



Adsorption of methylene blue (MB) dye on ozone, purified and sonicated sawdust biochars

Tarek M. Eldeeb¹ · Uyiosa O. Aigbe² · Kingsley E. Ukhurebor³ · Robert B. Onyancha⁴ · Mohamed A. El-Nemr⁵ · Mohamed A. Hassaan¹ · Safaa Ragab¹ · Otolorin A. Osibote² · Ahmed El Nemr¹

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Abstract

The synthesized biochars derived from sawdust (SD) SD ozone (SDO) biochar, purified SD (PSD) biochar, and sonicated SD (SSD) biochar, which was employed in the confiscation of methylene blue (MB) dye ion, were characterized employing “Brunauer–Emmett–Teller (BET), scanning electron microscope (SEM), Fourier Transform Infrared (FTIR), and Thermal gravimetric analysis (TGA).” The impact of various factors, such as pH, biochar dosage, and initial concentration, on MB dye sequestration, was tested in this study. It was found that the biosorption of MB dye to the various biochars was dependent on the solution pH, with optimum confiscation of MB observed at pH 12 for all biochars. Pseudo-second-order (PSO), Freundlich (FRH)- (SDO and SSD biochars), and Langmuir (LNR)- (PSD biochar) models were used to best describe the biosorption process of MB dye to various biochars. Based on the LNR model fitting to the experimental data, the optimum sorption capacities obtained using SDO, SSD, and PSD biochars were 200, 526, and 769 mg/g, respectively. Electrostatic interaction and hydrogen bonding played an important role in the interaction mechanism between the various biochars and MB dye. Hence, these studied SDO, PSD, and SSD biochars prepared from cheap, easily accessible, biodegradable, and non-hazardous agro-waste materials can be effectively used for the removal, treatment, and management of MB dye as well as other industrial effluents before their disposal into the environment.

Keywords Biochar · Biosorbents · Pollution · Wastewater · Methylene blue dye · Sawdust

1 Introduction

Environmental effluences ensuing as a result of the annihilation of the aquatic, terrestrial, and atmospheric ecosystems by the fast and aggressive increase in industrial activities and the global population are critical to the existence of man and other living organisms as well as the sustenance of the

ecosystem [1–10]. According to several research reports, these environmental effluences have extremely affected the quality of water due to the untreated wastes being disposed of, released, or discharged into the aquatic environments, mostly by industries via the production processes of textiles, paper, leather, petroleum, and paint, as well as metal plating, mining, and other industrial production processes [11, 12], consequently, contributing immensely to climate change and global warming [13–15], health complications [16–18], food shortage (agricultural shortfall) [19–21], etc.

The majority of these industries that use dyes (cosmetics, textiles, paper, leather, and paint industries) have a high infecting trail, and it is projected that up to 2.00×10^5 tons of dyes are disposed of, released, or discharged into the aquatic environments owing to the ineffective wastewater management and treatment processes [22–27]. Amongst these toxic and aromatic effluents being disposed of, released, or discharged into the aquatic environments without preceding proper treatment, the cosmetics, textiles, paper, leather, and

Highlights

- The adsorption of MB dye by SDO, PSD, and SSD is best modelled by LNR and PSO.
- SDO, PSD, and SSD are effective and cheap biosorbents for the confiscation of MB dye.
- The impact on the sorption efficiency of SDO, PSD, and SSD is influenced by the pH.
- The Q_m for MB dye onto SDO, SSD and PSD were 200, 526 and 769 mg/g, respectively.

✉ Ahmed El Nemr
ahmedmoustafaelnemr@yahoo.com;
ahmed.m.elnemr@gmail.com

paint industries are major users of synthetic and toxic dyes, basically aimed at the coloring of their products [28–30].

The global dye market is currently valued at over 32 billion US dollars (USD) and is expected to reach 42 billion USD in 2021 [31]. Synthetic dyes are produced in excess of 7.00×10^5 tons per year, with approximately 15.00% of these synthetic dyes being released into water bodies (aquatic environments) [32]. These dyes are carcinogenic, toxic, and xenobiotic and they are divided into solvent, reactive, basic, vat, and direct dyes based on their chromophore structure. These synthetic dyes are exclusively decomposable in 47.00% of cases [28, 33]. Hence, dye has been considered one of the foremost sources of severe environmental pollution owing to the fast and aggressive industrial advancement and extensive utilization of its products [34–36].

Industrial effluents, instigated by the production processes of the cosmetics, textiles, paper, leather, and paint industries, are known to have a significant quantity of toxic aromatic dyes, mostly the thiazine cationic dyes such as methylene blue (MB) [37–40]. Notwithstanding the valuable uses of MB ($C_{16}H_{18}ClN_3S$) in various scientific domains, the dye has detrimental effects on humans and other living organisms as well as the environment owing to its water solubility tendency [41, 42]. It is toxic, a mutagenic reagent, and is supposed to be a cancer-instigating dye [24]. The colored effluents disposed of, released, or discharged during the production processes of the cosmetics, textiles, paper, leather, and paint industries into the ecosystem are one of the predominant causes of the ensuing environmental pollution as well as awkwardness in the water bodies (aquatic environment) in particular [24, 29, 43, 44]. The MB is a characteristic industrial effluent, and it is one of the prevalent commercial thiazine and azo dyes [38, 39, 43, 45].

Also, MB dye is conceivably detrimental to human health and contributes to instigating chronic toxicity, mostly to the central nervous system [24]. The effluents and wastes generated by the cosmetics, textiles, paper, leather, and paint industries are highly colored, contain salt concentrations in high quantities, and have high biological oxygen demand as well as chemical oxygen demand values. As a result, removing MB dye and other toxic industrial waste is critical for a better and healthier environment and well-being [24, 29, 46]. For the removal of MB dye and other industrial effluents (generated by the cosmetics, textiles, paper, leather, and paint industries), a variety of effluents and waste treatment and management technologies has been investigated, including adsorption, electrochemical, ion exchange, photocatalysis, oxidation–reduction, membrane filtration, catalytic, and biological/organic treatment and processes [47–51]. Amongst the aforementioned removal and management technologies, adsorption seems to be the most economical and efficient technique, owing to its inexpensiveness, easy operational principle, and high effluent uptake capacities

for the removal of dyes and other industrial effluents from wastewater [24, 48, 52].

Some industrial processes usually utilize activated carbon (AC) as an adsorbing reagent (biosorbent) due to its high absorbency as well as its specific surface area. However, due to its high production cost for regeneration tenacities, AC acquired from the market is usually expensive. Hence, the concept of using nanomaterials (NMs) as adsorbing reagents (biosorbents) is now gaining traction [53]. Though some NMs, such as carbon nanotubes, nano zerovalent iron, and titania nanotubes, are believed to be toxic and ineffective at removing dyes [48]. Several efforts have been made to mitigate these limitations via the preparation of the NMs from cellulose-based, tannin-based, and lignin-based sources, all of which have been proven to have massive potential for the adsorption and treatment of dyes and other industrial effluents, and they are considered affordable, easily accessible, biodegradable, and non-hazardous materials for the amputation of effluents in general as well as cationic MB dye in particular, from wastewater [3, 24, 54, 55]. Reportedly, these cellulose-based, tannin-based, and lignin-based adsorbing reagents (biosorbents) are derived from the cells of plants, mostly from agro-waste materials such as waste from watermelon, sugarcane, orange, wheat straw, maize, jackfruit, rice, mango, cloves, palm fruits, coconut, wood, and other agroforestry ingredients [3, 24, 48].

Therefore, formulating innovative, easily accessible, and non-hazardous adsorbing reagents (biosorbents) with high-uptake proficiencies is a contemporary and continuous global issue for the adsorption and treatment of dyes and other industrial effluents from wastewater. Hence, this present study emphasizes and re-explores the prospects of using a new, affordable, easily accessible, biodegradable, and non-hazardous adsorbing reagent (biosorbents) prepared from sawdust (SD) agro-waste materials for the production of SD ozone (SDO) biochar, purified SD (PSD) biochar, and sonicated SD (SSD) biochar. The preparation, characterization, and morphological studies as well as the application of these produced SDO, PSD, and SSD biochars for the adsorption and treatment of MB dye from wastewater were considered. The batch adsorption studies for the adsorption

Table 1 BJH data analysis of PSD, SSD and SDO biochars

Biochar	ap ; $m^2 g^{-1}$	Vp ; $m^3 g^{-1}$	r_p , peak (area); nm
PSD	3.5890	0.012872	1.22
SSD	4.5740	0.015620	1.22
SDO	2.1516	0.0057151	1.66

Table 2 EDX analysis data of SD, SSD, and ASD biochars

Biochar Elements	SD biochar		SSD biochar		ASD biochar	
	Wt%	At%	Wt%	At%	Wt%	At%
C	48.23	66.33	55.35	63.39	57.19	64.32
N	ND	ND	ND	ND	7.63	7.32
O	28.15	28.98	28.48	28.31	32.65	27.42
S	23.62	12.13	16.17	8.30	2.23	0.94

ND, not detected

and treatment of MB dye from industrial toxic effluents were characterized, and the assessment of the optimization of the various adsorption factors and parameters was systematically considered. Also, the calculation of the adsorption rate isotherms, thermodynamics, and kinetics was essentially highlighted.

2 Materials and methods

2.1 Materials and equipment

Wood sawdust was collected from a local wood market in Alexandria, Egypt, and was used as a raw material for the preparation of biochar. The standard stock solution

Table 3 Determined parameters of PFO and PSO models using SDO biochar

Parameter			PFO			PSO		
SDO dosage (g.L ⁻¹)	MB dye Conc. (mg/L)	q_e (exp.)	q_e (calc.)	$K_1 \times 10^3$	R^2	q_e (calc.)	$K_2 \times 10^3$	R^2
0.5	20	35.41	5.00	236.41	1.000	37.59	1.18	0.969
	40	57.85	10.03	122.11	1.000	66.23	0.39	0.956
	60	84.95	15.58	12.08	0.998	88.50	0.34	0.920
	80	110.35	21.23	5.49	0.996	128.21	0.28	0.977
	100	134.34	27.55	2.32	0.992	144.93	0.27	0.976
	120	143.93	34.60	1.00	0.979	156.25	0.11	0.791
1.0	20	19.88	7.28	40.30	0.986	20.28	14.82	0.999
	40	39.34	33.55	56.65	0.869	42.74	2.05	0.993
	60	59.37	140.60	60.34	0.968	68.03	0.73	0.992
	80	78.30	79.74	23.72	0.935	91.74	0.32	0.979
	100	92.58	347.94	46.29	0.714	106.38	0.20	0.896
	120	92.35	73.54	8.29	0.991	104.17	0.17	0.854
2.0	20	9.95	2.78	44.45	0.176	10.09	45.55	0.999
	40	19.90	40.14	60.11	0.240	20.75	9.38	0.997
	60	29.81	6.77	51.82	0.987	33.00	2.22	0.990
	80	39.63	102.24	45.14	0.851	46.08	0.68	0.974
	100	49.44	55.49	22.57	0.895	58.82	0.42	0.945
	120	52.80	61.96	22.80	0.940	68.49	0.25	0.890
3.0	20	6.64	0.60	15.20	0.368	6.63	92.63	0.999
	40	13.30	1.24	38.00	0.900	13.42	62.79	1.000
	60	19.92	17.68	60.34	0.963	21.05	6.48	0.997
	80	26.45	20.22	49.74	0.938	28.99	2.72	0.992
	100	32.99	37.04	24.87	0.822	38.76	0.70	0.952
	120	37.56	53.59	34.08	0.913	46.73	0.53	0.947
4.0	20	4.98	0.31	24.64	0.871	5.00	236.41	1.000
	40	9.98	0.51	31.32	0.807	10.03	122.11	1.000
	60	14.95	4.96	48.13	0.812	15.58	12.08	0.998
	80	19.88	10.39	47.21	0.942	21.23	5.49	0.996
	100	24.85	38.42	56.88	0.935	27.55	2.32	0.992
	120	29.20	33.26	32.93	0.968	34.60	1.00	0.979

