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### Biosorption Studies of Heavy Metals from Aquatic Environments Using Plant Residues: Thermodynamics and Reaction Kinetics

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### ABSTRACT

The present study evaluated the performance of Sidr nabak leaves, Sebesten leaves, and Rachis Base in removing heavy metals from aqueous solutions. The effects of temperature, contact time, and various kinetic models-including fractional power, zero-order, first-order, pseudo-firstorder, Elovich, second-order, intraparticle diffusion, and four different linearized forms of the pseudo-second-order model-were examined to fit the kinetic data. The results demonstrated that the adsorption percentage increases with rising temperatures (10, 20, 30, 40, and 50°C). By applying thermodynamic concepts—standard free energy ( $\Delta G^{\circ}$ ), enthalpy ( $\Delta H^{\circ}$ ), and entropy ( $\Delta S^{\circ}$ )—to the adsorption of heavy elements on the surfaces of plant residues at different temperatures, it was found that the adsorption reaction is spontaneous (indicated by negative  $\Delta G^{\circ}$  values), endothermic (indicated by positive  $\Delta H^{\circ}$  values), and accompanied by an increase in randomness (indicated by positive  $\Delta S^{\circ}$  values). Regarding the kinetic models (Elovich, Fractional Power, Zero-Order, First-Order, Pseudo-First-Order, Second-Order. Pseudo-Second-Order I. Pseudo-Second-Order II. Pseudo-Second-Order III, Pseudo-Second-Order IV, and Intraparticle Diffusion) applied to the data for the adsorbed amount over time, the pseudo-second-order model (in its various forms) provided the best description of the adsorption kinetic system. This model achieved the highest coefficient of determination (R<sup>2</sup>) values, accurately describing the studied data for most relationships between heavy elements and plant residues under investigation.

## **INTRODUCTION**

Agricultural waste (plant residues) refers to organic materials discarded during agricultural production. It is characterized by its diverse sources, large quantities, renewability, biodegradability, and environmental friendliness. With the rapid development of industry and the overexploitation of natural and environmental resources, pollution has caused significant harm to human health. Addressing this issue is therefore imperative. Traditional methods for pollutant removal include biological treatment, chemical precipitation, adsorption, and ion exchange. Among these, adsorption is considered a cost-effective approach for eliminating various pollutants (Al-Eid *et al.*, 2022).

Plant residues possess loose, porous structures and contain functional groups such as carboxyl and hydroxyl, making them suitable as biomass for adsorption in pollution removal. This approach not only reduces the environmental burden but also facilitates the treatment of pollutants. Water pollution caused by heavy elements is a global concern. Trace amounts of heavy elements in freshwater often originate from the erosion of rocks and soil (Al-Juboury, 2009).

To address water contamination by heavy metals, cost-effective techniques such as adsorption technology have been employed. This method utilizes low-cost, economical adsorbent materials, including agricultural waste like rice husks, walnut shells, fly ash, as well as sider, Bamber, eucalyptus branches, and palm fronds. These materials are effective in removing organic and inorganic waste due to their pollutant-absorbing capabilities (Harja *et al.*, 2013).

Phytoremediation refers to the ability of plants to absorb large quantities of pollutants and concentrate them in their biomass (phytoextraction). This process involves removing contaminants from soil or water, releasing them into the air, and limiting the transfer of elements (minerals) in the environment by immobilizing them and preventing their leakage. Certain plants, known as hyperaccumulators, exhibit a high capacity for pollutant absorption.

This study aimed to investigate the physicochemical properties of plant residues, apply kinetic models to predict their interaction with heavy elements, calculate the thermodynamic functions of the adsorption process at varying temperatures, and explore the potential of using plant residues as sustainable alternatives to mitigate water pollution for agricultural purposes.

### **MATERIALS AND METHODS**

Plant residues such as Sidr nabak leaves, Sebesten leaves, and Rachis Base were used. These plant residues were air-dried for 15 days, washed with distilled water, and then dried at 50°C. Subsequently, they were ground and sieved through a 100-micron mesh.

