

**Supplementary File:**

**Synergetic Mono- and Bimetallic Tungstate-Biochar Composites for Efficient Adsorptive Removal of Aniline Blue from Simulated Wastewater: Reusability, Multivariate Analysis, and Greenness Assessment**

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**Table S1: Stoichiometric Composition of the Synthesized Composites**

Composite	Target Composition	Metal Precursors (mmol)	Tungstate Precursor (mmol)	Biochar (g)
MW/LB	MnWO <sub>4</sub> /Biochar 78.5:21.5	Mn <sup>2+</sup> = 5.0 mmol (MnCl <sub>2</sub> ·4H <sub>2</sub> O, 0.989 g)	WO <sub>4</sub> <sup>2-</sup> = 5.0 mmol (Na <sub>2</sub> WO <sub>4</sub> ·2H <sub>2</sub> O, 1.683 g)	0.50
ZW/LB	ZnWO <sub>4</sub> /Biochar 75.5:24.5	Zn <sup>2+</sup> = 5.0 mmol (Zn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O, 1.487 g)	WO <sub>4</sub> <sup>2-</sup> = 5.0 mmol (Na <sub>2</sub> WO <sub>4</sub> ·2H <sub>2</sub> O, 1.649 g)	0.50
ZMW/LB	Zn <sub>0.1</sub> Mn <sub>0.9</sub> WO <sub>4</sub> /Biochar 6.8:71.5:21.7	Mn <sup>2+</sup> = 4.5 mmol (MnCl <sub>2</sub> ·4H <sub>2</sub> O, 0.890 g) Zn <sup>2+</sup> = 0.5 mmol (Zn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O, 0.149 g)	WO <sub>4</sub> <sup>2-</sup> = 5.0 mmol (Na <sub>2</sub> WO <sub>4</sub> ·2H <sub>2</sub> O, 1.683 g)	0.50

**Table S2 Separation factor (RL) values for non-linear Langmuir isotherms, adsorption of Aniline Blue dye**

C <sub>o</sub> (mg/L)	RL				
	MW	ZW	MW/LB	ZW/LB	ZMW/LB
10	0.0255	0.273	0.862	0.893	0.877
20	0.0129	0.158	0.757	0.806	0.781
40	0.0103	0.131	0.610	0.676	0.641
60	0.0086	0.111	0.510	0.581	0.543
80	0.0065	0.086	0.439	0.510	0.471
100	0.0052	0.070	0.385	0.455	0.416

**Table S3:** Thermodynamic parameters at different temperatures in simulated wastewater

Adsorbent	T (K)	$\Delta G^\circ$ (KJ/mol)	Kd	$\Delta S^\circ$ (J/mol.K)	$\Delta H^\circ$ (KJ/mol)
MW/LB	298	-3.421	1.447	66.577	16.419
	308	-4.086	1.577		
	318	-4.752	1.737		
	328	-5.418	1.878		
	338	-6.084	2.285		
ZW/LB	298	-4.863	2.002	58.804	12.658
	308	-5.451	2.150		
	318	-6.039	2.198		
	328	-6.627	2.369		
	338	-7.215	2.656		
ZMW/LB	298	-3.299	1.398	66.753	16.591
	308	-3.967	1.471		
	318	-4.634	1.762		
	328	-5.302	1.882		
	338	-5.969	2.189		

**Table S4:** Energy and Chemical Inputs for LCA

Energy consumption	
Process	Energy (kWh)
Pyrolysis (biochar)	4
Hydrothermal synthesis	3
Drying	1
Total	8

**Table S5:** Chemical Consumption (per g adsorbent)

Chemical Consumption (per g adsorbent)			
Material	MW/LB	ZW/LB	ZMW/LB
MnCl <sub>2</sub>	0.20 g	—	0.18 g
Zn(NO <sub>3</sub> ) <sub>2</sub>	—	0.20 g	0.02 g
Na <sub>2</sub> WO <sub>4</sub>	0.30 g	0.30 g	0.30 g
NaOH	0.10 g	0.10 g	0.10 g

**Table S6:** CO<sub>2</sub> Emission Factor

CO <sub>2</sub> Emission Factor	
Input	CO <sub>2</sub> factor kg CO <sub>2</sub> kWh <sup>-1</sup>
Electricity	0.5
Mn salt	3
Zn salt	4
Na <sub>2</sub> WO <sub>4</sub>	6
NaOH	1.1

