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Review

Valorization of bamboo charcoal as a low-cost adsorbent for waste water treatment: A mini review

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ABSTRACT

The World Health Organization has reported that over one million individuals drink contaminated water, resulting in over 30,000 deaths daily. Every year, over 7×10^7 tons of synthetic dyes are produced globally, with the textile industry utilizing over 10^4 tons of such materials. To protect freshwater from pollutants, wastewater treatment methods such as permeable reactive barrier disinfection use activated carbon. Bamboo charcoal is an emerging substance with great potential in this area. Bamboos represent a renewable biological resource for long-term development. This paper reviews the dye removal processes that can be utilized to avoid water pollution, using bamboo charcoal as a natural adsorbent. A literature search using used various keywords from several bibliographic databases yielded seven studies that supported the adsorptive properties of bamboo charcoal. These investigations used FTIR, EDS, SEM and XRD to demonstrate the porous nature of bamboo charcoal, activated bamboo charcoal and/or modified bamboo charcoal, as well as showing the effects of pH and temperature on dye removal. The best-fitting kinetic model and isotherm data were identified. Bamboo charcoal was an effective adsorbent, while modified or activated bamboo charcoal rapidly increased absorptive capacity, indicating the future potential of bamboo charcoal in the cleaning up of water pollutants and contributing to a clean environment.

Introduction

Water contamination stemming from the discharge of harmful textile effluents is a major environmental challenge worldwide (Khan and Malik, 2018). In developing nations, the textile, paper and leather, food and cosmetic industries are experiencing rapid growth (Nitayaphat, 2014). Because of their use of a wide range of colours, vivid hues, strong colour retention, ease of application and low energy use, reactive dyes dominate more than half of the market share (Roessler and Jin, 2003). The most prevalent pollutants in the industrial waste associated with the use of dyes are surplus dyes and heavy metal ions. Synthetic dyes are used in paper printing, culinary, pharmaceutical, textile, photographic and cosmetics sectors. William Henry Perkin created the first aniline dye, mauveine, in 1856 and since then many more have come into use. Dyes contain intricate structures with unsaturated groups and conjugated chemical bonds, which aid in absorption and release of visible light while also making the removal of water challenging (Premkumar et al., 2018).

Freshwater accounts for only 3% of the total volume of water on earth, while around 20% of the world's population lives in areas where freshwater scarcity is a concern. The World Health Organization (WHO) has reported that over 1 million individuals consume contaminated water, with the cumulative impact resulting in over 30,000 daily fatalities (Premkumar et al., 2018). Annually, the global production of synthetic dyes exceeds 7×10^7 tons, with the textile industry alone utilizing over 10^4 tons of these colorants (Chandanshive et al., 2020). Textile wastewater is laden with various toxic substances, including dyes, aromatic compounds, and heavy metals such as mercury, chromium, cadmium, lead and arsenic, essential for producing colour pigments in textile dyes (Singha et al., 2021). The rising unpredictability and

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challenges in handling textile waste have spurred an ongoing quest for novel techniques that are both efficient and economically feasible (Singha et al., 2021).

Environmental contamination is defined as “any harmful or undesirable change in the physical, chemical or biological quality of air, water or soil” (Lawrence et al., 1998). To protect freshwater from contamination, permeable reactive barrier (PRB) technology employs activated carbon. The micropores within activated carbon trap pollutants present in wastewater, aiding in their removal. Bamboo activated carbon has garnered scientific attention in wastewater treatment due to its peculiar porous structure, which sets it apart from conventional wood charcoal (Nyika and Dinka, 2022). Bamboo charcoal (BC) is a relatively novel material that has emerged fairly recently (Isa et al., 2017; Nyika and Dinka, 2022). Bamboo is a renewable biological resource valuable to sustainable development as bamboo culms can be harvested year after year (Basumatary et al., 2015). Carbon chars can be made by carbonizing bamboo culms in an oxygen-free furnace at high temperatures. Because of its porous structure and excellent adsorption capabilities, BC could be utilized in the mitigation of gaseous and liquid pollutants from industrial waste and for the filtration of potable water (Zhu et al., 2009). This review concentrates on the methodologies employed for dye removal aimed at preventing water contamination, with a particular emphasis on the utilization of BC as a natural adsorbent.