#### 1. Batch kinetic experiments

Standard solutions of the studied elements (iron, zinc, and manganese) were prepared by weighing the salts of these elements to achieve an initial concentration of  $1000\mu g m L^{-1}$ . The salts were dissolved in distilled water, and the solutions were stored in tightly sealed plastic containers at a temperature of 4°C until the commencement of the laboratory experiments.

For the adsorption experiments, 1g of plant residues was placed in 100mL plastic containers. Subsequently, 40mL of each element solution was added to the containers containing the plant residues. The samples were subjected to mechanical shaking at a speed of 2000rpm for varying durations (10, 20, 40, 60, and 120 minutes). After shaking,

the mixtures were filtered through filter paper. The concentration of heavy elements in the filtrate was determined using atomic absorption spectroscopy (AAS), and the amount of adsorbed elements was calculated.

To describe the adsorption kinetics, the following equations were applied. The least squares method was employed for linear regression analysis to plot the lines representing the equations and calculate the constants. The suitability of each equation was evaluated based on the coefficient of determination ( $\mathbb{R}^2$ ), with the best-fitting equation identified by achieving the highest  $\mathbb{R}^2$  value and the lowest standard error.

The zero-order kinetic model was applied to the data for the studied elements. The equation was expressed as:

 $q_t = q_e - K_0 t - - - -(1)$ 

Where,  $K_0$  is the adsorption rate constant and t is the time when t>0,  $q_e$  is the amount of the element adsorbed at equilibrium ( $\mu g/g^{-1}$ )

 $q_t$  is the amount adsorbed per minute ( $\mu g/g^{-1}$ ). The pseudo-first-order model was applied as follows:

 $\ln(q_e-q_t) = \ln q_e - (K_{1p}t) - - - -(2)$ 

Where,  $q_i$ : amount of element adsorbed per minute ( $\mu g g^{-1}$ ) (Ho, 2006),  $K_{1p}$ : represents the pseudo-first-order kinetic model constant (min)<sup>-1</sup>,  $q_e$ : amount of element adsorbed at equilibrium ( $\mu g g^{-1}$ ), t: time per minute and apply the First order model

$$q_t = q_e - \exp(K_1 t) - - - - (3)$$

Where, K<sub>1</sub>: Kinetic model constant (min)<sup>-1</sup>, q<sub>e</sub>: Amount of adsorbed element at equilibrium ( $\mu g g^{-1}$ ), q<sub>t</sub>: Amount of adsorbed element per minute ( $\mu g g^{-1}$ ) (Ho, 2006), t: Time per minute. The Second-order model was applied as follows:

$$q_t = \frac{q_e}{1 + q_e K_2 t} - - - -(4)$$

Where, K<sub>2</sub>: Kinetic model constant of the equation  $(g/\mu g/min/\mu g)$ , q<sub>e</sub>: amount of element adsorbed at equilibrium  $(\mu g/g/min)$ , q<sub>t</sub>: amount of element adsorbed per minute  $(\mu g/g/min)$  (Ho, 2006), t: time per minute. Pseudo-second order model was applied as follows:

$$\frac{\mathrm{t}}{\mathrm{q}_{\mathrm{t}}} = \left(\frac{1}{\mathrm{K}_{2}\mathrm{q}_{\mathrm{e}}^{2}}\right) + \frac{\mathrm{t}}{\mathrm{q}_{\mathrm{e}}} - - - (5)$$

Where K<sub>2</sub>: second-order kinetic model constant (g/µg/min/min), q<sub>e</sub>: amount of adsorbed element at equilibrium (µg/g/min), q<sub>t</sub>: amount of adsorbed element per minute (µg/g/min) (**Ho, 2006**), t: time per minute. The Intraparticle diffusion model was applied as follows: q<sub>t</sub> = K<sub>t</sub>t<sup>0.5</sup> - - - (6) Where,  $K_t$ : Kinetic model constant ( $\mu g/g^{-1} \min^{-1}$ ) and represents the diffusion rate constant within the particles. The adsorption process is controlled by the diffusion of the particles only,  $q_t$ : the amount of the element adsorbed per minute ( $\mu g/g^{-1}$ ) (Ho, 2006). Elovich model was applied as follows:  $q_t = \beta \ln(\beta \alpha t) - - - (7)$ 