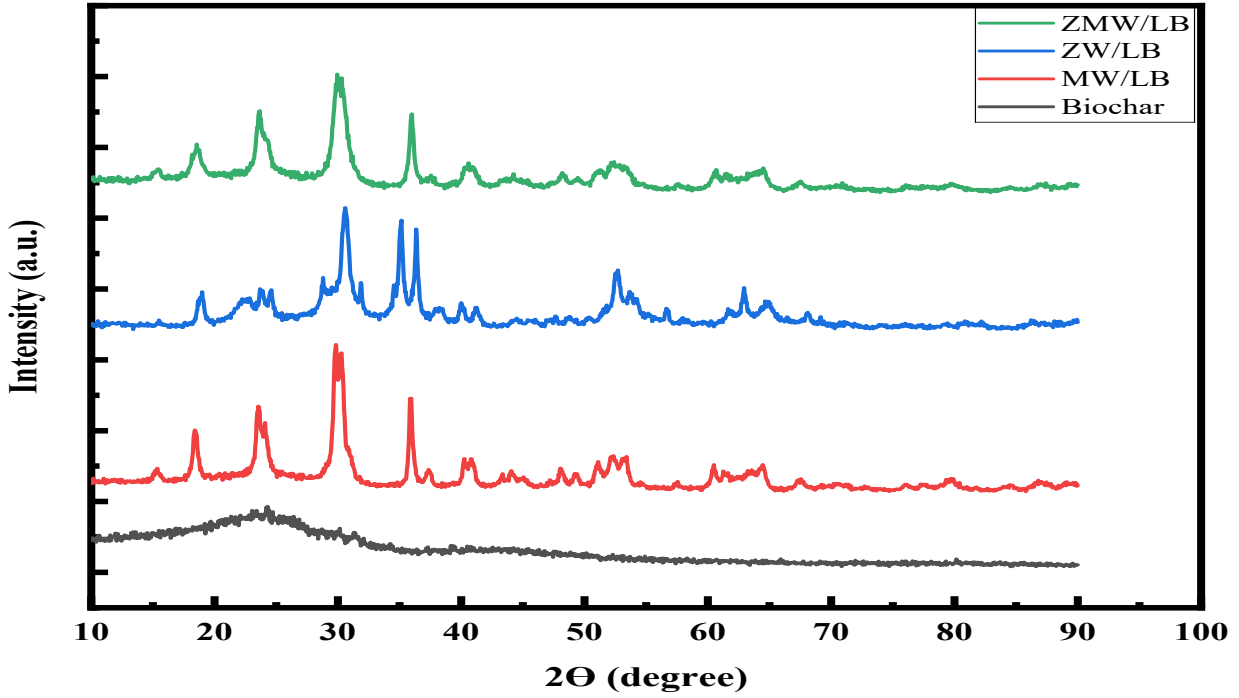


Figure S1: XRD for LB, MW/LB, ZW/LB, ZMW/LB