Methods

This study of dye removal from wastewater using BC followed the PRISMA principles (Moher et al., 2009).

Data Collection

The keywords given below were used to search for original research publications in the Google Scholar, PubMed and Scopus databases (Fig. 1) (Narzary et al., 2023).

Accessed on 13.12.2023

(“dye contaminants” [Compendex Terms]) OR (“Bamboo Charcoal” [Compendex Terms] AND “textile waste” [Compendex Terms][All Fields]) OR “BC adsorbent” [All Fields] OR (“BC”[All Fields] AND “dye”[Compendex Terms][All Fields] AND “adsorbent”[Compendex Terms][All Fields]) OR “BC on wastewater”[Compendex Terms][All Fields]) AND (“plants”[All Fields] OR “planted”[All Fields] OR “planting”[All Fields] OR “plantings”[All Fields] OR “plants” OR “plants”[All Fields] OR “plant”[All Fields]) AND “experimental”[All Fields] OR “adsorbent”[All Fields] OR “dye adsorbent”[All Fields] OR “contaminants”[All Fields] TITLE-ABS-KEY (BC AND low-cost AND adsorbent AND dye AND treatment); TITLE-ABS-KEY (modified AND BC AND dye AND wastewater AND treatment); TITLE-ABS-KEY (dye AND textile AND wastewater AND treatment AND BC); TITLE-ABS-KEY (dye AND contaminants AND BC AND treatment) “textile dye”, “BC” and “treatment”.

Inclusion standards

The standards for inclusion included significant research that focused on dye removal from wastewater using BC, activated BC and/or modified BC. Only abstracts and the complete texts that met the given criteria were evaluated.

Exclusion standards

Research findings published in a non-English script were eliminated. Furthermore, any information on the removal of non-dye pollutants using BC was completely excluded.

Data retrieval standards

To collect data, the findings supporting the investigation, such as the dye used, the method of preparing BC, the mode of application, and its effects as an adsorbent were chosen from full-text publications and uploaded to an Excel spreadsheet (Microsoft Office Version 2018 for Windows, Washington, United States).

Adsorptive characteristics of bamboo charcoal

Seven investigations demonstrating the adsorptive characteristics of BC were identified, all of which could aid in the commercialization of bamboo charcoal for colour removal and the cultivation of a green environment for humans (Fig. 2). This research shows that BC might aid in the prevention of freshwater pollution caused by the textile industry (Table 1). Zhang et al. (2019) examined the adsorptive capacity of BC altered with Cu^{2+} and 3-aminopropyl trimethoxy silane (BC-Cu/Si-NH_2) using acid fuchsin dye (AF). A ratio of 1:2 molar mass (2.08 g $CuSO_4$.5 H_2O and 3.0 g Si-NH_2) were added to a flask containing 50 mL n-hexane. 3.0 g BC powder was added to the flask after 30 minutes of swirling with a magnetic stirrer, then mixed for the next 17 hours. The fusion was washed and ultrasonically treated. After oven drying at