Table 4 Determined parameters of FD and INT models using SDO biochar

SSD dosage (g.L ⁻¹)	MB Conc. (mg/L)	INT		FD	
		K_{dif}	R^2	K_{FD}	R^2
0.5	20	1.826	0.957	-0.051	0.704
	40	3.919	0.991	-0.015	0.944
	60	4.775	0.983	-0.009	0.962
	80	7.887	0.910	-0.026	0.968
	100	7.887	0.995	-0.050	0.713
	120	8.877	0.903	-0.047	0.637
1.0	20	0.525	0.709	-0.040	0.986
	40	2.351	0.767	-0.057	0.869
	60	4.308	0.839	-0.060	0.968
	80	5.703	0.964	-0.005	0.063
	100	6.165	0.967	-0.046	0.714
	120	5.943	0.949	-0.001	0.006
2.0	20	0.214	0.623	-0.044	0.982
	40	0.924	0.606	-0.052	0.857
	60	1.960	0.755	-0.060	0.987
	80	2.752	0.969	-0.045	0.851
	100	3.499	0.961	-0.024	0.807
	120	4.123	0.948	-0.022	0.870
3.0	20	0.112	0.498	-0.015	0.368
	40	0.264	0.461	-0.038	0.900
	60	1.037	0.693	-0.050	0.938
	80	1.658	0.776	-0.060	0.963
	100	2.262	0.962	-0.025	0.822
	120	2.948	0.919	-0.034	0.913
4.0	20	0.038	0.576	-0.025	0.871
	40	0.152	0.415	-0.031	0.807
	60	0.693	0.635	-0.048	0.812
	80	1.109	0.711	-0.047	0.942
	100	1.595	0.836	-0.057	0.935
	120	2.191	0.903	-0.033	0.968

was made from MB dye (Assay 99%) obtained from Sigma-Aldrich, USA. Pg instrument model T80 UV/visible high-performance double beam spectrophotometer matched with glass cells of 1 cm optical path, Shaker [A JS shaker (JSOS-500)], and pH meter JENCO (6173) was used in this study. The adsorption–desorption isotherm of PSD, SDO, and SSD biochars was carried out in an N₂ atmosphere based on a thermodynamic model. The PSD, SDO, and SSD biochars' surface area was calculated by N₂ adsorption at 77 K with the aid of a surface area and pore analyzer (BELSORP – Mini II, BEL Japan, Inc.) [56, 57]. Surface area (S_{BET}) (m²/g), monolayer volume (V_m) (cm³ (STP)), average pore diameter (MPD) (nm), total pore volume (p_0/p_0) (cm³/g), and energy constant (C) values of PSD, SDO, and SSD biochars were calculated using the graph (Fig. 1). The mesoporous surface

area (S_{mes}), microporous surface area (S_{mi}), mesoporous volume (V_{mes}), and microporous volume (V_{mi}) of PSD, SDO, and SSD biochars were evaluated using the Barrett–Joyner–Halenda (BJH) method. The BELSORP analysis program software was used to perform the calculations. The pore size dispersion was also determined from the desorption isotherm using the BJH technique [58]. With the help of a scanning electron microscope (SEM), the shape of the biochars surface was investigated (QUANTA 250). The functional groups on the surface of biochars' were studied using Fourier transform infrared (FTIR) spectroscopy (VERTEX70) connected with ATR unit model V-100. IR-observable functional groups on the PSD, SDO, and SSD biochars' surface were detected in the wavenumber range of 400–4000 cm⁻¹. Thermal analyses were carried out using the SDT650-Simultaneous Thermal Analyzer device at a temperature range of 50–1000 °C and a ramped temperature of 5 °C/min.

2.2 Methods

2.2.1 SD Biochar preparation

The collected sawdust was thoroughly washed with tap water several times to remove dust and subsequently dried in an oven at 70 °C for 72 h. A total of 500 g of wood sawdust in 2000 ml solution of 80.00% H₂SO₄ was boiled in a refluxed system at 220 °C for 2 h, and then, the samples were filtered and washed with distilled water until the washing solution become neutral followed by washing with ethanol. The final product of biochar was dried in an oven at 120 °C, and its weight was then determined (220 g). The obtained biochar from this reaction was labelled (SD).

2.2.2 SSD biochar preparation

The prepared (SD) biochar was suspended in water and subsequently subjected to ultrasonic energy (Elma, TRANSSONIC NIC T890H/Germany, High Frequency peak 600 W, 35 kHz) for 60 min for physical activation to take place. The sonicated solution was filtered and washed with distilled water and dried at 120 °C. The obtained sonicated sawdust biochar from this treatment was labelled as SSD.

2.2.3 PSD biochar preparation

The SD biochar (30 g) was boiled in ethanol (200 ml) for 2 h and then collected and filtered. The solid biochar was dried at 120 °C for 24 h and labelled as PSD.

Table 5 Determined parameters of PFO and PSO models using SSD biochar

Parameter			PFO			PSO		
SSD dosage (g.L ⁻¹)	MB Conc. (mg/L)	q_e (exp.)	q_e (calc.)	$K_f \times 10^3$	R^2	q_e (calc.)	$K_2 \times 10^3$	R_2
0.5	20	39.6	1.543	26.48	0.941	39.68	51.63	1.00
	40	78.8	3.542	33.16	0.941	78.74	32.92	1.00
	60	118.3	7.384	32.47	0.810	119.05	8.60	1.00
	80	157.4	18.026	30.17	0.836	158.73	5.29	1.00
	100	196.7	102.353	44.45	0.988	204.08	1.08	1.00
	120	236.6	140.217	45.14	0.963	243.90	0.89	1.00
1.0	20	19.8	0.701	26.71	0.894	19.84	132.30	1.00
	40	39.6	0.756	26.95	0.737	39.53	112.30	1.00
	60	59.5	1.216	26.25	0.927	59.52	64.15	1.00
	80	79.0	4.398	38.92	0.991	79.37	25.61	1.00
	100	98.7	4.092	32.70	0.891	99.01	23.18	1.00
	120	118.5	19.329	23.49	0.927	120.48	3.09	1.00
2.0	20	9.9	0.240	22.57	0.950	9.96	325.17	1.00
	40	19.9	0.572	27.87	0.846	19.92	186.67	1.00
	60	29.8	0.231	18.65	0.782	29.76	313.60	1.00
	80	39.7	2.064	23.26	0.837	39.68	181.44	1.00
	100	49.7	0.656	27.41	0.870	49.75	115.43	1.00
	120	59.6	6.380	30.40	0.970	59.88	13.74	1.00
3.0	20	6.6	0.209	32.93	0.971	6.65	520.00	1.00
	40	13.3	0.305	32.47	0.907	22.12	141.88	1.00
	60	19.9	0.132	18.42	0.938	19.92	475.48	1.00
	80	26.5	0.233	15.20	0.955	26.53	245.05	1.00
	100	33.2	0.236	16.58	0.889	33.22	232.31	1.00
	120	39.9	0.829	25.56	0.899	40.00	78.13	1.00
4.0	20	5.0	0.126	32.01	0.935	4.99	846.86	1.00
	40	10.0	0.055	14.51	0.520	9.98	1091.31	1.00
	60	15.0	0.097	11.52	0.884	14.97	697.23	1.00
	80	20.0	0.103	17.96	0.789	19.96	612.20	1.00
	100	24.9	0.190	27.41	0.901	24.94	402.00	1.00
	120	29.9	0.177	20.73	0.685	29.94	371.85	1.00

2.2.4 SDO biochar preparation

The prepared SD was subsequently subjected to ozone treatment in distilled water. For the treatment of SD with ozone, 50 g of prepared SD was ozonated in 200 ml distilled water for 2 h, then filtered, and washed with distilled water followed by ethanol. Finally, the ozonated SD biochar was dried at 120 °C for 48 h and labelled as SDO.

2.3 Adsorption measurement for MB dye

A stock solution of MB dye (1000 mg L⁻¹) was prepared by dissolving 1.0 g of MB dye in 1000 ml of distilled water, and this solution was diluted to have the required concentration for the removal test and the standard curve. The batch adsorption experiments were employed to evaluate

the adsorption capability, thermodynamic and kinetic parameters of SDO, SSD, and PSD which were prepared from SD. A series of Erlenmeyer flasks (300 ml) containing 100 ml of different concentrations of MB dye solution and different amounts of biochar was shaken at 200 rpm for a certain time. The sample pH was adjusted to the desired values with 0.1 M HCl or 0.1 M NaOH. About 0.5 ml of the solution in the Erlenmeyer flask was then separated from the adsorbent, and the concentration of MB dye was detected at different interval times and the equilibrium. The concentration of MB dye was determined by spectrophotometry at $\lambda_{\max}$ 665 nm [38, 59].

Initially, the slope of the standard curve correlated between known MB dye concentrations and related absorbance has been used to calculate the unknown MB dye concentration

Table 6 Determined parameters of FD and INT models using SSD biochar

SSD dosage (g.L ⁻¹)	MB conc. (mg/L)	INT			FD		
		K_{dif}	C	R^2	K_{FD}	C	R^2
0.5	20	0.18	37.66	0.656	-0.03	3.24	0.94
	40	0.28	75.79	0.637	-0.03	3.10	0.94
	60	1.18	105.96	0.736	-0.03	2.77	0.81
	80	1.70	138.76	0.693	-0.03	2.17	0.84
	100	6.52	127.30	0.788	-0.04	0.65	0.99
	120	5.66	172.08	0.912	-0.05	0.52	0.96
1.0	20	0.05	19.30	0.888	-0.03	3.34	0.89
	40	0.06	38.91	0.721	-0.03	3.96	0.74
	60	0.15	57.84	0.722	-0.03	3.89	0.93
	80	0.32	75.58	0.830	-0.04	2.89	0.99
	100	0.60	92.58	0.540	-0.03	3.18	0.89
	120	1.88	97.45	0.847	-0.02	1.82	0.93
2.0	20	0.02	9.71	0.847	-0.02	3.72	0.95
	40	0.03	19.55	0.924	-0.03	3.55	0.85
	60	0.03	29.46	0.693	-0.02	4.86	0.78
	80	0.05	39.13	0.629	-0.02	4.41	0.84
	100	0.08	0.48.85	0.736	-0.03	4.33	0.87
	120	0.39	55.07	0.931	-0.03	2.24	0.97
3.0	20	0.01	6.51	0.913	-0.03	3.56	0.97
	40	0.01	13.13	0.942	-0.03	3.93	0.91
	60	0.02	19.73	0.753	-0.02	4.86	0.94
	80	0.03	26.23	0.859	-0.02	4.60	0.95
	100	0.04	32.75	0.730	-0.02	4.60	0.93
	120	0.07	39.05	0.816	-0.03	3.87	0.90
4.0	20	0.01	4.90	0.896	-0.03	3.68	0.94
	40	0.01	9.88	0.632	-0.01	5.20	0.52
	60	0.01	14.85	0.857	-0.01	5.04	0.88
	80	0.01	19.82	0.850	-0.02	5.27	0.79
	100	0.03	24.66	0.703	-0.03	4.88	0.90
	120	0.04	29.56	0.617	-0.02	5.13	0.69

(C_t) at time intervals from the absorbance value practically detected. Equation (1) shows the C_t calculation.

$$C_t = \frac{\text{absorbance at interval time } t}{\text{slope of standard curve}} \quad (1)$$

MB dye concentration at equilibrium C_e ; at stable values of absorbance. Equation (2) shows the C_e calculation.

$$C_e = \frac{\text{absorbance at equilibrium}}{\text{slope of standard curve}} \quad (2)$$

The adsorption capacities of MB dye at equilibrium (q_e) were calculated from Eq. (3):

$$q_e = \frac{C_0 - C_e}{W} \times V \quad (3)$$

where q_e is the amount of MB dye per unit of adsorbent at equilibrium (mg g⁻¹); C_0 and C_e are the initial and equilibrium concentrations of MB dye in the liquid phase (mg.L⁻¹), respectively; V is the volume of the solution (L) and W is the mass of adsorbent (PSD, SDO, or SSD) in gram.