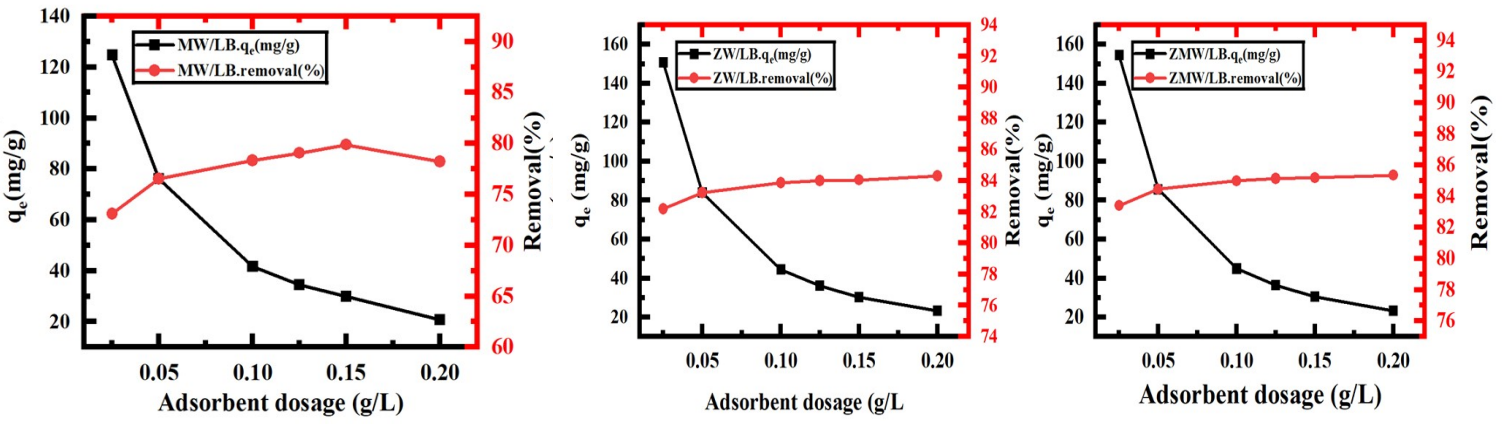
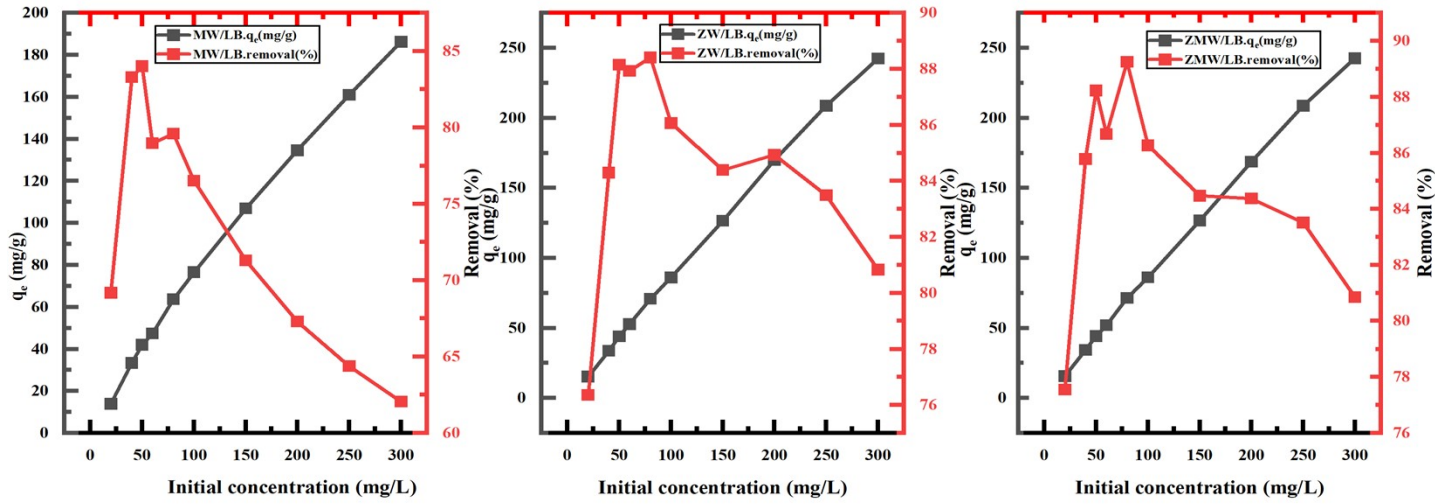
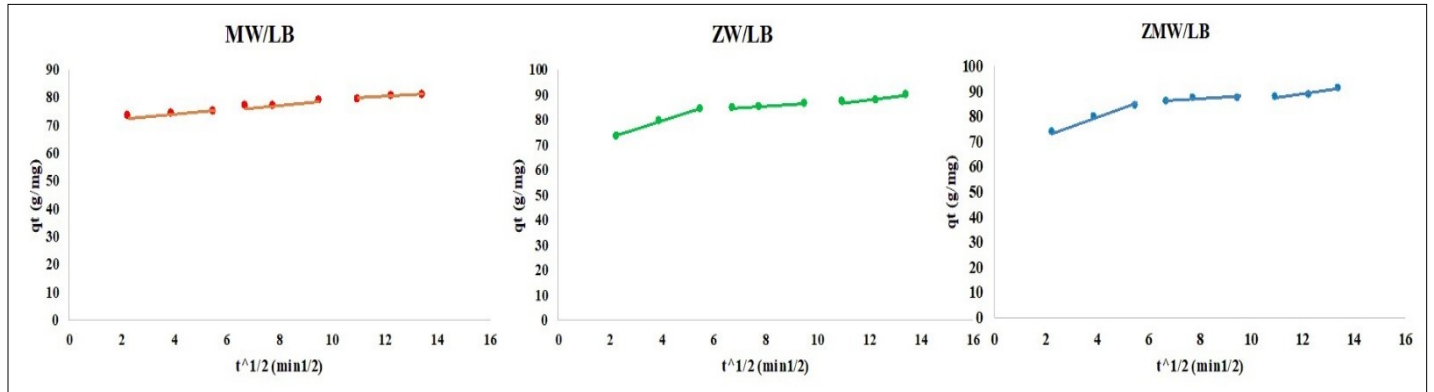