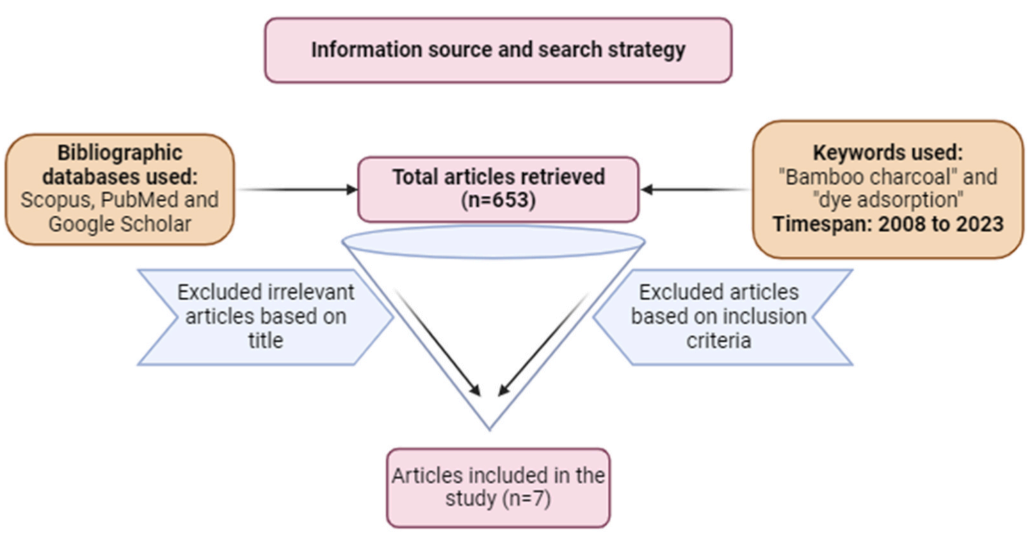

Fig. 1. Schematic representation of the methodology adopted to retrive the desired information.

Fig. 2. Schematic representation of Bamboo charcoal in dye adsorption.

102°C for 24 hours, the processed powder (BC-Cu/Si-NH_2) was obtained and kept in a sealed container. The adsorption result matched the Sips and Dubinin-Radushkevich (D-R) models, showing a single layer, uniform and physical adsorption mechanism. The best adsorption capacity calculated from the D-R model at 40 °C approached 14.91 mg/g1, whereas that of Sips achieved 10.77 mg/gl at the same temperature. The data from the kinetic experiment was well-fitted to the Spahn and Schlunder, as well as the pseudo-second-order models. The rate of removal of AF using BC as an adsorbent was rather poor, but utilizing BC-Cu/Si-NH_2, adsorption increased significantly and reached 86.22%. The BC-Cu/Si-NH_2-AF XRD pattern revealed that the layout of BC-Cu/Si-NH_2 was not damaged throughout the process of adsorption. The Fourier transform infrared (FTIR) spectrum demonstrated that the significant functional groups might be engaged in the adsorption process, causing a decrease in amount and an increase in transmittance. The scanning electron microscopy (SEM) picture of BC-Cu/Si-NH_2-AF revealed a few minute particulate materials on the adsorbent surface, which might be related to AF load (Zhang et al., 2019).

Using BC and microwave modified BC (BC-MW), Liao et al. (2012) demonstrated the adsorption of methylene blue (MB) and acid orange 7 (AO7) from aqueous solutions. BC-MW was created by washing and drying BC particles at 105°C. A quartz crucible was placed at the bottom of a 2450 MHz MW oven and irradiated at 550 W for 5 minutes. Based on the environmental scanning electron microscopy (ESEM) images, the experiment indicated that BC-MW had a bigger outer surface area, smaller micropore area and larger pore diameter than BC and that the surface area and pore volumes of Brunauer-Emmett-Teller (BET) were approximate. The MW treatment reduced O/C, polarity index (O + N)/C and H/C ratios of BC, demonstrating elevated hydrophobicity plus the presence of aromatic structure. The kinetic data fitted a pseudo second order model, showing that the rate-controlling mechanisms in adsorption were surface and intraparticle diffusion. Freundlich and Dubinin-Radushkevich models were well suited to all adsorption isotherms. MB adsorbed more at pH values below 5, but AO7 adsorbed more at pH values below 3, indicating pH-dependent adsorption. BC adsorption capacity for MB and AO7 was 68.2% and 33.0%, respectively, whereas that of BC-MW was 73.2% and 47.0%. According to the thermodynamic analysis, the adsorption was endothermic and spontaneous (Liao et al., 2012).