2.3.1 Effect of solution pH, initial MB dye concentration, adsorbent dosage, and contact time

The effect of pH was studied for SDO, SSD, and PSD using 100 ml of 100 ppm of initial MB dye concentration using solution pH (2–12). The pH_{PZC} has been studied for the SDO, SSD, and PSD biochars following the literature-reported method [60].

The isotherm study for sawdust biochars was performed using various initial concentrations of MB dye solution

Table 7 Determined parameters of PFO and PSO models using PSD biochar

Parameter			PFO			PSO		
PSD dosage (g.L ⁻¹)	MB Conc. (mg L ⁻¹)	q_e (exp.)	q_e (calc.)	$k_f \times 10^3$	R^2	q_e (calc.)	$k_2 \times 10^3$	R^2
0.5	100	198.25	8.44	23.72	0.870	200.00	4.90	1.000
	150	297.86	203.24	35.93	0.993	312.50	0.32	0.999
	200	396.56	493.06	38.23	0.993	434.78	0.13	0.997
	300	590.75	1378.16	33.62	0.836	746.27	0.03	0.955
	400	722.88	2327.02	34.55	0.727	854.70	0.03	0.989
1.0	100	99.28	1.61	18.654	0.849	99.01	27.57	1.000
	150	149.25	3.39	20.036	0.810	149.25	9.98	1.000
	200	198.91	22.37	35.006	0.870	204.08	1.24	0.999
	300	298.55	176.73	44.218	0.960	312.50	0.34	0.997
	400	397.94	428.35	41.684	0.943	434.78	0.17	0.998
1.5	100	66.27	1.64	12.44	0.944	66.23	69.09	1.000
	150	99.53	1.58	26.48	0.864	100.00	52.63	1.000
	200	132.68	1.70	20.96	0.824	133.33	23.44	1.000
	300	199.15	6.06	25.10	0.793	200.00	4.63	1.000
	400	265.50	74.15	36.85	0.898	277.01	0.49	0.998
2.0	100	49.76	3.10	9.67	0.951	49.75	115.43	1.000
	150	74.69	1.65	18.42	0.961	74.63	85.50	1.000
	200	99.54	1.02	20.73	0.936	100.00	52.63	1.000
	300	149.42	2.55	25.56	0.814	149.25	12.13	1.000
	400	199.24	17.21	35.47	0.827	204.08	1.44	0.999
2.5	100	39.84	0.39	17.96	0.987	39.84	131.25	1.000
	150	59.77	0.41	11.75	0.954	59.88	99.6	1.000
	200	79.64	0.61	23.26	0.958	79.37	99.23	1.000
	300	119.61	2.32	23.95	0.843	120.48	16.02	1.000
	400	159.48	5.25	26.71	0.76	161.29	3.84	1.000

(20, 40, 60, 80, 100, and 120 mg.L⁻¹) using different doses of SDO and SSD biochars (0.5, 1.0, 2.0, 3.0, and 4.0 g.L⁻¹) as well as the various concentrations of MB dye solution (100, 150, 200, 300, and 400 mg.L⁻¹) using different doses of PSD biochar (0.5, 1.0, 1.5, 2.0, and 2.50 g.L⁻¹). The samples were shaken at 200 rpm, and the MB dye concentration was analyzed at different time intervals at room temperature (25 ± 2 °C).

In the kinetics study, SDO and SSD biochars of various doses (0.5, 2.0, 3.0, and 4.0 g L⁻¹) were added to 300-ml Erlenmeyer flasks containing 100 ml of initial MB dye solution (20, 40, 60, 80, 100, and 120 mg L⁻¹), and PSD biochar of various doses (0.5, 1.0, 1.5, 2.0, and 2.5 g L⁻¹) was added to 300-ml Erlenmeyer flasks containing 100 ml of initial MB dye solution (100, 150, 200, 300, and 400 mg L⁻¹). The flasks were shaken at 200 rpm and samples were taken from the solution at different interval times for the analysis of the residual concentration of MB dye.

3 Results and discussion

3.1 Characterization of biochars

3.1.1 Estimation of biochar surface functional groups by FTIR

FTIR analysis was performed on SDO, SSD, and PSD biochars to identify the functional groups on their surfaces and to know the effect of modification on the disappearance or existence of a new functional group. Figure 1 shows the FTIR spectra of SDO, SSD, and PSD biochars. Bands at 3350 and 3215 cm⁻¹ represent the O–H stretching vibration that existed in PSD, SDO, and SSD biochars, while the band at 2931.5 cm⁻¹ represents –C–H stretch of the alkyl in PSD, SDO, and SSD biochars. The band from 1800–1450 cm⁻¹ known as “overtones” as band 1695.2 cm⁻¹ in PSD and SSD was dramatically reduced in SDO, whereas the band at 1592 cm⁻¹ –C–C– stretch

Table 8 Determined parameters of FD and INT models using PSD biochar

PSD dosage (g.L ⁻¹)	MB Conc. (mg/L)	INT			FD		
		K_{dif}	C	R^2	K_{FD}	C	R^2
0.5	100	1.26	182.86	0.460	-0.02	3.16	0.870
	150	9.30	179.18	0.783	-0.04	0.38	0.993
	200	17.79	169.12	0.756	-0.04	-0.22	0.993
	300	36.78	94.85	0.829	-0.03	-0.85	0.836
	400	40.90	130.16	0.980	-0.03	-1.17	0.727
1.0	100	0.02	9.67	0.415	-0.02	4.12	0.849
	150	0.07	14.08	0.387	-0.02	3.79	0.810
	200	0.42	14.81	0.438	-0.04	2.19	0.870
	300	1.02	17.27	0.610	-0.04	0.52	0.960
	400	1.55	20.24	0.726	-0.04	-0.07	0.943
1.5	100	0.05	65.60	0.748	-0.01	4.69	0.944
	150	0.09	98.37	0.606	-0.03	4.14	0.864
	200	0.26	129.43	0.508	-0.02	4.36	0.824
	300	1.54	180.61	0.379	-0.03	3.49	0.793
	400	7.89	168.43	0.587	-0.04	1.28	0.898
2.0	100	0.03	49.37	0.896	-0.01	4.97	0.951
	150	0.05	74.05	0.704	-0.02	4.81	0.961
	200	0.08	98.48	0.740	-0.02	4.62	0.939
	300	0.63	141.85	0.363	-0.03	4.07	0.814
	400	3.74	154.04	0.459	-0.04	2.45	0.827
2.5	100	0.03	39.49	0.895	-0.02	4.64	0.987
	150	0.03	59.30	0.838	-0.01	4.99	0.954
	200	0.04	79.15	0.829	-0.02	4.87	0.958
	300	0.45	114.19	0.375	-0.02	3.94	0.843
	400	1.78	138.11	0.360	-0.03	3.41	0.760

(in-ring) was unaffected by the different treatments applied to SD biochar [61]. Bands in biochars between 1470 and 900 cm⁻¹ represent C-O functional groups and show no significant changes as a result of the different treatments applied to the SD biochar. The bands at 1027, 1029, and 1033 cm⁻¹ in SDO, PSD, and SSD, respectively, are related to the C-O-H functional group [36, 37, 62].

Figure 2 shows the FTIR spectrum of PSD, SSD, and SDO biochars after they have been treated with MB dye for 3 h. It was discovered in all of the FTIR analyses of all tested biochars after they had been exposed to an MB dye removal process that there were bands at 1591, 1485, 1392, and 1340 cm⁻¹, which correspond to the MB dye.

Table 9 The experimental two-parameter isotherm models utilized for the MB dye confiscation to SBO biochar and its parameters adopted from experimental data fitting

Isotherm model	Isotherm parameter	SDO dosage (0.5 g. L ⁻¹)
FRH	$1/n$	0.491
	K_F (mg ^{1-1/n} L ^{1/n} g ⁻¹)	21.662
	R^2	0.957
LNR	Q_m (mg/g)	200.0
	K_L	0.05
	R^2	0.851

Table 10 The experimental isotherm models utilized for the MB dye confiscation to SSB biochar and its parameters adopted from experimental data fitting

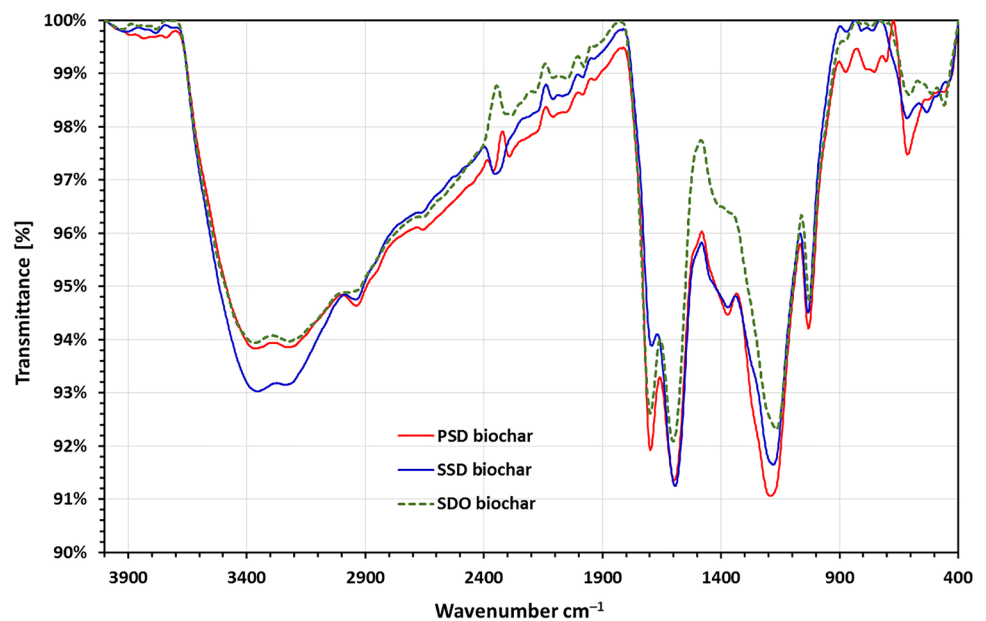
Isotherm model	Isotherm parameter	SSD dosage (0.5 g. L ⁻¹)
FRH	$1/n$	0.832
	K_F (mg ^{1-1/n} L ^{1/n} g ⁻¹)	132.98
	R^2	0.986
LNR	Q_m (mg/g)	526.3
	$K_L \times 10^3$	333.3
	R^2	0.831

Table 11 The experimental isotherm models utilized for the MB dye confiscation to PSB biochar and its parameters adopted from experimental data fitting

Isotherm model	Isotherm parameter	PSD dosage (0.5 g. L ⁻¹)
FRH	$1/n$	0.30
	K_F (mg ^{1-1/n} L ^{1/n} g ⁻¹)	284.32
	R^2	0.785
LNR	Q_m (mg/g)	769.23
	K_L	0.57
	R^2	0.999

3.1.2 Biochars' surfaces analysis

The influence of sonication and ammonia solution treatment on the surface properties of wood sawdust biochar was investigated by N₂ adsorption–desorption. The Brunauer–Emmett–Teller (BET) and BJH methods were used to calculate the specific characteristic of biochar surfaces. Figure 3 shows that the BET-specific surface area of biochars decreased as SSD (4.0098 m².g⁻¹) > PSD (2.92 m².g⁻¹) > SDO (1.975 m²/g). It is noted that modifications affect the specific surface area and the effect of physical modification by sonication is more than chemical modification with ozone treatment. The mean pore diameter decreased with modifications in the order PSD (16.98 nm) > SSD (14.73 nm) > SDO (10.716 nm). The effect of ozone modification is greater than sonication on pore diameter decreasing due to the introduction of OH groups. Pore types are mesoporous. The total pore volume of PSD, SSD, and SDO biochars were 12.254 × 10⁻³, 14.77 × 10⁻³ and 5.291 × 10⁻³ cm³ g⁻¹, respectively. Figure 3c shows the BJH data of PSD, SSD, and SDO biochars, and Table 1 includes their surface attributes.