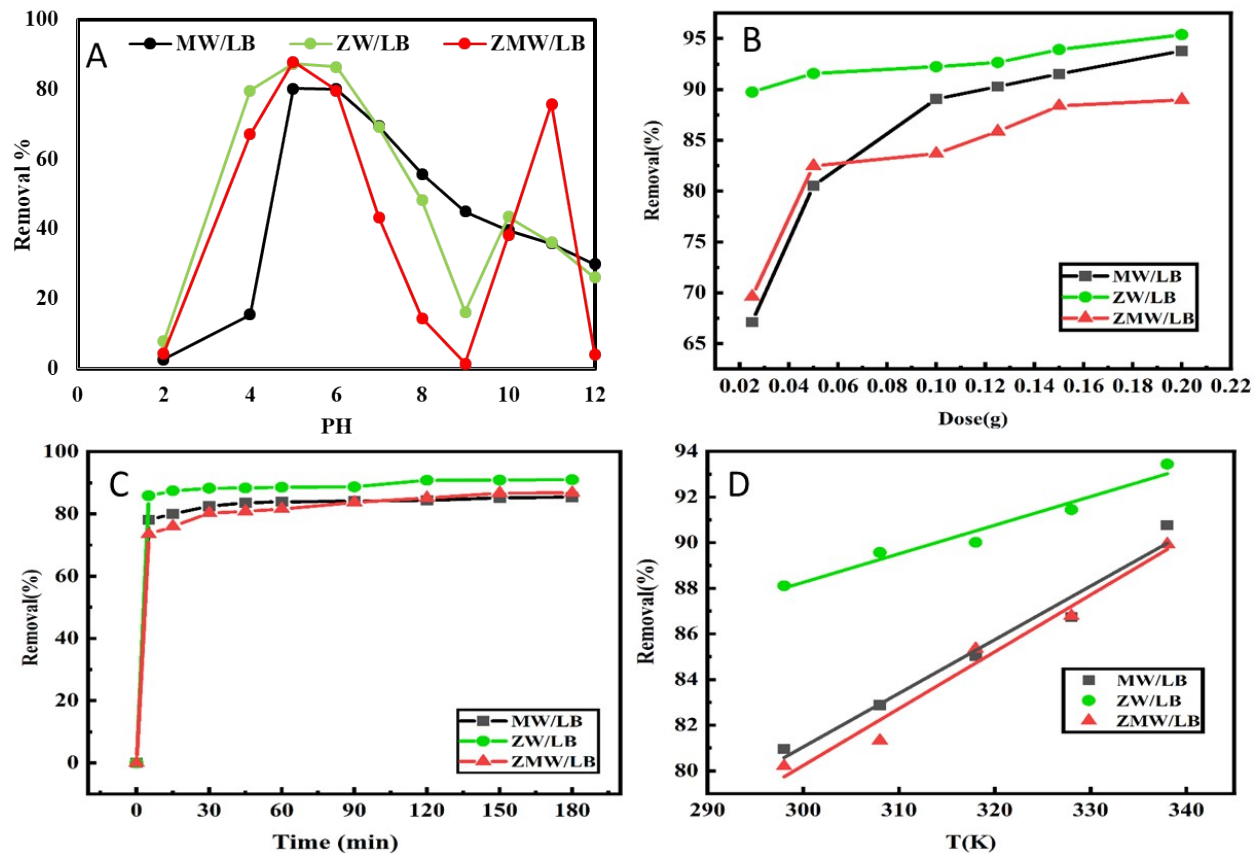
Figure S2: The influence of adsorbent dosage from 0.025–0.20 on AB adsorption onto the MW/LB, ZW/LB, and ZMW/LB in DIW