Where,  $\beta$ : Kinetic model constant  $(g/\mu g^{-1})$ ,  $\alpha$ : Elovich kinetic model constant  $(\mu g/g^{-1} min^{-1})$ , t: time in minutes. A fractional power model was applied as follows:  $\ln(q_t) = \ln(k) + \nu \ln(t) - - - -(8)$ 

Where, v: fractional power constant, k: fractional power constant ( $\mu g/g/min/min$ ), qt: the amount of element adsorbed per minute ( $\mu g/g/min$ ) (Ho, 2006), t: time per minute.

# 2. Thermodynamic study of adsorption

A-  $\Delta$ H: represents enthalpy and is extracted from the value of the slope of the equation 1\t and the logarithm of the dynamic equilibrium constant (Log KD) extracted from the following law:

 $LogKD = \Delta S/2.303R - \Delta H/2.303RT -----(14)$ Additionally, KD was calculated from the law below:

KD=((Co-Ce))/Ce\*V/m-----(15)

**B**-  $\Delta S^{\circ}$ : represents entropy and is extracted from the value of the slope of the above relationship.

C-  $\Delta G^{\circ}$ : represents the change in standard free energy and is calculated using the following equation:

 $\Delta G^{\circ} = \Delta H^{\circ} - T \Delta S^{\circ} - \dots - (16)$ 

T: absolute temperature

## **RESULTS AND DISCUSSION**

## 1. Effect of temperature

The results indicated that as temperature increased, the adsorption percentage for all studied elements and plant residues (dry plant residues) also increased (Table 1). The lowest adsorption percentage was observed during the treatment of Sidr leaves with zinc at 303K, recording 57.935%, while the highest adsorption percentage was achieved during the treatment of palm fronds with manganese at 343K, reaching 93.100%.

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The increase in adsorption capacity with rising temperature may be attributed to either an expansion in the size of voids or pores within the adsorbent material, facilitating the diffusion of heavy element ions into these pores, or an enhancement in the chemical affinity between the adsorbent surface and the ions of these elements (Jain, 2004). These findings align with **Ren** *et al.* (2020), who reported that increasing temperatures influence the active sites of the adsorbent within a specific temperature range. Temperature changes affect factors related to motion and equilibrium, which are reflected in an increase in kinetic energy. This facilitates the migration of ions to the active sites and enhances the surface activity of plant residues, thereby increasing the number of active sites.

Plant	Matala	Temperatures (Kelvin)				
residues	wietais	303	313	323	343	
Sidr nabak	Fe	71.667	74.192	82.775	91.882	
	Mn	66.667	79.087	92.690	92.657	
	Zn	57.935	64.812	68.585	75.720	
Sebesten	Fe	71.740	78.245	83.710	86.450	
	Mn	85.347	89.417	91.870	93.100	
	Zn	72.512	75.140	77.167	83.435	
Rachis Base	Fe	70.320	74.287	87.557	89.560	
	Mn	64.610	66.852	89.256	92.520	
	Zn	69.512	71.460	75.812	83.315	

**Table 1.** The amount removed  $\mu g$  gm -1 of the heavy metals iron, manganese, and zinc on the plant residues at different temperatures (Kelvin)

When applying thermodynamic concepts based on temperature and its effects—such as changes in standard free energy ( $\Delta G^{\circ}$ ), enthalpy ( $\Delta H^{\circ}$ ), and entropy ( $\Delta S^{\circ}$ )—the linear relationship between Log KD and 1/T was utilized.  $\Delta H^{\circ}$  was determined from the slope of this relationship, while  $\Delta S^{\circ}$  was derived from the intercept, as illustrated in Figs. (1-3) and Table (2). The linear nature of the relationship between 1/T and Log KD (Figs. 1-3) indicates that the adsorption mechanism may remain unchanged with temperature variations. However, the amount of adsorption is influenced by differences in energy supply (**Dandanmozd & Hosseinpur, 2010**).