Fig. 1 FTIR analysis of PSD, SSD, and SDO biochars before being subjected to MB dye**Table 12** Assessment of the optimum sorption capacity (Q_m) for MB dye employing different biochars

Biosorbents	Q_m (mg g ⁻¹)	References
SDO biochar	200.0	This Study
SSD biochar	526.3	This Study
PSD biochar	769.23	This Study
Activated carbon from <i>Ulva Lactuca</i>	344.83	[38]
Rice husk-activated carbon	370.71	[59]
Inactivated rosemary (RM) plant	153.17	[69]
Activated carbon from rosemary plant (RMAC)	110.67	[69]
Algae <i>D. Antarctica</i>	702.9	[74]
Jute stick charcoal	29.32	[75]
Citric acid-modified apricot stone	19.01	[78]
Marine green alga <i>Ulva lactuca</i>	40.2	[82]
Corn stigmata	106.3	[83]
Rice husk carbon	370.71	[84]
Sugar beet pulp	244.76	[85]
Sesame seed cake	108.69	[86]
Activated rice husk biochar	356.99	[87]
Watermelon rind	231.48	[88]
Cedar sawdust and	142.36	[89]
Crushed brick	96.61	[89]
Orange peel	280	[90]

3.1.3 Morphological properties of sawdust biochar surfaces

The surface morphology of sawdust raw material (RSD), PSD, SSD, and SDO biochars was investigated using SEM and reported in Fig. 4. As shown in Fig. 4a, b, the PSD

Fig. 2 FTIR analysis of PSD, SSD, and SDO biochars after being subjected to MB dye for 3 h

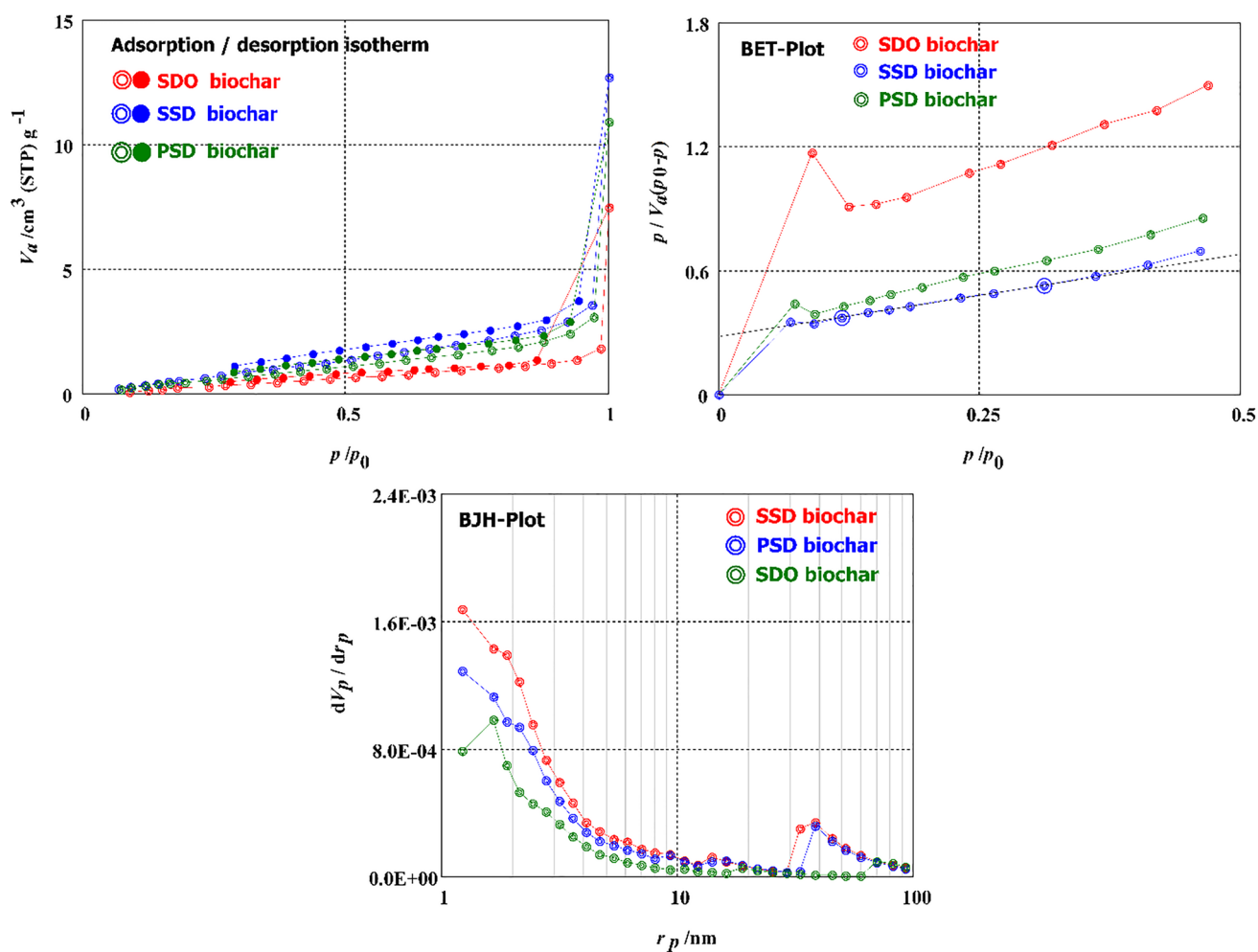
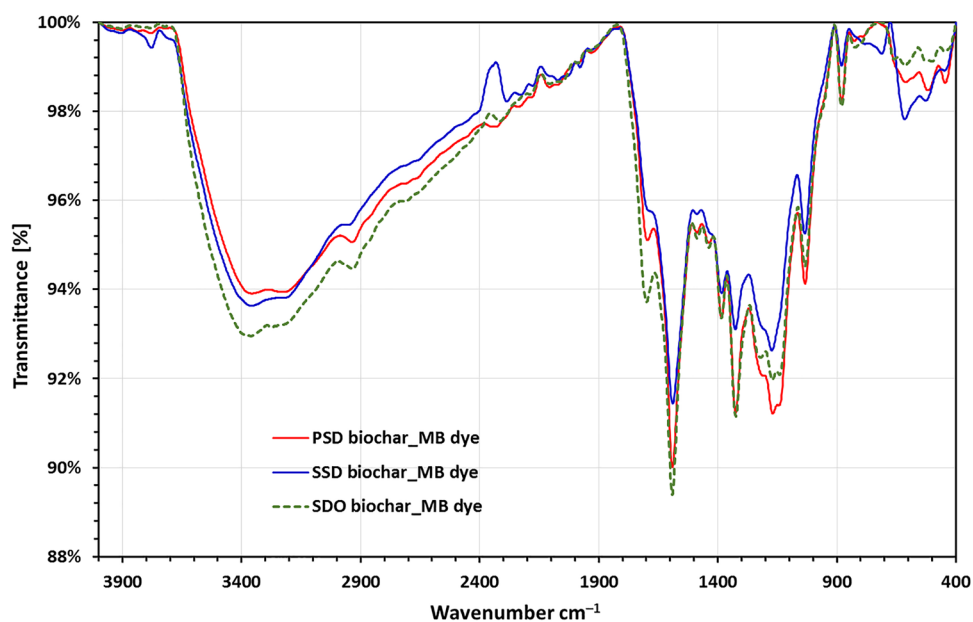


Fig. 3 a Adsorption–desorption, b BET, c BJH analyses of PSD, SSD, and SDO biochars.

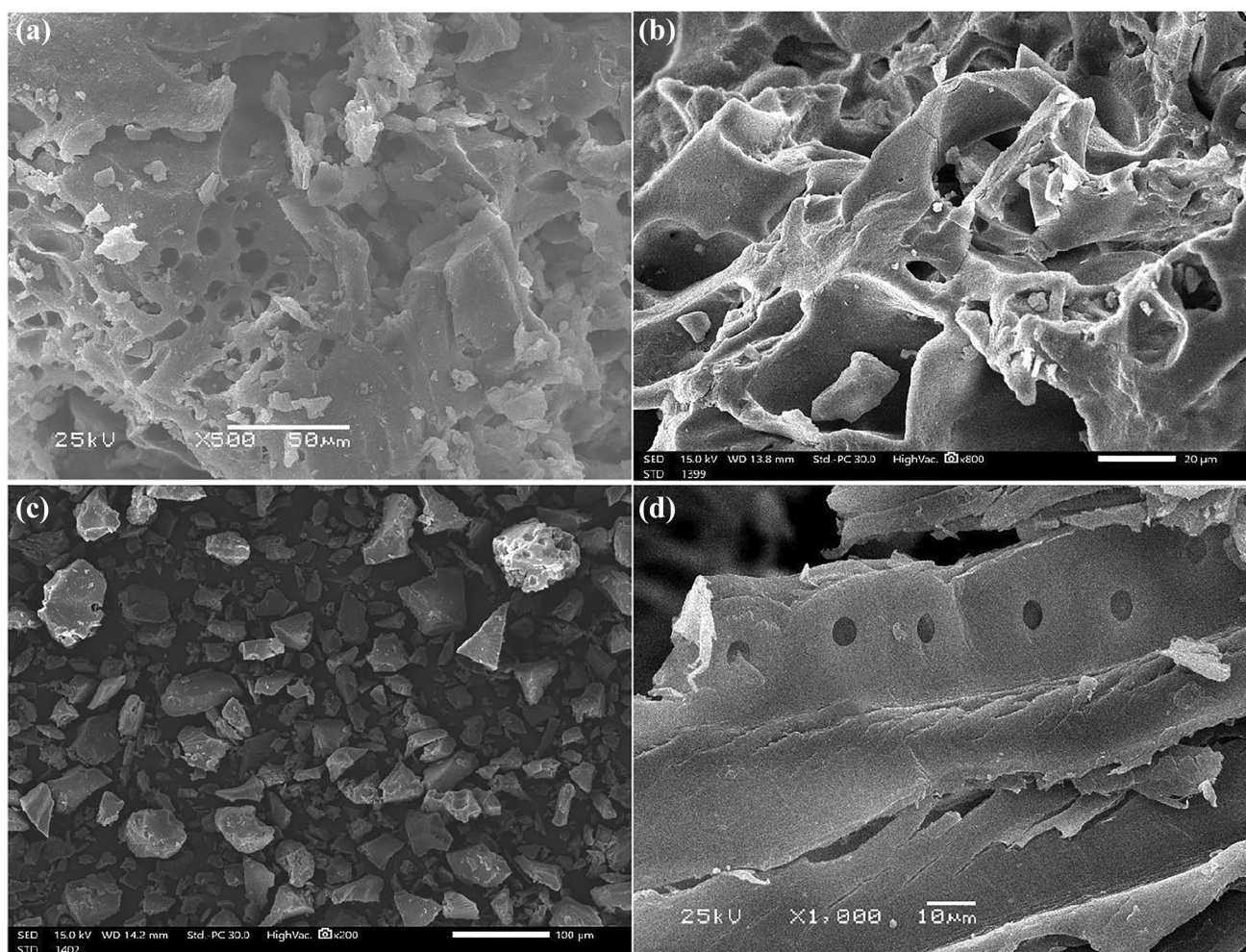


Fig. 4 SEM analysis of **a** PSD biochar, **b** SSD biochar, **c** SDO biochar, and **d** SD raw material

and SSD biochars appear clean and free of any particulate impurities; besides, there is no damage in the pores of the SSD which was observed as a result of sonication. Also, a small increase in the pore volume and the number of pores in SSD biochar due to sonication treatment of PSD biochar, which explains the small increase in the surface area of SSD biochar. Figure 4c shows the SDO biochar that little pores existed which reflects the small surface area for SDO biochar. This proves our previous finding that the treatment of biochar with ozone in water led to a decrease in the surface area due to pore blocking [36, 37, 62]. It is obvious that new pores of different sizes are created in SSD biochar as a result of sonication treatment; thus, the surface areas of the sonicated biochar increased while treatment with ozone in water led to the blocking of the pore and decrease the surface area of the produced SDO biochar. The SEM image of sawdust raw material represented in Fig. 4d showed no pores.