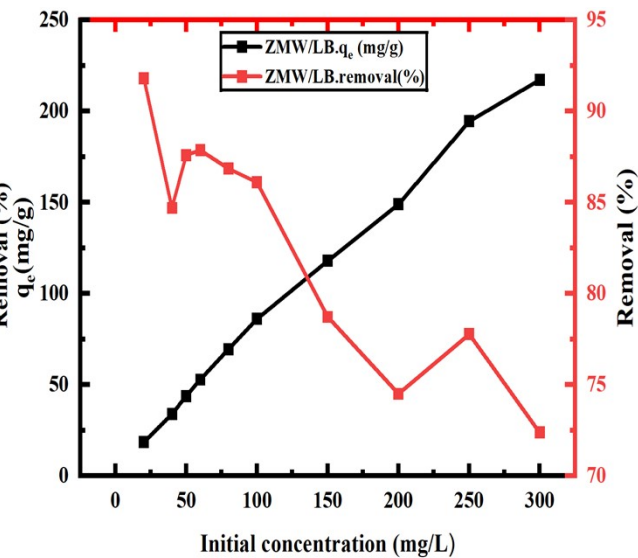
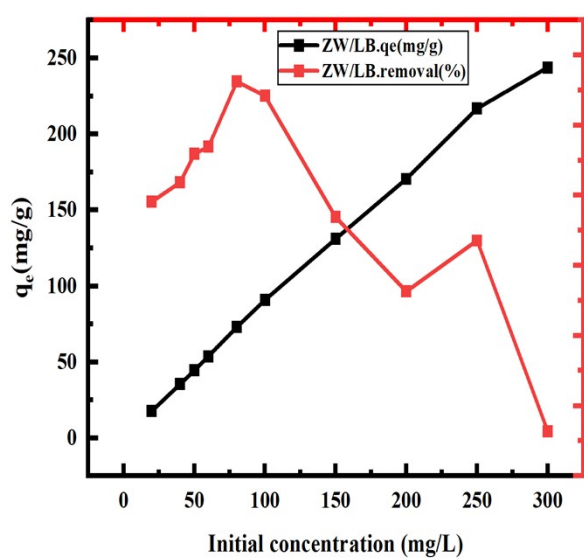
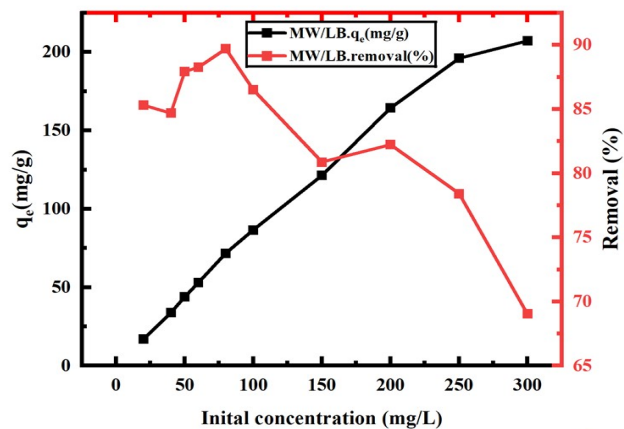
**Figure S3:** Effect of Initial dye concentration (AB) from 25 to 300 mg L<sup>-1</sup> on MW/LB, ZW/LB, ZMW/LB composite in DIW



