) Sorption of ionized dyes on high-salinity microalgal residue derived biochar: Electron acceptor-donor and metal-organic bridging mechanisms. *J Hazard Mater.* <https://doi.org/10.1016/j.jhazmat.2020.122435>
- Tatarchuk T, Myslin M, Mironyuk I, Bououdina M, Pędziwiatr AT, Gargula R, Bogacz BF, Kurzydło P (2020) Synthesis, morphology, crystallite size and adsorption properties of nanostructured Mg–Zn ferrites with enhanced porous structure. *J Alloys Compd* 819:152945. <https://doi.org/10.1016/j.jallcom.2019.152945>
- Uddin MK, Baig U (2019) Synthesis of Co₃O₄ nanoparticles and their performance towards methyl orange dye removal: characterisation, adsorption and response surface methodology. *J Clean Prod* 211:1141–1153. <https://doi.org/10.1016/j.jclepro.2018.11.232>
- Varjani S, Upasani VN, Pandey A (2020) Bioremediation of oily sludge polluted soil employing a novel strain of *Pseudomonas aeruginosa* and phytotoxicity of petroleum hydrocarbons for seed germination. *Sci Total Environ* 737:139766. <https://doi.org/10.1016/j.scitotenv.2020.139766>
- Vijayaraghavan K, Ashokkumar T (2019) Characterization and evaluation of reactive dye adsorption onto Biochar Derived from *Turbinaria conoides* Biomass. *Environ Prog Sustain Energy* 38(4):13143. <https://doi.org/10.1002/ep.13143>
- Vyavahare GD, Gurav RG, Jadhav PP, Patil RR, Aware CB, Jadhav JP (2018) Response surface methodology optimization for sorption of malachite green dye on sugarcane bagasse biochar and evaluating the residual dye for phyto and cytogenotoxicity. *Chemosphere* 194:306–315. <https://doi.org/10.1016/j.chemosphere.2017.11.180>
- Wang H, Wang S, Gao Y (2020) Cetyl trimethyl ammonium bromide modified magnetic biochar from pine nut shells for efficient removal of acid chrome blue K. *Bioresour Technol* 312:123564. <https://doi.org/10.1016/j.biortech.2020.123564>
- Wang Q, Zhang Z, Xu G, Li G (2021) Magnetic porous biochar with nanostructure surface derived from penicillin fermentation dregs pyrolysis with K₂FeO₄ activation: characterization and application in penicillin adsorption. *Bioresour Technol* 327:124818. <https://doi.org/10.1016/j.biortech.2021.124818>
- Xiao X, Chen Z, Chen B (2016) H/C atomic ratio as a smart linkage between pyrolytic temperatures, aromatic clusters and sorption properties of biochars derived from diverse precursory materials. *Sci Rep* 6:1–13. <https://doi.org/10.1038/srep22644>
- Xu S, Niu X, Hou Z, Gao C, Lu J, Pang Y, Fang M, Lu Y, Chen Y, Joshy K (2020) A multifunctional gelatine–quaternary ammonium copolymer: an efficient material for reducing dye emission in leather tanning process by superior anionic dye adsorption. *J Hazard Mater* 383:21142. <https://doi.org/10.1016/j.jhazmat.2019.121142>
- Yao X, Ji L, Guo J, Ge S, Lu W, Chen Y, Cai L, Wang Y, Song W (2020) An abundant porous biochar material derived from wakame (*Undaria pinnatifida*) with high adsorption performance for three organic dyes. *Bioresour Technol* 318:124082. <https://doi.org/10.1016/j.biortech.2020.124082>
- Yu CX, Chen J, Zhang Y, Song WB, Li XQ, Chen FJ, Zhang YJ, Liu D, Liu LL (2021) Highly efficient and selective removal of anionic dyes from aqueous solution by using a protonated metal-organic framework. *J Alloys Compd* 853:157383. <https://doi.org/10.1016/j.jallcom.2020.157383>
- Zhai S, Li M, Wang D, Ju X, Fu S (2020) Cyano and acylamino group modification for tannery sludge bio-char: enhancement of adsorption universality for dye pollutants. *J Environ Chem Eng.* <https://doi.org/10.1016/j.jece.2020.104939>
- Zhang Y, Akindolie MS, Tian X, Wu B, Hu Q, Jiang Z, Wang L, Tao Y, Cao B, Qu J (2021) Enhanced phosphate scavenging with effective recovery by magnetic porous biochar supported La (OH)₃: kinetics, isotherms, mechanisms and applications for water and real wastewater. *Bioresour Technol* 319:24232. <https://doi.org/10.1016/j.biortech.2020.124232>