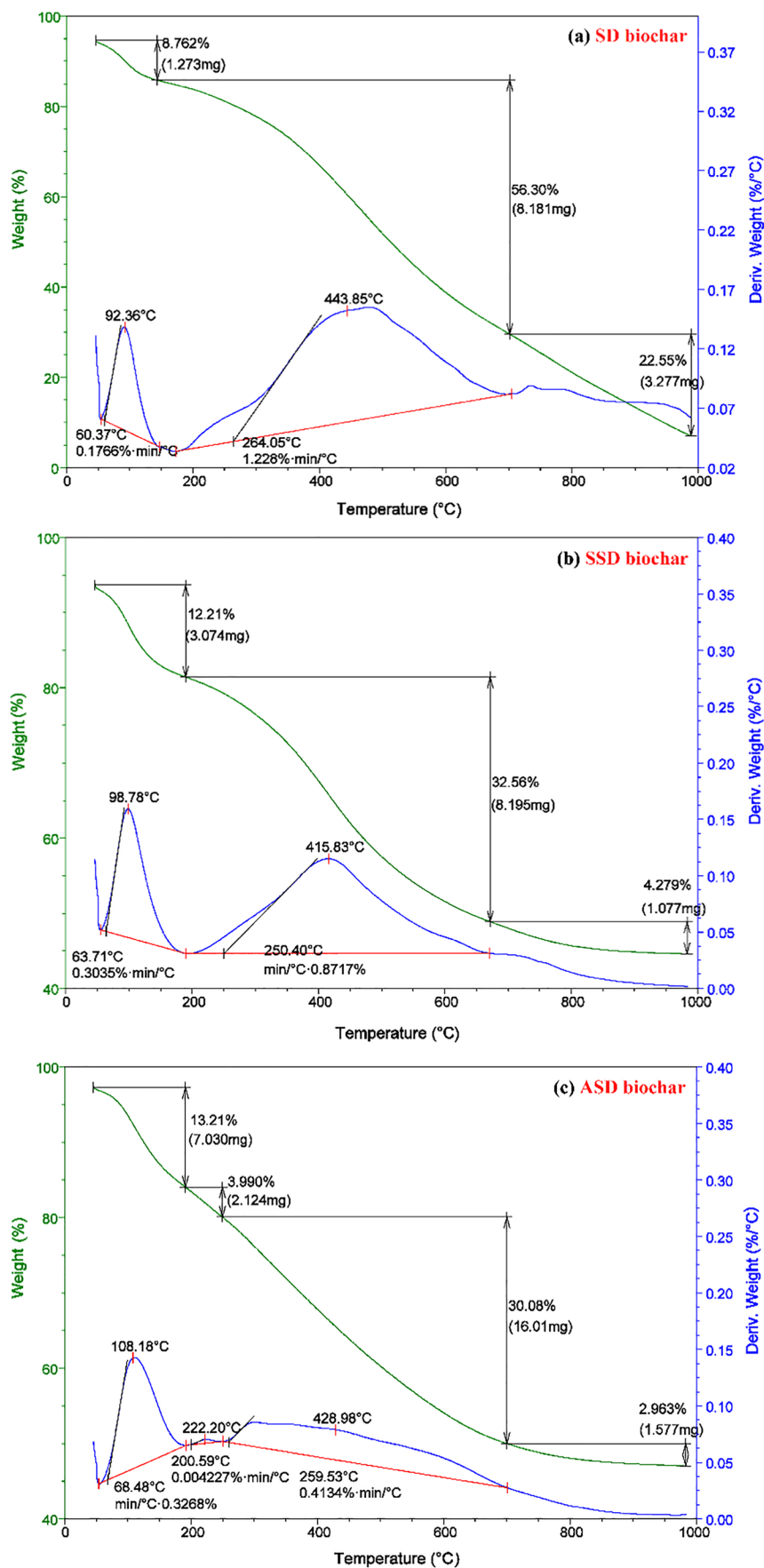
3.1.4 Elemental analysis of sawdust biochars

Energy dispersive X-ray spectrometer (EDX) was used to analyze the chemical compositions of sawdust biochar. The chemical compositions of the samples were analyzed with a dispersive X-ray spectrometer (EDAX). The element percent of SD, SSD, and ASD biochars were examined and reported in Table 2, which shows the absence of nitrogen peak before the modification with the NH_4OH reagent. The EDX analysis of ASD biochar proved the presence of about 7.63% nitrogen in sample weight.

3.1.5 Thermal characterization of biochars

Thermal gravimetric analysis (TGA) or thermogravimetric analysis in general means the measurement of

Fig. 5 Thermal gravimetrical analysis of **a** SD biochar, **b** SSD biochar, and **c** ASD biochar



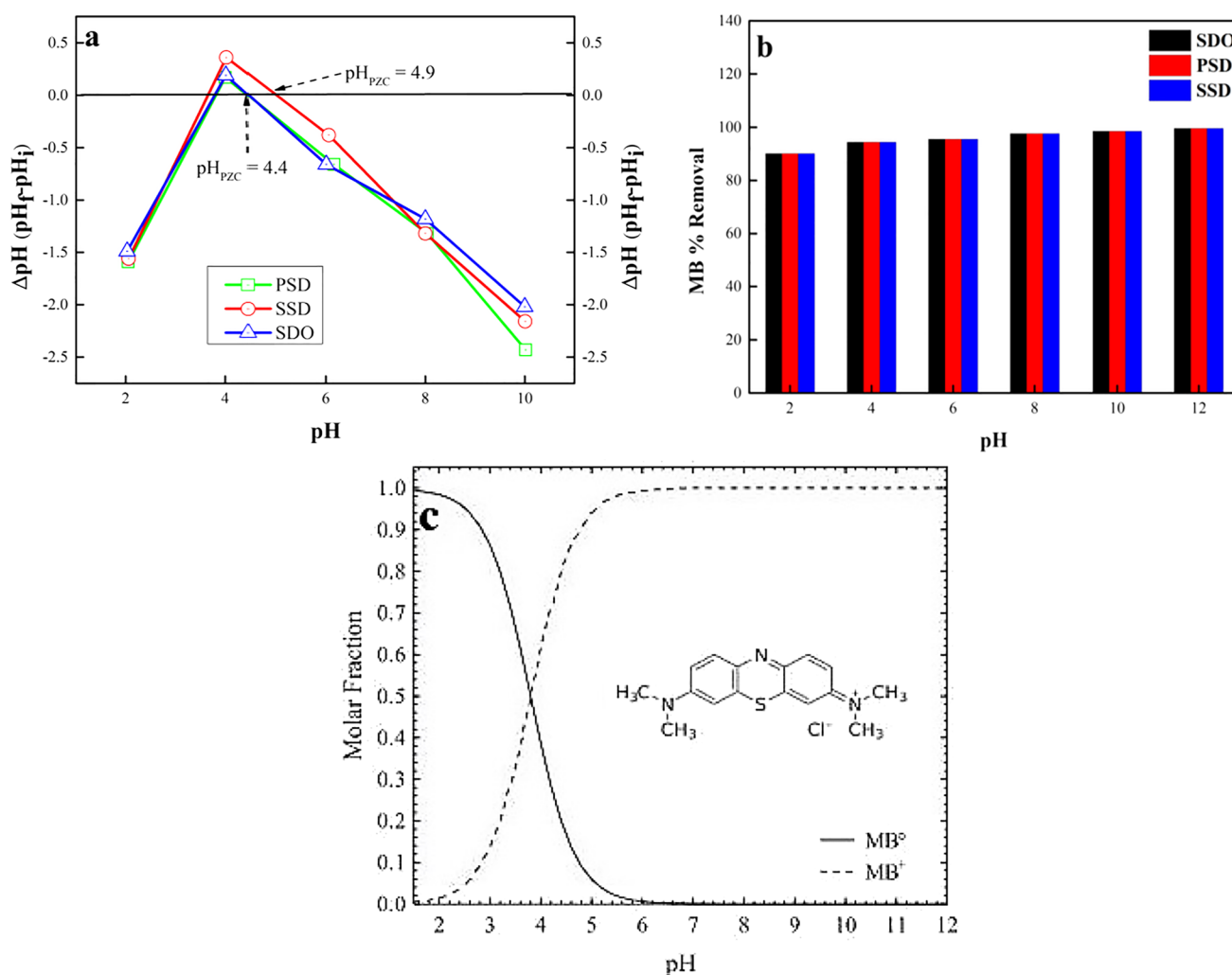


Fig. 6 **a** Determined pH_{PZC} of SDO, PSD, and SSD biochars **b** impact of pH on MB sorption to biochars and **c** the speciation and molecular structure diagram (insert) of MB was adapted from [63]

the weight loss during a user-defined temperature or heating process. Figure 5a and b show the decomposition of SD and SSD biochars, respectively, which takes place in three steps while the decomposition of the ASD biochar takes place in four steps (Fig. 5c). In SD biochar, the first step of decomposition occurs at temperatures ranging from 50 to 150 °C and involves the loss of surface-bound water and moisture present in the sample with an approximate weight loss of 6.76%. In the second step, temperatures ranging from 150 to 700 °C and an approximate weight loss of 56.30%, and in the third decomposition step, temperatures ranging from 700 to 1000 °C and an approximate weight loss of 22.55%. In SSD biochar, the first step of decomposition occurs at temperatures ranging from 50 to 180 °C, with an approximate weight loss of 12.21%; the second step, temperatures ranging from 180 to 675 °C and

approximate weight loss of 32.31%; and in the third decomposition step, temperatures ranging from 675 to 1000 °C and approximate weight loss of 4.28%. While in ASD biochar, the first step of decomposition occurs at temperatures ranging from 50 to 180 °C and involves approximately weight loss of 13.21%; the second step, temperatures ranging from 180 to 250 °C and approximate weight loss of 3.99%; and in the third decomposition step, temperatures ranging from 250 to 700 °C and approximate weight loss of 30.08%; and in fourth step, temperatures ranging from 700 to 1000 °C and approximate weight loss of 2.96%.