Rosli et al. (2018) explored the removal of ruthenium dye (N3) from imitated wastewater using BC and activated BC. They prepared activated BC by splitting BC samples into three equal 5 g parts and impregnating them overnight with varied volumes of 100 mL distilled water and NaOH in 2:1 and 3:1 mass ratio of NaOH to BC. The resulting slurry was oven dried for 2 hours at 105 ℃ before being activated for 1 hour in a muffle furnace set to 600 ℃ with a heating rate of 10 ℃ per minute. The activated bamboo-based charcoal (ABC) was cooled and then washed using hot distilled water until the pH lowered to 6.5–7.5. ABC was isolated using filter paper during the washing process. The completed activated carbon was dehydrated for 24 hours in a 105 ℃ furnace before being stored in sealed bottles for future use. AC-2 and AC-3 have been designated to ABC at impregnated ratios of 2:1 and 3:1, respectively.

BC has a porous and coarse surface that does not change following NaOH activation, according to SEM micro-graphs. However, after activation, additional pores have been observed to form with significantly expanded pore size (width). SEM images revealed that as the impregnation ratio increased, there was a widening of pore width and the emergence of new pores along the periphery of the original ones, thereby enhancing the adsorption capacity. ABCs showed more carbon content than BC, and the material was found to be predominantly amorphous, a characteristic known for imparting superior adsorbent properties, according to the Energy dispersive X-ray (EDX) and x-Ray diffraction (XRD) spectrum analysis. Initially, adsorption efficacies of dye by BC, AC-2, and AC-3 at 0.03 mM concentration were 58%, 61%, and 59%, while at 0.15 mM concentration, the adsorption efficacy of BC, AC-2, and AC-3 became 51%, 52%, and 53%, respectively, indicating higher adsorption efficacy of ABC than BC (Rosli et al., 2018).

In another study, Wang and Yan (2011) used activated BC to test the removal of direct yellow 161 dye (DY-161) from aqueous solution. They created activated BC by infusing it for two days with orthophosphoric acid (50%), zinc chloride (50%), potassium hydroxide (50%) and nitric acid (50%), and vigorously mixing it with an ultrasonic assistant. After dehydrating overnight at 105 °C, the combinations were pyrolyzed to 750 °C in a tube furnace with a 0.1 m^3/h flow of high-quality nitrogen (99.99%) then left for 3 hours for activation. Once activated, it was allowed to cool at room temperature with a nitrogen gas flow, condensed for several hours with ethanol (95% v/v), and rinsed with hot deionized water until the pH reached 6–7 and was void of apparent inorganic ions. Subsequently, the solution was dried in a vacuum drier

Table 1
Dye adsorption capacities of bamboo charcoal from aqueous solutions.

