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ORIGINAL RESEARCH ARTICLE

Sustainable amorphous porous carbon for efficient removal of industrial dyes

Supplementary Files

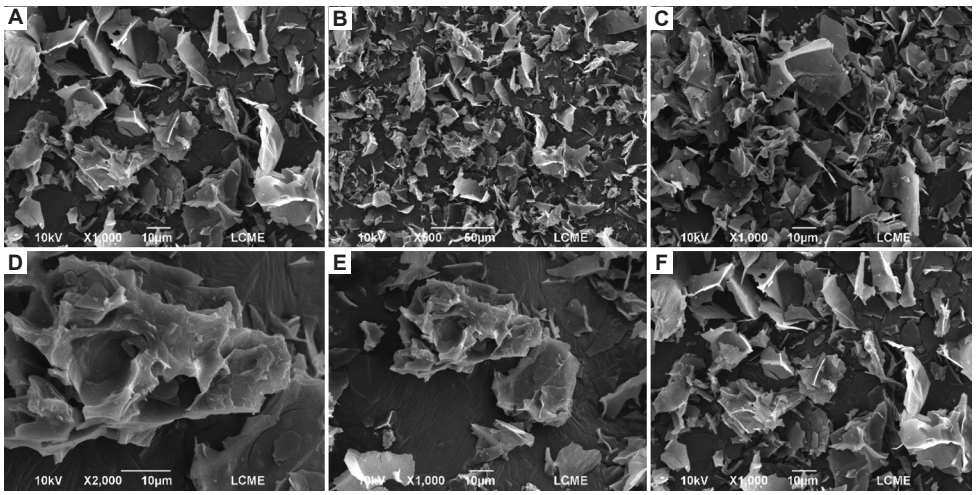

Figure S1. Scanning electron microscopy images of cork-derived activated carbon. Scale bars: (A, C, D, E, F) 10 μM, (B) 50 μM; magnification: (A, C, E, F) ×1,000, (B) ×500, (D) ×2,000.

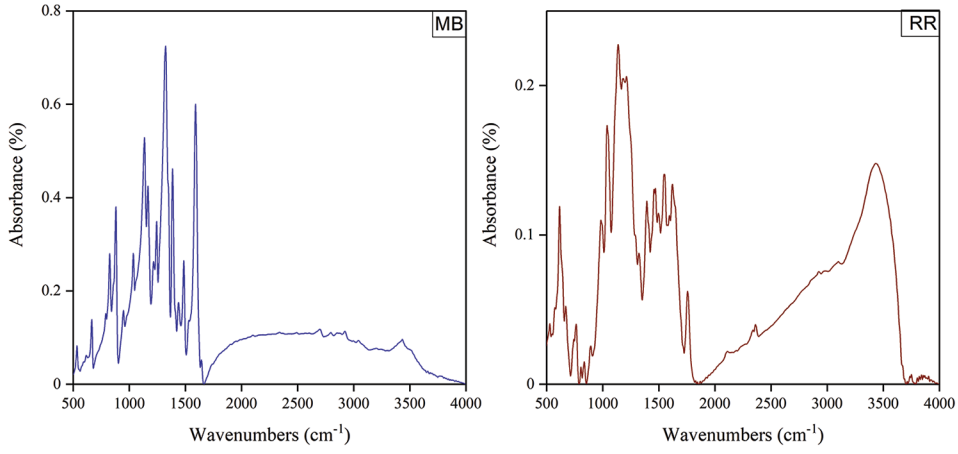

Figure S2. Fourier transform infrared spectra of methylene blue (MB) and reactive red (RR) dyes