3.2 Effect of pH on the adsorption of MB dye

The adsorption of MB dye to different biomaterials is extremely conditional on the pH of the solution and the

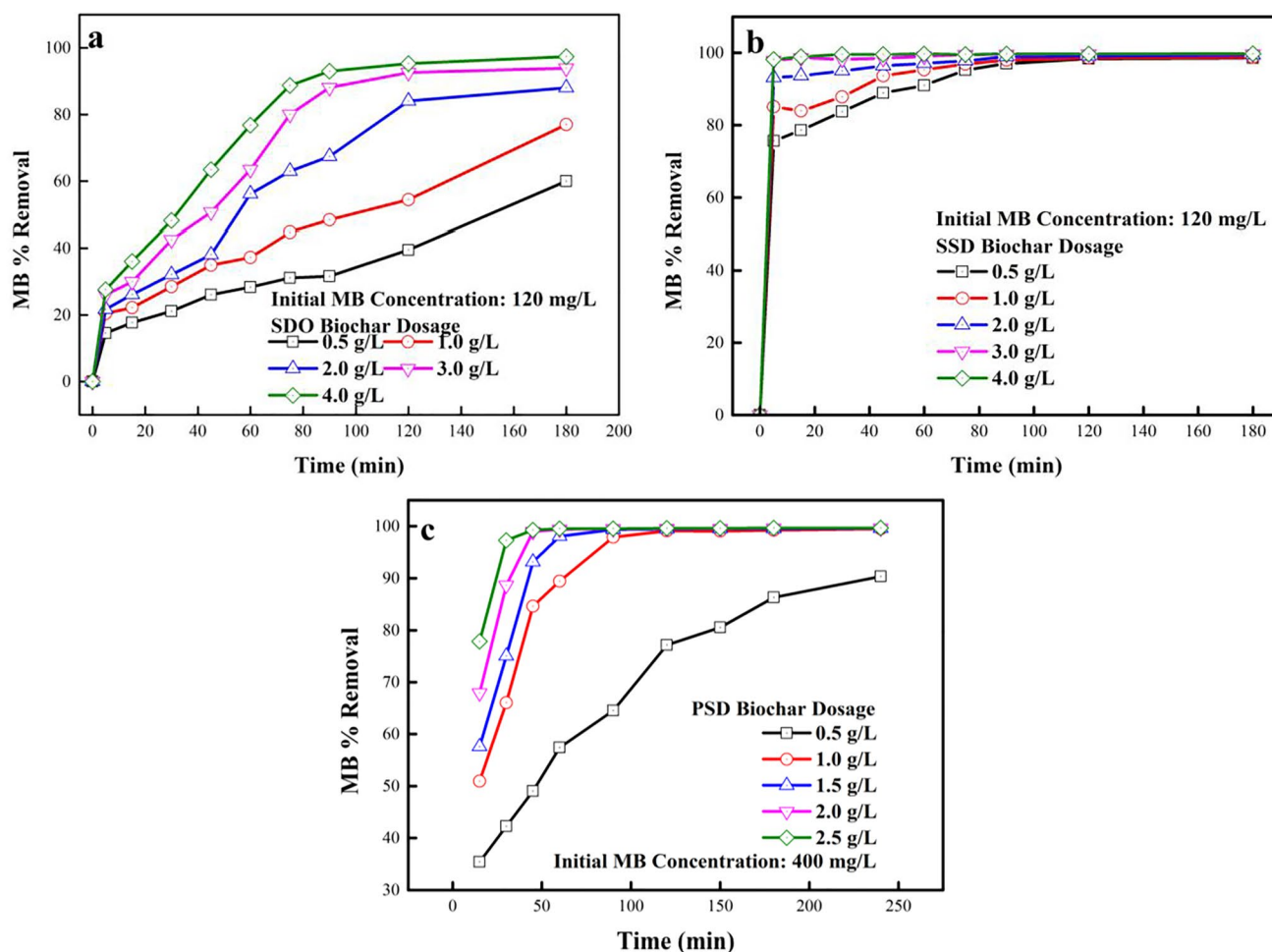


Fig. 7 Impact of biochar dosage on the removal of MB using **a** SDO, **b** SSD and **c** PSD biochars

biomaterial surface charge distribution. The electrostatic interactions of attractive or repulsive character between MB dye species and active sites on the surface of various biomaterials are affected by the solution pH. In a water-soluble solution, MB dye exists as undissociated molecules (MB^0) and cationic species (MB^1) (Fig. 6c). As observed in Fig. 6c, MB^0 and MB^1 (50% species each) coexist at $\text{pH} = \text{pK}_a = 3.8$. While MB^0 species (86%) and MB^1 species dominate and are only present at pH 3 and $\text{pH} > 6$ [63]. The surface charge distribution (pH_{pzc}) of SDO, SSD, and PSD biochars employed for the sequestration of MB dye ions is depicted in Fig. 6a. The determined pH_{pzc} for SDO, SSD, and PSD showing the near association that exist between the surface groups of the biochars and their surface charge were 4.4, 4.9, and 4.4. Hence, the surface charge was positively or negatively charged when the solution pH was $<$ or $>$ the pH_{pzc} . Figure 6b shows the impact of varying solution pH on MB dye confiscation and it was noticed that the % of MB dye ions sorbed to the SDO, SSD, and PSD biochars increased considerably as

the solution pH was varied from pH 2 to 12, with optimum % removal of MB dye ions noticed at pH 12. The low % of MB dye confiscated to the various biochars at pH 2 was ascribed to the electrostatic repulsion between the negative surface charges and the cationic sorbate undissociated species (MB^0), as surface sites on biochars are suggestive of having a considerably extra amount of negatively charged groups at low pH. Also, the increased competition between MB^+ with the H^+ and H_3O^+ ions for the biochar sorption sites leads to a reduced % of MB dye removed at acidic pH. The removal of MB dye to the various biochars at low pH values was due to interactions such as hydrogen bonding, π - π or π^+ - π interaction, and porous diffusion [64]. The improved % of MB dye removed to the various biochars was attributed to the electrostatic attraction between the dominant negatively surface charges (which increased with improving the solution pH) and the predominant MB dye species (MB^1 dye). Improving the solution pH was reported to increase the amount of hydroxyl ($-\text{OH}$) and carboxylate anion ($-\text{COO}^-$) groups on the biochar surface

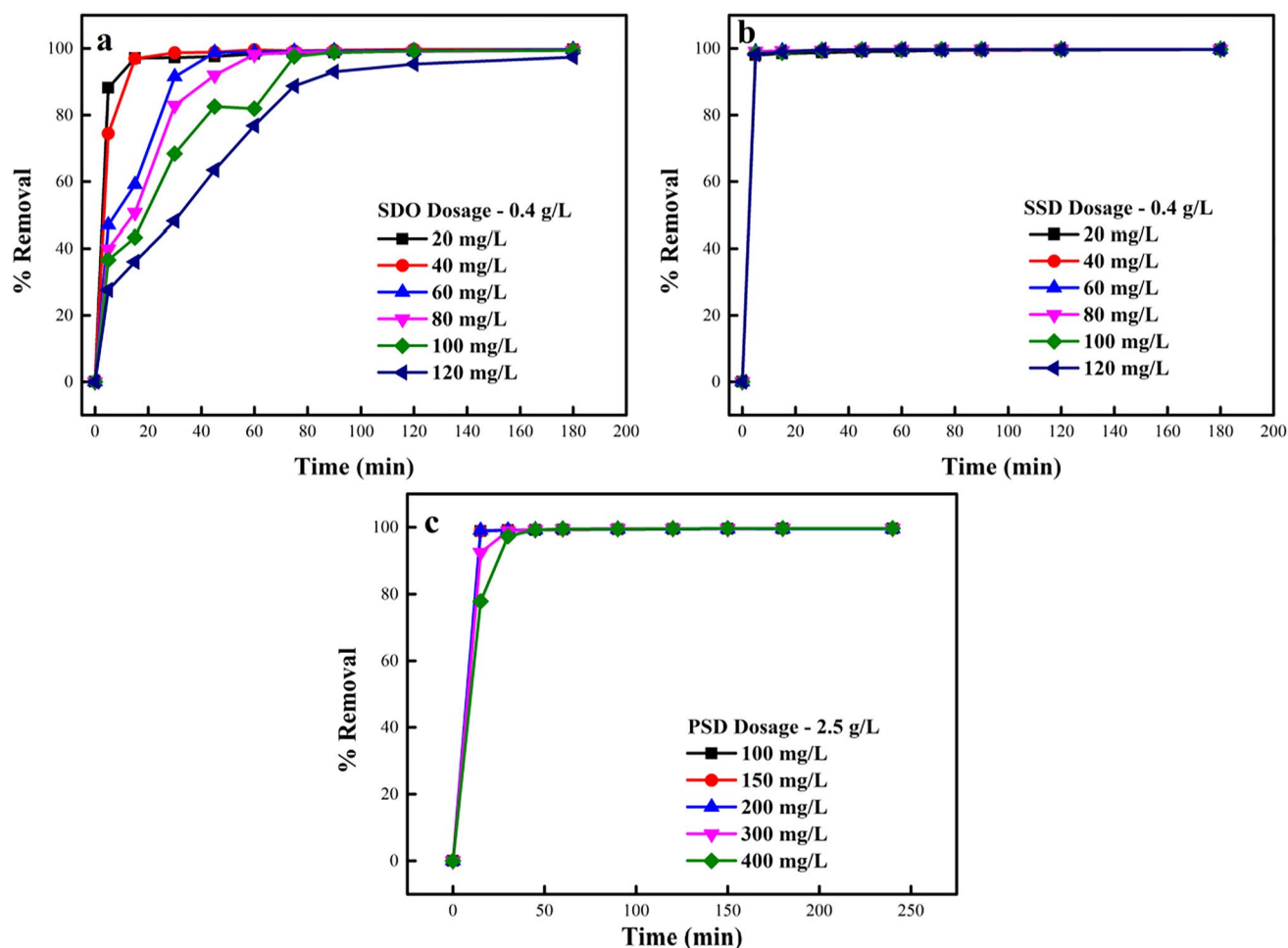


Fig. 8 Impact of MB concentrations on the removal of MB using **a** SDO, **b** SSD, and **c** PSD biochars

and hence improve the amount of negatively charged sites on the surface of the biochar [64]. A similar trend was also reported in the studies by Salazar-Rabago et al. [63], Phuong et al. [64], Al-Ghouti and Al-Absi [65], and Pandey et al. [60]. Electrostatic interaction and hydrogen bonding are suggested as the key biosorption mechanism of MB dye at acidic and basic pH [65].

3.3 Effect of biochar dosage on the biosorption of MB dye

An important factor that impacts the biosorption process, which assesses the biosorbent-sorbate system equilibrium, is the biosorbent dosage [54, 60]. The impact of biochar dosage on the sequestration of MB dye ions using SDO, SSD, and PSD biochars is reported in Fig. 7. The % of MB dye confiscated to SDO, SSD, and PSD biochars was observed to be directly comparative to the improved biochar dosage used and initial MB dye concentrations. These trends were ascribed to the surge in the accessible

biosorption sites existing on the surface of each biochar. But elevated biochar dosage led to a saturation of the % of MB dye removal ascribed to particle aggregation which resulted in reduced biochar surface area available and improvement in the diffusion path length, thereby resulting in reduced removal. A comparable pattern was illustrated in the studies relating to MB dye removal to different bio-materials by [64, 66–68].

3.4 Impact of initial concentration on MB dye removal

The driving force offered by the dye concentration assists to stun the mass transfer resistance of molecules of dyes at the interfaces of a solid liquid [69, 70]. The impact of MB's initial dye concentration was studied at various concentrations ranging from 20 to 120 mg/L using varying biosorbent dosages of 0.1–0.4 g/L at pH 12. It was observed in Fig. 8 that the % of MB dye ions confiscated onto the various