Product and Species	Modification (if any)	Dye used	Duration (in hours)	Temperature	pH	Kinetic model	Adsorption capacity	Characterisation of the adsorbent	Inference	References
Bamboo charcoal (BC)	Cu^{2+} and 3-amino-propyl trimethoxy silane (BC-Cu/Si-NH2)	Acid fuchsin (AF) (10 mg L^{-1})	3	40°C	6.0	Sips model; Dubinin–Radushkevich (D–R) model	10.77 mg g^{-1}; 14.91 mg g^{-1}	FTIR: O-H, C═N, C═O, C═C, C-O, Ammonium salts. SEM: Rough surface and abundant pores. EDS: Carbon, Oxygen, Copper, Silicon, Sulfur	Modified BC was efficient adsorbent for the removal of acid fuchsin from aqueous solution	Zhang et al., 2019
Bamboo charcoal (BC), Moso bamboo	-	Methylene blue (50 mg/L) and Acid orange 7 (50 mg/L)	48	293 K	7.0	Freundlich and Dubinin–Radushkevich models	68.20%; 33.03%	DRIFT: C-C C═C, C-O, -OH, XPS: C-C, C-O, C═O, C═N	BC is an efficient adsorbent for the removal of methylene blueat pH below 5 and acid orange 7 at pH below 3 from aqueous solution	Liao et al., 2012
Bamboo charcoal (BC), Moso bamboo	Microwave (550 W for 5 min)	Methylene blue (50 mg/L) and Acid orange 7 (50 mg/L)	48	293 K	7.0	Freundlich and Dubinin–Radushkevich models	73.22%; 47.01%	DRIFT: C-C C═C, C═O XPS: C-C, C-O, C═O, C═N	Modified BC was efficient adsorbent for the removal of methylene blue at pH below 5 and acid orange 7 at pH below 3 from aqueous solution	Liao et al., 2012
Bamboo charcoal (BC) *Gigantochloa sp.*		Ruthenium complex N3 (353.3 mg 100 m/L)	Overnight	Room temperature (RT)	6.5–7.5	NR	1.44 mg/g	SEM: porous and course surface EDS: Carbon, calcium, silicon, and aluminium XRD: indication of amorphous material	BC was efficient adsorbent for the removal of Ruthenium complex N3 from wastewater	Rosli et al., 2018
Activated Bamboo-based charcoal (ABC)	NaOH	Ruthenium complex N3 (353.3 mg 100 m/L)	Overnight	RT	6.5–7.5	NR	1.50 mg/g	SEM: more pores with increased pore size EDS: Carbon (high), calcium, silicon, and aluminium XRD: indication of amorphous material	ABC was more efficient adsorbent for the removal of ruthenium from wastewater compared to BC	Rosli et al., 2018
Activated Bamboo-based charcoal (ABC)	Orthophosphoric acid	Direct yellow 161	21	289 K	0.1	Avramic kinetic model, Elovich kinetc model, Langmuir, Freundlich Jovanovic, Koble-Corrigan isotherm model	2.27 mg/g	SEM: large pores were clearly found on surface of all produce bamboo activated Carbone	Activated charcoal the BC activated with orthophosphoric acid was the best adsorbent for removal of direct yellow 161 dye from aqueous solution.	Wang and Yan, 2011
Activated Bamboo-based charcoal (ABC)	Nitric acid	Direct yellow 161	21	289 K	0.1	Avramic kinetic model, Elovich kinetc mo	1.95 mg/g	SEM: large pores were clearly found on surface of all produce bamboo activated Carbone	Activated charcoal the BC activated with orthophosphoric acid was the best adsorbent for removal of direct yellow 161 dye from aqueous solution.	Wang and Yan, 2011
Activated Bamboo-based charcoal (ABC)	Potassium hydroxide	Direct yellow 161	21	289 K	0.1	Avramic kinetic model, Elovich kinetc model, Langmuir, Freundlich Jovanovic, Koble-Corrigan isotherm model	1.72 mg/g	SEM: large pores were clearly found on surface of all produce bamboo activated carbone	Activated charcoal the BC activated with orthophosphoric acid was the best adsorbent for removal of direct yellow 161 dye from aqueous solution.	Wang and Yan, 2011
Activated Bamboo-	Zinc chloride	Direct yellow 161	21	289 K	0.1	Avramic kinetic model, Elovich kinetc model, Langmuir, Freundlich	1.95 mg/g	SEM: large pores were clearly found on surface of all produce bamboo activated Carbone	Activated charcoal the BC activated with orthophosphoric acid was	Wang and Yan, 2011

(*continued on next page*)

Table 1 (*continued*)

Product and Species	Modification (if any)	Dye used	Duration (in hours)	Temperature	pH	Kinetic model	Adsorption capacity	Characterisation of the adsorbent	Inference	References
based charcoal						Jovanovic, Koble-Corrigan isotherm model.			the best adsorbent for removal of direct yellow 161 dye from aqueous solution.	
Activated bamboo charcoal	Chitosan	Laquous reactive red 152	8	30	4.0		3.47 mg/g, 4.32 mg/g	SEM: Porous and heterogenous pores	Modified bamboo charcoal with chitosan was effective adsorption for the removal of reactive red152	Nitayaphat, 2014
Bamboo charcoal		Methylene blue	6	30°C, 40°C, 50°C	9.1	Pseudo-second-order kinetic model (R^2>0.9968)	58.48 mg/g, 64.10 mg/g, 69.93 mg/g	-	MB Adsorption on BC was shown to be strong	Zhu et al., 2009
Bamboo charcoal, *Phyllostachys pubescens*	Bamboo Charcoa–Iron Oxide Nanocomposite	Methylene blue	2	30°C to 60°C	3–7	Pseudo-second-order (PSO)	9.87 mg/g to 17.62 mg/g	XRD: nano-sized iron-oxide particles in the range of 13.1 nm to 15.6 nm. Peaks at 2θ values of 18.48°, 18.89°, 22.92°, and 29.76° corresponds to the (−202), (200), (002), and (−402) crystal planes, indicating the presence of humboldtine (H), with empirical formula of Fe(C2O4) 2H2O SEM: sample particle size is 0.182 µm with 0.192 m2/g, the adsorbent material's surface area	Bamboo charcoal-iron oxide nanocomposite composites have been shown to be excellent methylene blue dye adsorbents in the removal of synthetic dye-bearing effluents.	Sen, 2023