Table S1. Equations utilized in this study

Adsorption model	Equation	Parameters	References
Kinetic model equations			
Pseudo-1st-order kinetic	$q_t = q_e(1-e^{k_1 t})$	k_1 (min^{-1}) rate constants; *qt*, *qe*, and q_{AV}=theoretical values for the adsorption capacity.	1
Pseudo-2nd-order kinetic	$q_t = \frac{t}{\left(\frac{1}{k_2 q_2^2}\right)+\left(\frac{t}{q_2}\right)}$	*qt*, *qe*, and q_{AV}=theoretical values for the adsorption capacity, k_2 ($g \cdot mg \cdot min^{-1}$) are the rate constant ($mg \cdot g^{-1}$).	2
Intraparticle diffusion	$q_t = K_{diff} t^{1/2} + C$	qt ($mg \cdot g^{-1}$) is the adsorption capacity at a given time, t (min) is the time of the adsorption process studied, k_{diff} is the intraparticle diffusion rate constant (g·mg/min), and C (mg/g) is a constant related to the diffusion resistance and the thickness of the boundary layer.	3
Elovich	$q_t = \frac{ln(\alpha\beta)}{\beta} + \frac{1}{\beta} lnt$	α (mg g/min) is the initial adsorption rate, β (g/mg) is related to the extent of surface coverage and activated energy in the chemisorption process, (mg/g) is the amount adsorbed in a time *t* (min), and the intercept of qt versus lnt corresponds to the amount adsorbed during the initial phase of adsorption.	4
Isotherm model equations			
Langmuir	$q_e = q_L \frac{K_L C_e}{1+K_L C_e}$	q_L=maximum adsorption capacity of the Langmuir model ($mg \cdot g^{-1}$); k_L=Langmuir constant (L/mg^{-1}).	5
Freundlich	$q_e = K_f C_e^{\frac{1}{n}}$	k_F=Freundlich constant ($mg \cdot g^{-1}$) $(mg \cdot L^{-1})^{-1/nF}$; $1/n$=heterogeneity factor.	6
Redlich-Peterson (R-P)	$N = \frac{KC}{(1+\alpha C^n)}$	N is the amount adsorbed at equilibrium; K is the R–P constant; C is the equilibrium concentration; α is R–P parameter, and n is the exponential factor.	7
Equations thermodynamic parameters			
Thermodynamics model	$\Delta G^0 = -RTln(K_e)$ $\Delta G^0 = -RTln(K_e)$ $\Delta G^0 = \Delta H^0 - T\Delta S^0$ $k_e = \frac{kM_W \gamma^D}{\gamma}$	k_e=equilibrium constant; *k*=constant parameter from the most suitable isotherm fit ($L \cdot mg^{-1}$); M_W=molecular weight of the dyes ($g \cdot mol^{-1}$); γ^D=activity coefficient of dyes in solution (dimensionless, assuming γ = 1); γ = unitary activity coefficient of MB ($1\ mol \cdot L^{-1}$); *T*=temperature (K); *R*=universal gas constant (8.31×10^{-3} $kJ \cdot mol^{-1} \cdot K^{-1}$).	8
Column equation models			
Clark	$\frac{C_t}{C_i} = \frac{1}{[1+Ae^{-rt}]^{\frac{1}{n-1}}}$	*n* is the Freundlich constant; *r* is the Clark or fractal-like Clark constant (min^{-1}); *A* is the Clark constant.	9
Thomas	$\frac{C_t}{C_i} = \frac{1}{1+e^{(\frac{K_{Th}}{Q})q_t^{\ x} - C_0 v_{eff}}}$	K_{Th} is the Thomas model constant ($mL \cdot min \cdot mg^{-1}$); Veff is the effluent volume (mL).	10
Yoon-Nelson	$\frac{C_t}{C_i} = \frac{1}{1+e^{K_{YN}(\tau - t)}}$	K_{YN} is the rate constant (1/min); τ, the time required for 50% adsorbate breakthrough (min); and t is the breakthrough (sampling) time (min).	11

Table S2. Structural parameters of cork-derived activated carbon produced by chemical activation with potassium hydroxide (KOH) under different experimental conditions

Material	Activation type	KOH quantity	Temperature (°C)	SSA_{BET} ($m^2 \cdot g^{-1}$)	V_{mic} ($cm^3 \cdot g^{-1}$)	References
Cork	KOH	0.25 g	500	354	0.15	12
		0.5 g		427	0.18	
		1 g		507	0.21	
		0.25 g	600	498	0.21	
		0.5 g		561	0.24	
		1 g		723	0.30	
		0.25 g	700	73	0.34	
		0.5 g		1,050	0.45	
		1 g		106	0.45	
		0.25 g	800	1,044	0.43	
		0.5 g		1,190	0.51	
		1 g		1,336	0.56	
Cork	KOH	1:1[a]	700	729	0.32	13
		1:1[a]	800	948	0.41	
		1:2[a]	700	874	0.38	

Note: [a]Mass ratio between activated carbon and KOH.