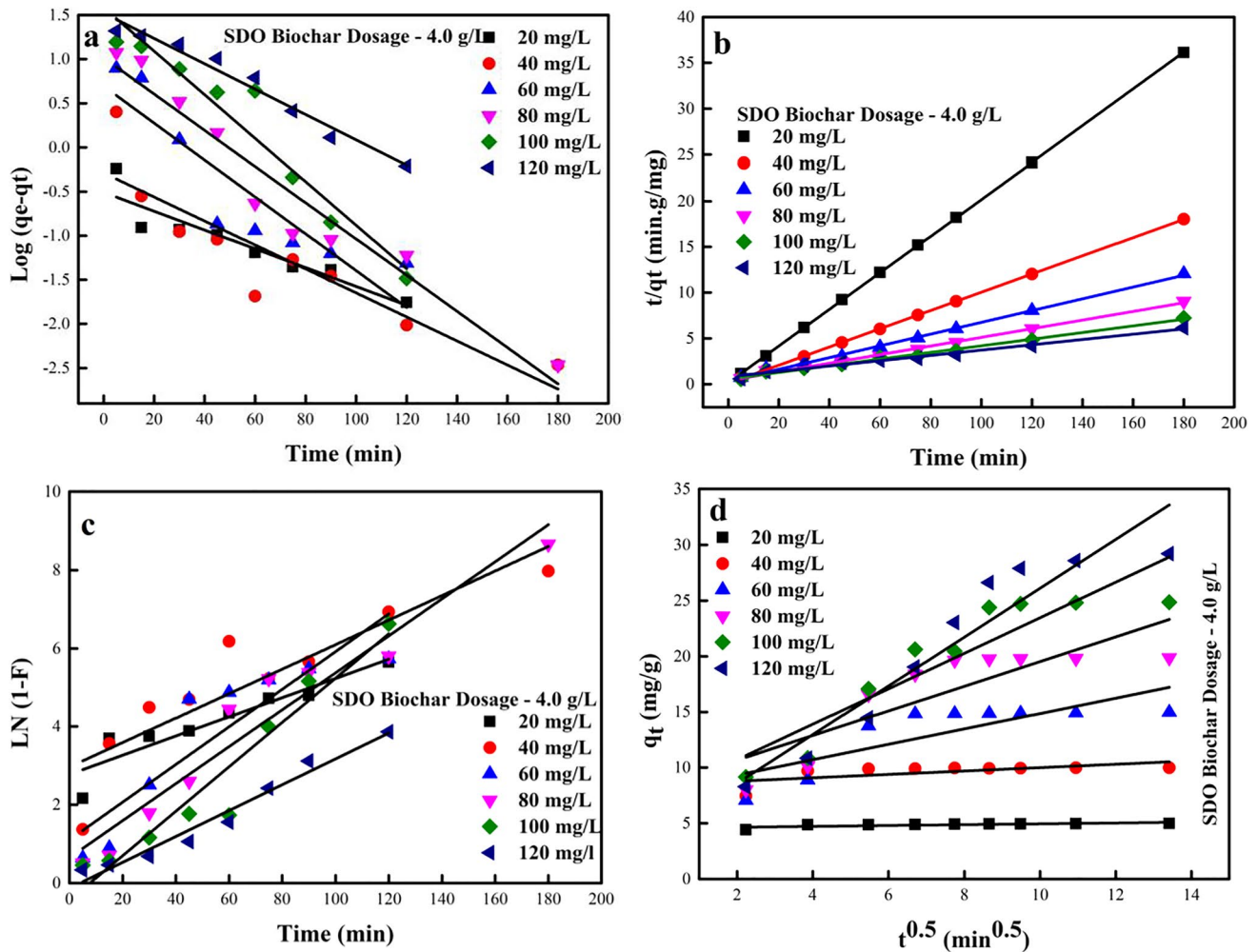


Fig. 9 Linear plots of the **a** PFO model **b** PSO model, **c** FD model and **d** INT model using a SDO biochar

biochars decreased with increasing MB dye concentrations (20–120 mg/L of SDO and SSD and 100–400 mg/L of PSD biochars) as contact time was improved from 0 to 180 min and 0 to 250 min. The optimum % of MB dye removed was obtained using MB dye concentrations of 20 and 100 mg/L. This decrease in the % of MB dye ions confiscated onto the biochars with increasing MB dye concentrations was attributed to the saturation of the accessible active sites on the surface of the biochars at elevated concentrations of MB dye [71].

3.5 Kinetic studies

The sorption kinetics is employed to study the change in sorption quantity over time that could offer a source for engineering process design and give an understanding of the mechanism of sorption [72]. To evaluate the kinetic data of MB dye adsorption by SDO, SSD, and PSD biochars under

the experimental conditions examined, the pseudo-first-order (PFO), pseudo-second-order (PSO), film diffusion (FD), and intraparticle diffusion (ITD) models were employed. The linearized form of these models is given by Eqs. 4, 5, 6, 7.

$$\log(q_e - q_t) = \log q_e - K_1/2.303 t \quad (4)$$

$$t/q_t = 1/K_2 q_e^2 + 1/q_e t \quad (5)$$

$$\ln(1 - F) = -k_{FD} \times t \quad (6)$$

$$q_t = K_{diff} t^{0.5} + C \quad (7)$$

q_e , q_t , t , K_1 , K_2 , $F = q_t/q_e$, k_{FD} , K_{diff} , and C indicate the equilibrium sorption capacity of the sorbent (mg g^{-1}), and the sorption capacity (mg g^{-1}) at time t , the contact time, the rate constants of the PFO and PSO models, fractional attainment of equilibrium, film diffusion rate coefficient (L/

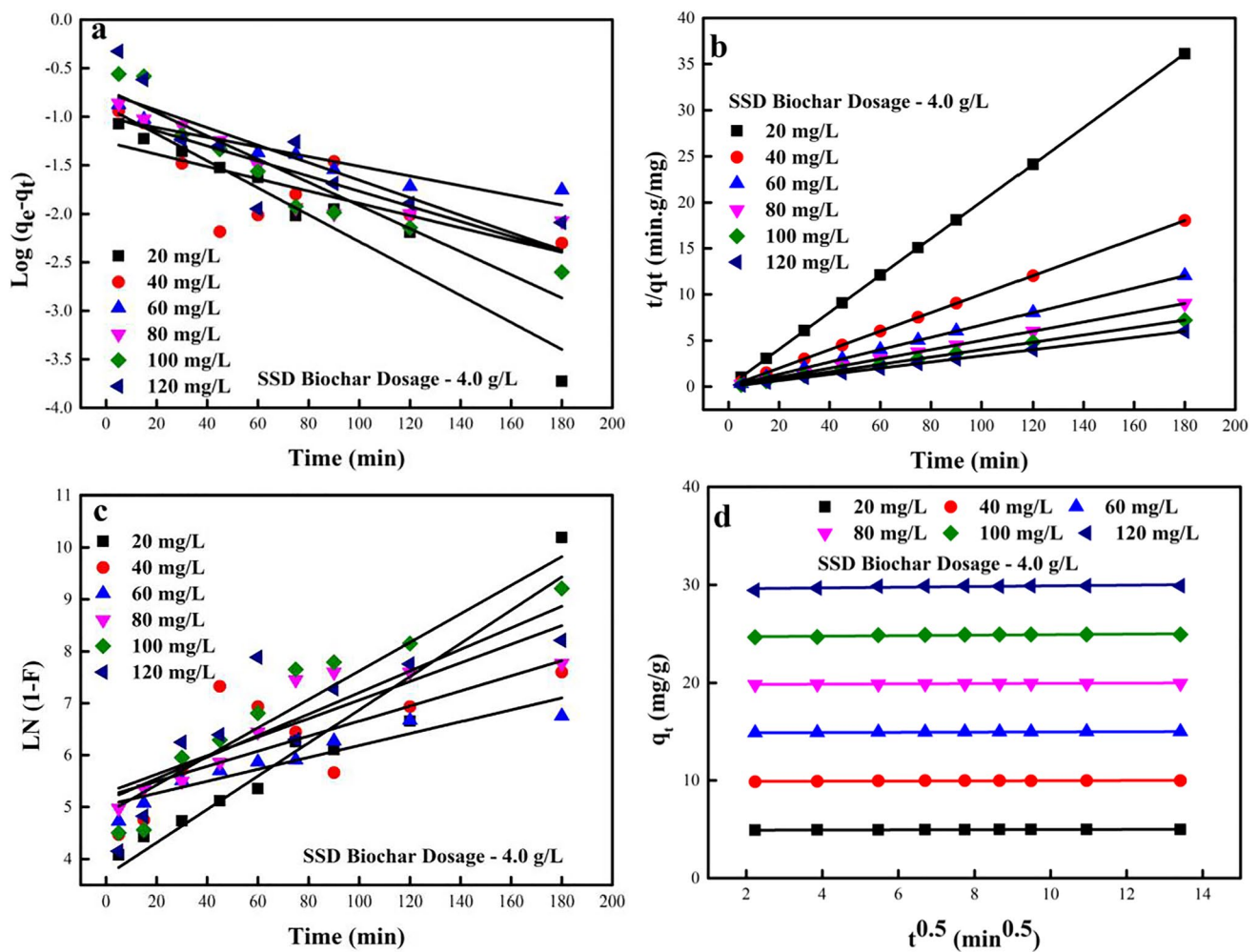


Fig. 10 Linear plots of the **a** PFO model **b** PSO model, **c** FD model and **d** INT model using a SSD biochar

min), intraparticle diffusion rate constant ($\text{mg/gmin}^{0.5}$), and the thickness of boundary layer [73–75].

The coefficient of regression (R^2) closeness to unity (1) defines the extent the calculation model fits the data [76]. The linear plots of the PFO, PSO, FD, and INT models are given in Figs. 9, 10, and 11 and the determined parameters using these models are summarized in Tables 3, 4, 5, 6, 7, and 8. Comparing the R^2 of the PFO and PSO models, it was found that the PSO model ideally demonstrates the sorption of MB to SDO, SSD, and PSD with R^2 values which were > 0.9 (Tables 3, 5, and 7). The calculated q_e (mg/g) values of SDO, SSD, and PSD biochars were very close to the obtained experimental values of q_e (mg/g) using the PSO model, which validate the fitness of this model.

While Figs. 9, 10, and 11c and d show the linear plots of the FD and INT models. The determined parameters from these models are presented in Tables 4, 6, and 8. The plots of these models (INT and FD models) of the sorption process

were not controlled by rate-determining steps and diffusion via liquid film surrounding the biochars, as their plots did not pass through the origin. The values of R^2 of the FD and INT models were comparatively low and not above 0.9 for all values when compared to that of the PSO model [73, 77, 78]. Hence, the biosorption of MB dye to the various biochars was based on the assumption of a rate-limiting step of chemical sorption or chemisorption involving valency forces via sharing or electron exchange between the sorbate and the biosorbents [72, 79].

3.6 Isotherm studies

To evaluate the sorption mechanism, forecast the optimum sorption capacity of the biosorbents used, assess the relationship between the sorbate and the biosorbent, and improve the sorption system design, the sorption isotherm is employed [72]. In this study, linearized isotherm models were used to

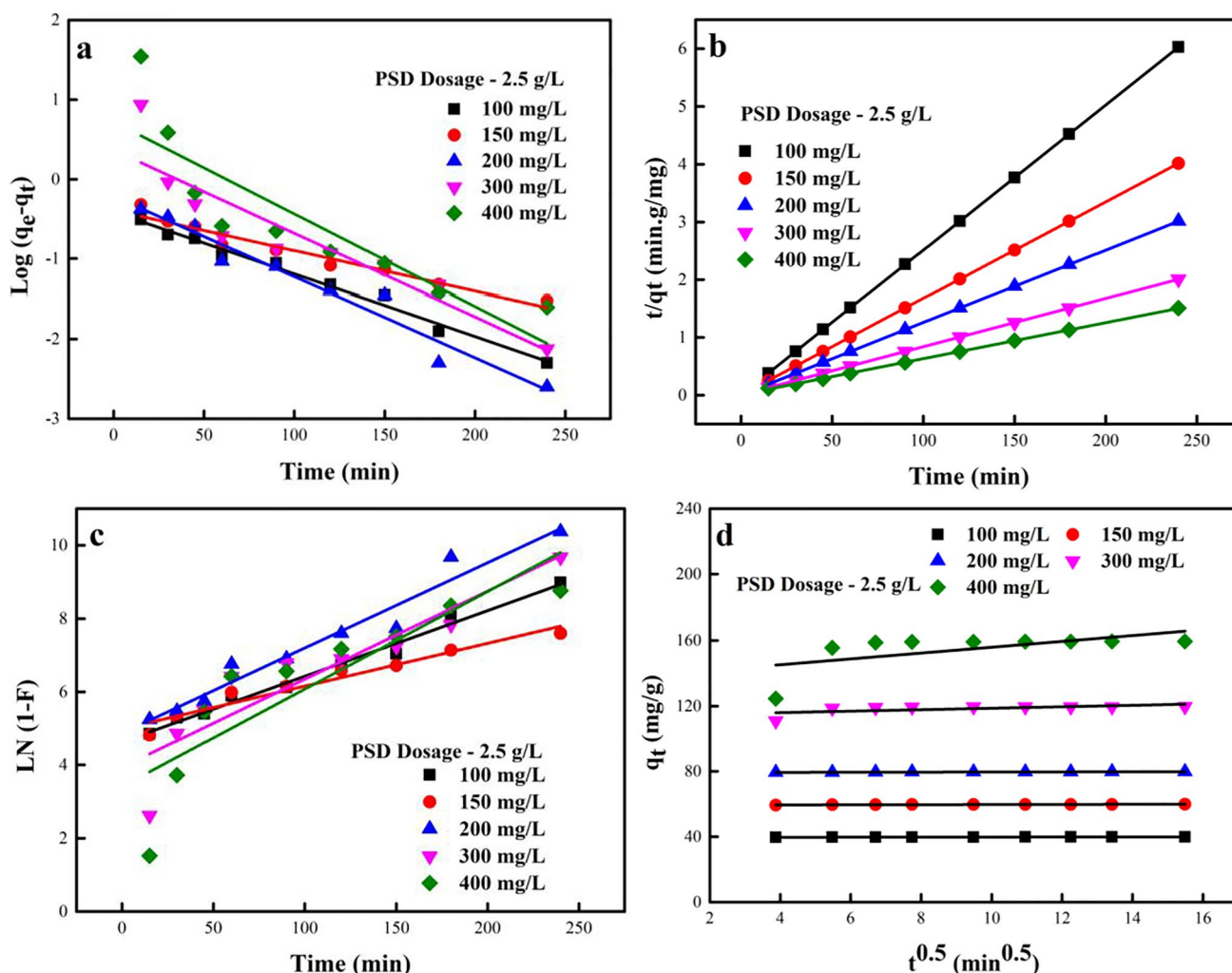


Fig. 11 Linear plots of the **a** PFO model **b** PSO model, **c** FD model and **d** INT model using a PSD biochar