for 4 hours at 110 °C and allowed to cool at room temperature. The resulting activated bamboo carbon was then stored in a desiccator. The activated products were labeled as follows: OBC for orthophosphoric acid, NBC for nitric acid, ZBC for zinc chloride, and PBC for potassium hydroxide. The activated bamboo carbons produced had large surface pores, which varied in size, quantity, shape, and arrangement. In comparison to the other three activated bamboo carbons, OBC showed a higher degree of regularity and order in its pores, with fewer instances of blockages. Because activated carbon has a bigger surface area and a highly porous framework, enabling dyes to be trapped and absorbed effectively, it exhibits a higher adsorption potential. The data revealed that as the dye concentration increased, so did the dye adsorption. Among the activated carbons tested, OBC had the highest dye removal rate of 90.1%, corresponding to an adsorption potential of 2.218 mg/g. Conversely, PBC demonstrated the lowest dye removal rate of 69.5%, corresponding to an adsorption capacity of 1.711 mg/g. The Avrami fractionary kinetic model emerged as the most suitable fit, characterized by a low Marquardt's percent standard deviation error function (F_{error}) and a high correlation coefficient (R^2). The isotherm results show that the Koble-Corrigan model matched the tested activated carbons the best, whereas the Jovanovic model exhibited the poorest fit, indicating the endothermic and physical nature of adsorption (Wang and Yan, 2011).

Nitayaphat (2014) used chitosan/BC complex as a reactive dye adsorbent. In 50 mL (2% (v/v) acetic acid) solution, 0.2, 0.6, and 1.0 g of BC powder was combined with 1.8, 1.4, and 1.0 g of chitosan, respectively. The premixes were whirled for 3 hours at room temperature. The solutions were syringed into a condensation bath containing an alkaline coagulating mixture of 1 dm^3, generating chitosan/BC complex pellets with varying chitosan/BC weight ratios of 90/10, 70/30, and 50/50. The addition of BC enhanced the surface area of the chitosan/BC complex over chitosan pellets, implying that the chitosan/BC complex pellets could potentially enhance the adsorption of reactive dyes. The dye removal by the chitosan/BC complex pellets demonstrated an increase with the concentration of BC in the complex. 84.4% of the highest dye removal was reported in chitosan/BC complex pellets with a weight ratio of 50/50 chitosan to BC. At pH 4, the greatest dye removal was 87.5%. The SEM micrograph showed densely and uniformly bound dye on the adsorbent surface, attributed to the porous structure of BC causing spontaneous entrapment, along with the action of electrostatic forces. The highest dye removal, reaching 98.4%, was achieved under above-optimal conditions. The adsorption isotherms of chitosan and chitosan/BC complex pellets closely matched the Langmuir isotherm model. Based on the findings, it was determined that chitosan/BC complex pellets possess superior adsorption capability compared to chitosan alone (Nitayaphat, 2014).