Table S3. Kinetic parameters for the adsorption of methylene blue (MB) and reactive red (RR) dyes

Parameter	MB	RR
Pseudo-first-order		
q_e (mg/g)	249.96±0.02	97.17±1.23
K_1 (min^{-1})	5.98±0.11	0.20±0.01
R^2	0.9935±0.005	0.9936±8.15
Pseudo-second-order		
q_e (mg/g)	250.05±0.01	102.86±0.67
K_1 (g·mg/min)	1.54±0.12	0.01±2.08
R^2	0.9985±0.002	0.9987±1.56
Elovich		
B (mg/g)	0.407±0.09	0.10±0.01
R^2	0.9977±16.25	0.9837±22.37

Table S4. Parameters of isotherms for the adsorption of methylene blue (MB) and reactive red (RR) dyes

Parameter	MB	RR
Langmuir		
q_m (mg/g)	607.89±28.27	252.40±56.79
B (L/mg)	2.42±0.51	0.08±0.06
R^2	0.9857±0.81	0.8454±0.79
Freundlich		
K_F	359.89±22.52	49.04±0.73
n	0.26±0.03	0.37±0.004
R^2	0.9658±0.75	0.9998±0.71
Redlich-Peterson		
q_m (mg/g)	3517.47±3.34	457.36±3.56
α (L/mg)	7.88±4.17	8.83±3.12
β (L/mg)	0.84±0.04	0.63±0.95
R^2	0.9941±0.52	0.8562±0.72

Table S5. Thermodynamics parameters for the methylene blue (MB) and reactive red (RR) dyes

Dye	Temperature (K)	kc	ΔG (kJ/mol)	ΔH (kJ/mol)	ΔS (J/mol/K)
MB	298	8.251×10^{2}	-1.25×10^{4}	75.456	56.092
	308	8.272×10^{2}	-1.31×10^{4}		
	318	8.276×10^{2}	-1.36×10^{4}		
	328	8.275×10^{2}	-1.42×10^{4}		
RR	298	14.681	9.067×10^{5}	-11.96×10^{4}	−45.601
	308	6.079	9.071×10^{5}		
	318	5.971	9.076×10^{5}		
	328	6.760	9.081×10^{5}		

Table S6. Parameters of the Thomas, Yoon-Nelson, and Clark kinetic models of adsorption in a fixed-bed column for the methylene blue (MB) and reactive red (RR) dyes

Model	Parameter	MB	RR
Thomas	K_{Th} (mg/g)	0.0083±0.002	0.0072±0.001
	Q_0 (mg/g)	1992.07±1.19	4500.48±6.66
	R^2	0.9916±0.001	0.9963±0.007
Yoon-Nelson	Kyn (min^{-1})	0.03±0.01	0.0413±0.02
	R^2	0.9843±0.002	0.9941±0.001
	τ (h)	0.51±0.42	0.44±0.34
Clark	A (L/mg)	1.9313×10^{7}±2.70	91814.5±5.12
	r	0.0176±0.001	0.01723±0.08
	R^2	0.9852±0.002	0.9950±0.001

Table S7. Dye adsorption capacity of activated carbons

Precursor	SSA (m^2/g)	Dye	Adsorption capacity (mg/g)	References
Almond shells	1,133	Methylene Blue	788	14
Mangosteen peel	1,621	Methylene Blue	1,193	15
Rice husk	752	Methylene Blue	362.60	16
Seaweed	683	Reactive Red 23	59.88	17
		Reactive Blue 171	71.94	
		Reactive Blue 4	131.93	
Sewage sludge	159	Remazol Brilliant Blue R	33.07	18
Cork	1,793	Methylene Blue	250	This work
		Reactive Red	105	

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