fit the sorption process, which includes Langmuir (LNR) and Freundlich (FRH) models. The linearized forms of these models are depicted in Eqs. 8–9. The linearized fitting of the curve of the confiscation MB dye to SDO, SSD, and PSD biochars is given in Fig. 12.

$$C_e/q_e = (1/Q_m)C_e + 1/Q_m K_L \quad (8)$$

$$\log q_e = 1/n \log C_e + \log K_F \quad (9)$$

C_e (mg.L⁻¹), Q_m (mg.g⁻¹), K_L (L.mg⁻¹), K_F (mg.g⁻¹) (L.mg⁻¹)^{1/n}, and $1/n$ (dimensionless; $0 < n < 10$) represent the sorbate concentration in the solution at equilibrium, the determined saturated monolayer biosorption capacity of the sorbent under the given circumstances, and the LNR constant which relates to the affinity between the biosorbent and sorbate, FRH constant, and FRH intensity parameter,

signifying the sorption driving force or surface heterogeneity magnitude [4, 60, 63].

Tables 3, 4, 5, 6, 7, and 8 depict the established parameters of isotherm models with their corresponding R^2 relating to the most ideal model that explained the sorption of MB dye to SBO, SSB, and PSB models. It was noticed from the R^2 values in Tables 9, 10, and 11 that the FRH model better described the sorption process of MB dye when compared to the LNR model using SBO ($R^2=0.957$) and SSB ($R^2=0.986$) biochars and the LNR model ideally describes the sorption process of MB dye with an R^2 value of 0.999 employing PSB. The determined optimum sorption capacities from the LNR model were 200.0, 526.3, and 769.23 mg g⁻¹. The values of n from the FRH model were greater than 1, suggesting that SDO and SSB biochars were suitable for MB dye confiscation from water-soluble solutions. High K_F values using these biochars also showed that

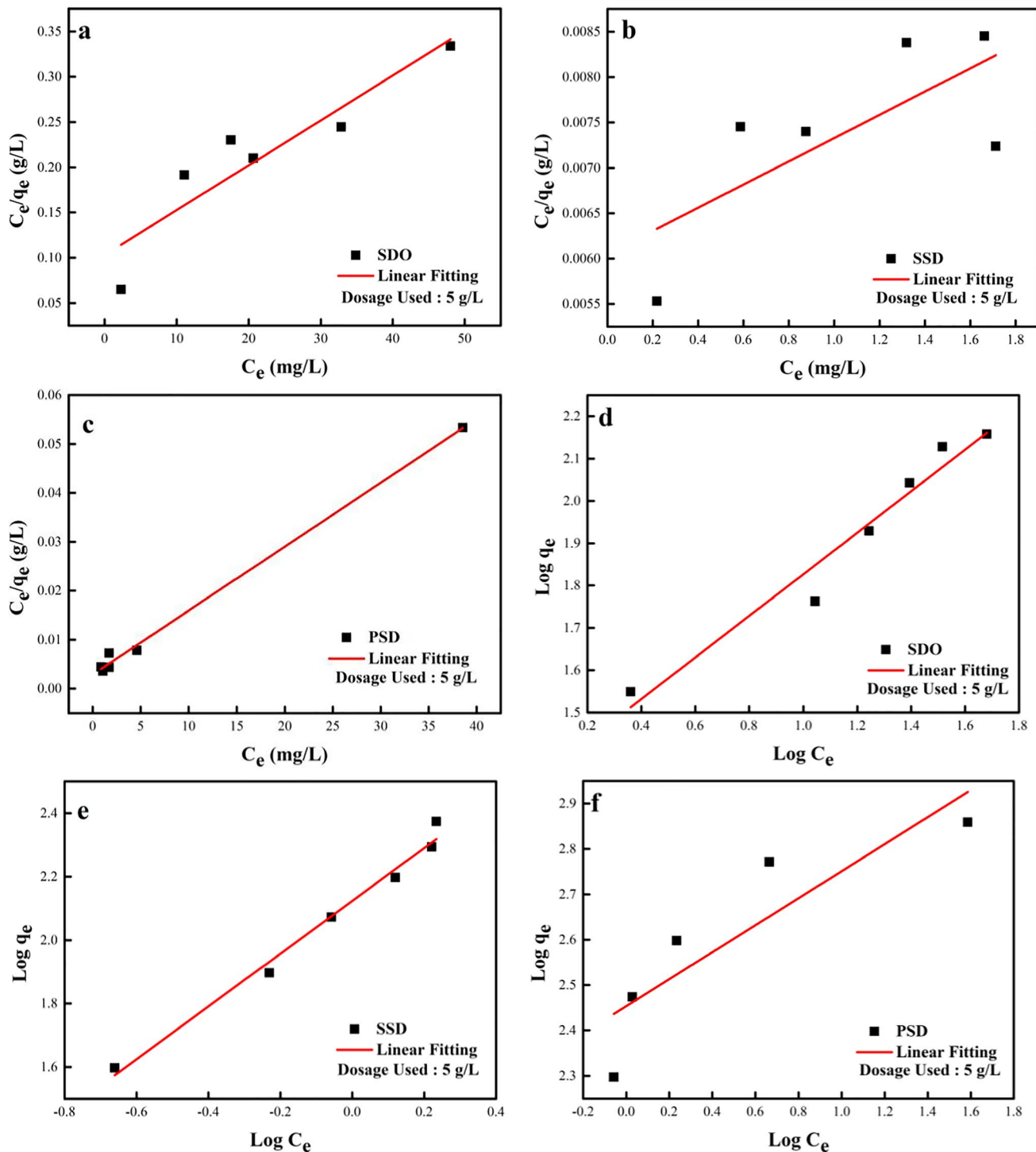


Fig. 12 Linear plot of the LNR model using **a** SDO, **b** SSD, and **c** PSD biochars and FRH model using **d** SDO, **e** SSD, and **f** PSD biochars

the various biochars could effortlessly sorb MB dye. The sorption capacities of the SDO, SSB, and PDB biochars were comparatively high when associated with other biosorbents employed for the confiscation of MB dye (Table 12). The sorption of MB dye to various biochars demonstrates

monolayer sorption with uniform energy of a finite number of active sites and less sorbate transmigration in the plane surface using PSB biochar and multilayer layer sorption on a diverse surface with a diverse distribution of active sites and energies using SDO and SSB biochars. This was

possibly due to their low cost, easy accessibility, greenest, and non-producing secondary contamination [76, 78, 80]. The adsorption mechanism of MB dye using the SDO, SSB, and PDB biochars may be understood via electrostatic attraction between cationic MB dye molecules and negatively charged biochar surface, a hydrogen bonding attraction force between MB dye molecules and biochar surface, and/or surface to pore diffusion of dye molecules [81].

4 Conclusion

The possibility of exploring and using new, cheap, easily accessible, biodegradable, and non-hazardous biosorbents prepared from SD agro-waste materials for the production/synthesis of SDO, PSD, and SSD biochars in the treating and removing of MB dye was considered and emphasized. The characterization of the synthesized/produced SDO, PSD, and SSD biochars was carried out using BET, SEM, FTIR, and TP. The biosorption of the MB dye using SDO, PSD, and SSD biochars was observed to be dependent on the solution pH, with optimum removal of MB observed at pH 12 for all (SDO, PSD, and SSD) biochars. Also, the biosorption process of MB to the SDO, PSD, and SSD biochars was ideally defined using the PSO, FRH-SDO, and SSD biochars and LNR-PSD biochar models. Based on the LNR model fitting to the experimental data, the optimum sorption capacities obtained using SDO, SSD, and PSD biochars were 200, 526, and 769 mg/g respectively. It was also observed that the electrostatic interaction and hydrogen bond played a critical role in the interaction mechanism between the various (SDO, PSD, and SSD) biochars and MB. In conclusion, this study has again shown that adsorbing reagents (biosorbents) prepared from cheap, easily accessible, biodegradable, and non-hazardous agro-waste materials such as SDO, PSD, and SSD biochars can effectively be useful for the removal of dyes such as MB and other industrial toxic wastes and effluents before their disposal into the environment. Therefore, it is suggested that further research on the use of cheap, easily accessible, biodegradable, and non-hazardous agro-waste materials for the control and mitigation of environmental effluents vis-à-vis industrial toxic wastes and effluent management, and research on the toxicity (toxicity assays) of synthesized biochars using at least cell lines or animal models should be given considerable attention.

Author contribution Mr. T. M. Eldeeb, Eng. M. A. El-Nemr conducted the experimental part, calculation, and theoretical models. M. A. Hassaan conducted the calculation and characterization part, Dr. S. Ragab read the manuscript and supervised the experimental work. Dr. U. O. Aigbe, Dr. K. E. Ukhurebor, Dr. R. B. Onyancha, and Dr. O. A. Osibote wrote the original manuscript. Prof. A. El Nemr supervised the

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Data availability Data sharing does not apply to this article.

Declarations

Consent to participate Not applicable.

Conflict of interest The authors declare no competing interests.

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Authors and Affiliations

Tarek M. Eldeeb¹ · Uyiosa O. Aigbe² · Kingsley E. Ukhurebor³ · Robert B. Onyancha⁴ · Mohamed A. El-Nemr⁵ · Mohamed A. Hassaan¹ · Safaa Ragab¹ · Otolorin A. Osibote² · Ahmed El Nemr¹ 

Tarek M. Eldeeb
tarikeldeeb77@yahoo.com

Uyiosa O. Aigbe
uyi4we@gmail.com

Kingsley E. Ukhurebor
ukeghonghon@gmail.com

Robert B. Onyancha
08muma@gmail.com

Mohamed A. El-Nemr
mohamedelnemr1992@yahoo.com

Mohamed A. Hassaan
mhss95@mail.com

Safaa Ragab
safaa_ragab65@yahoo.com

Otolorin A. Osibote
osibotea@cput.ac.za

¹ Environment Division, National Institute of Oceanography and Fisheries (NIOF), Kayet Bey, Elanfoushy, Alexandria, Egypt

² Department of Mathematics and Physics, Faculty of Applied Sciences, Cape Peninsula University of Technology, Cape Town, South Africa

³ Department of Physics, Faculty of Science, Edo State University Uzairue, Edo State, Nigeria

⁴ Department of Technical and Applied Physics, School of Physics and Earth Sciences Technology, Technical University of Kenya, Nairobi, Kenya

⁵ Department of Chemical Engineering, Faculty of Engineering, Minia University, Minia, Egypt