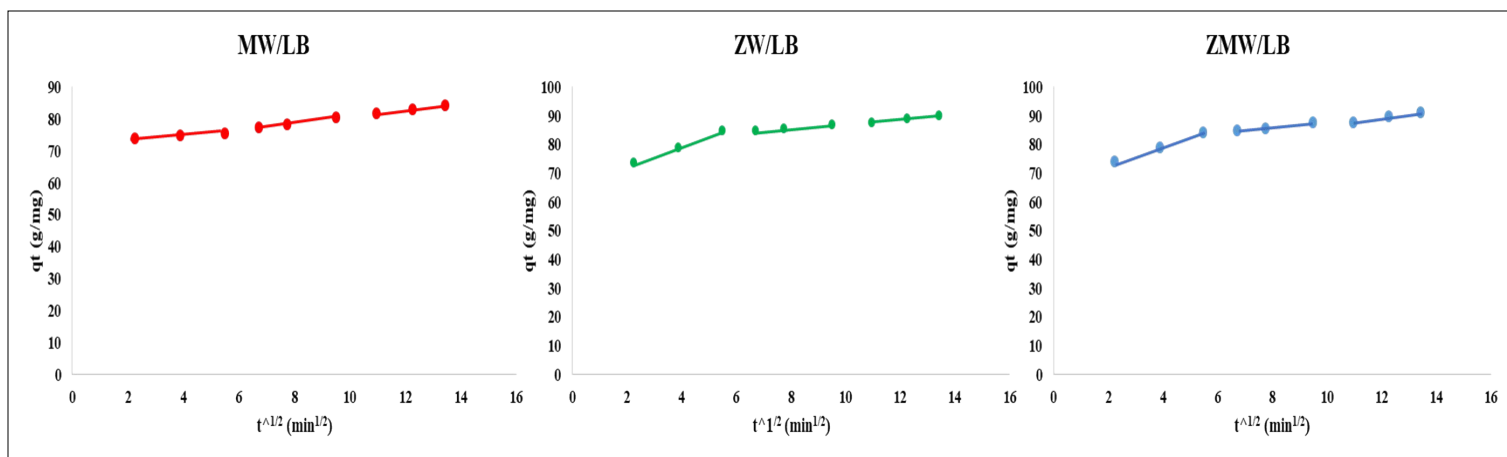
**Figure S4:** The intra-particle diffusion model for MW/LB, ZW/LB, ZMW/LB composite in DIW



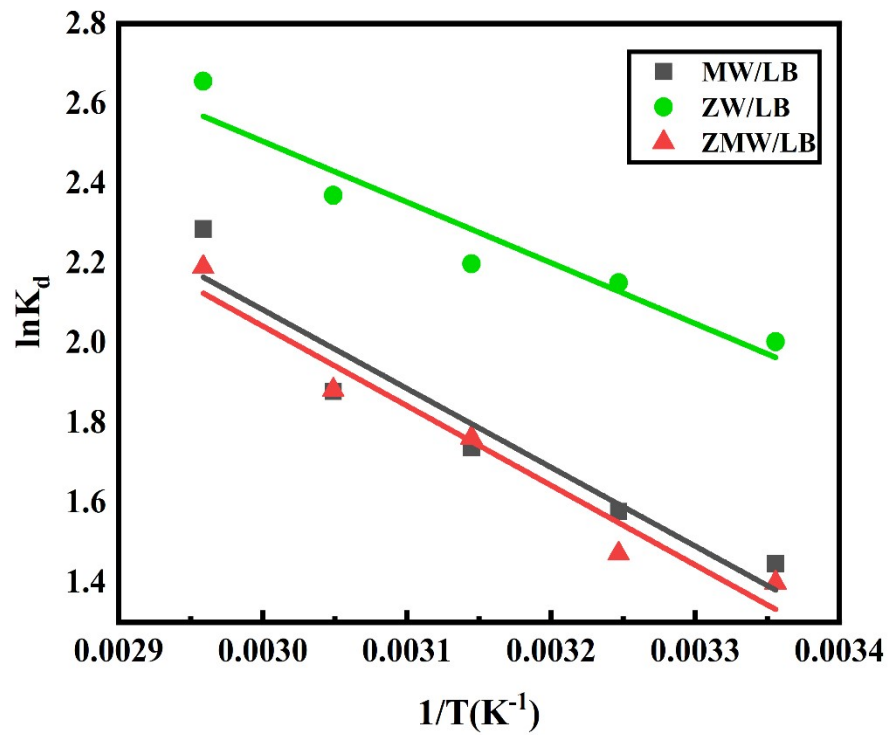
**Figure S5: Effects in SWW** (A) Impact of PH on the adsorption of AB onto the MW/LB, ZW/LB, and ZMW/LB at 25 °C; (B) the influence of adsorbent dosage from 0.025–0.20 on AB adsorption onto the MW/LB, ZW/LB, and ZMW/LB, (C) Impact of contact time on the adsorption of AB onto the MW/LB, ZW/LB, and ZMW/LB at 25 °C, and (D) Temperatures effects the adsorption of AB onto the MW/LB, ZW/LB, and ZMW/LB.



**Figure S6:**The effect of initial dye concentration on removal efficiency and adsorption capacity (mg/g) in SWW



**Figure S7:** The intra-particle diffusion model for MW/LB, ZW/LB, ZMW/LB composite in SWW



**Figure S8:** Van't Hoff curve for AB dye in SWW onto MW/LB, ZW/LB and ZMW/LB adsorbents