Zhu et al. (2009) used BC for adsorbing MB from an aqueous solution. The equilibrium period for a 100 mg/L dye at 30–50 °C was 300 minutes. The dye adsorption quantity at equilibrium rose to 49.5 from 42.5 mg/g when the temperature was elevated to 50 °C from 30 °C. At 50 °C and a dye content of 100 mg/L, about 90% of total dye was adsorbed within the first 120 minutes with a standard adsorption rate of 0.369 mg/(g.min), and the adsorption rate then began to drop. A similar pattern was seen at 30 °C and 40 ℃ for the same dye content (100 mg/L). When the adsorbent dose was 0.1 g/50 mL, the dye extracted from the solution was more than 90% at 30 ℃, 95% at 40 ℃, and 99% at 50 ℃. The dynamic data closely matched the pseudo second-order kinetic model, showing an endothermic process. The Langmuir model fitted the experimental data well. The highest adsorption potential was 58.48 mg/g, 64.10 mg/g, 69.93 mg/g at 30 °C, 40 °C, and 50 °C, respectively, according to the Langmuir analysis (Zhu et al., 2009).

Sen (2023) synthesized adsorbents made of biomass BC-iron oxide "BC/Fe" nanocomposite for removing cationic MB dye from wastewater. In a solution of ethylene glycol and H_2O (15 mL +10 mL), 2.5 g of synthetic BC and ferric nitrate ($Fe(NO_3)_3$ 9 H_2O) with carbon/Fe molar ratios of 35, 40, and 80 were added. Finally, the entire mixture was combined, degassed for an hour using a vacuum degassing chamber, cooled, filtered, and oven dried at 70 ℃ for 12 hours. The degree of adsorption of MB dye by the processed adsorbents increased to 15.30 mg/g from 9.5 mg/g with an increase in dye content (10–30 ppm), as measured through varying contact times, but decreased when the temperature rose from 30 to 60 ℃ and the adsorbent doses increased from 20 to 40 mg. The kinetic investigation demonstrated that equilibrium was attained within 120 minutes and the adsorption kinetics were well-described by the pseudo-second-order model. Additionally, when the solution pH rose from 3 to 7, the degree of MB dye adsorption surged to 17.62 mg/g from 9.87 mg/g, but at 30 ℃ and pH 10, it lowered to 20 ppm. Both the Freundlich and the Langmuir isotherm models suit the equilibrium data. The highest adsorption capacity of 111.11 mg/g was obtained by the Langmuir isotherm, which was comparable to or superior to the adsorption potential of various other magnetic adsorbents for MB dye (Sen, 2023).

Conclusions

In these studies, BC has been shown to be an excellent adsorbent for several dyes. Modified BC was successfully synthesized and demonstrated to be an effective adsorbent for removing dyes from aqueous solutions. While pH and temperature had a minor impact on adsorption capacity, isotherm and kinetic models were utilized to fit the experimental results and investigate the means of adsorption. According to the kinetic analysis, the amount of adsorption increased with prolonged contact time until equilibrium was reached. Depending on the modified BC, the Spahn and Schlunder models, the pseudo-second-order model, and the Avrami fractionary kinetic model were found to be suitable for describing the kinetic behavior observed in the research.

Common characterization techniques such as XRD, FTIR, SEM and EDS demonstrated that the pores were packed following adsorption. Conversely, an increase in adsorbent dosage led to a higher proportion of dye being removed from the solution. The thermodynamic parameters of the adsorption process also indicated that it was endothermic and natural. Thus, this study suggests that BC/activated BC/modified BC might be employed as low-cost and effective adsorbents for removing dyes from wastewater, thereby contributing to a more sustainable and environmentally friendly approach. Apart from adsorption properties, BC infused with silver (BC/Ag) exhibited antibacterial characteristics, rendering it suitable for antibacterial fabrics. Furthermore, the combination of bamboo vinegar (BV) with BC powder lowered egg damage and harmful microorganisms in the digestive tracts of laying hens. BC also has the ability to absorb moisture from its surroundings when humidity levels are high, subsequently releasing it to maintain dynamic equilibrium. This property suggests its potential application in healthcare products to modify microenvironments. Scaling up the bamboo charcoal production process could potentially yield significant economic benefits.

CRediT authorship contribution statement

Arvind Kumar Goyal: Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Talambedu Usha:** Writing – review & editing, Writing – original draft, Data curation. **Sushil Kumar Middha:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Rinki Kumari Mahato:** Validation, Data curation. **Illora Narzary:** Writing – original draft, Data curation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

No data was used for the research described in the article.

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