Fig. 1. Linear relationship between LogKD and 1/T for adsorption of iron ions on plant residue surfaces



Fig. 2. Linear relationship between LogKD and 1/T for adsorption of manganese ions on plant residue surfaces







**Fig. 3.** Linear relationship between LogKD and 1/T for adsorption of zinc ions on plant residue surfaces

The results presented in Table (2) indicate that the change in standard free energy ( $\Delta G^{\circ}$ ) exhibits negative values, suggesting that the adsorption reaction of the studied heavy elements with plant residues is spontaneous. This implies that the process occurs without the need for external energy. As temperature increases, the change in free energy ( $\Delta G^{\circ}$ ) becomes more negative, indicating an enhancement in the adsorption capacity of plant residues to bind with heavy element ions. The heavy elements were ranked in the following order based on their increasing adsorption by the studied plant residues:

Fe<sup>+2</sup>: Sidr leaves > Palm frond base> Bamber leaves

 $Mn^{+2}$ : Sidr nabak leaves > Bamber leaves > Palm frond base

 $Zn^{+2}$ : Bamber leaves > Sidr leaves > Palm frond base

The lowest negative values for the change in standard free energy ( $\Delta G^{\circ}$ ) were recorded at a temperature of 303K for the zinc ion with Sidr leaves, while the highest negative values for  $\Delta G^{\circ}$  were observed at 343K for the manganese ion with Sidr leaves. These findings are consistent with the results of the percentage of the removed amount (1). The increase in the negative values of  $\Delta G^{\circ}$  indicates a greater preference of the surface sites of plant residues for ion exchange with the ions of the studied elements (Saltali et al., 2007).

The values of  $\Delta G^{\circ}$  show that most are less than -20 kJ mol<sup>-1</sup>, except for the interaction of the manganese ion with Sidr nabak leaves, Sebesten leaves, and Rachis Base, as well as the iron ion with Sidr leaves and palm kernels. This suggests that the interaction is predominantly electrostatic (physical) between the adsorption sites and the element ions. **Hefne** *et al.* (2008) demonstrated that  $\Delta G^{\circ}$  values less than -20 kJ mol<sup>-1</sup> typically indicate physical adsorption, while values exceeding -40 kJ mol<sup>-1</sup> involve charge sharing and transfer from the adsorption surface to the element ions, forming a covalent bond (chemical adsorption). These results align with the findings of Okoye and Obi (2012) in their study of copper, cadmium, and lead, as well as **Yassin** (2020) in his study on nickel.

The positive values of the change in standard enthalpy ( $\Delta H^{\circ}$ ), as shown in Table (3), indicate the endothermic nature of the interactions between plant residues and heavy metals. This supports the observation that the adsorption of heavy metals on plant residue surfaces increases with rising temperature. The  $\Delta H^{\circ}$  values for heavy metals, ranging from 8.4 to 12.6 kJ mol<sup>-1</sup>, suggest that these adsorption reactions are ion exchange processes in nature (**Helfferich, 1965**). Although there is no definitive standard for  $\Delta H^{\circ}$  values to determine the type of adsorption, values between 5 and 100 kcal mol<sup>-1</sup> (20.9 to 418.4 kJ mol<sup>-1</sup>)—typically associated with chemical reaction heats—are often considered indicative of chemical adsorption processes (**Ünlu & Ersoz, 2006**). In this study, the  $\Delta H^{\circ}$  values ranged from 14.085 to 46.918 kJ mol<sup>-1</sup>, with more than half exceeding 20.9 kcal mol<sup>-1</sup>. These values were distributed as follows: Sidr leaves (Fe<sup>2+</sup> and Mn<sup>2+</sup>) and palm carob (Fe<sup>2+</sup> and Mn<sup>2+</sup>). This suggests that, in addition to ion exchange, another mechanism, such as chelation by active groups present on the surfaces of plant residues, may contribute to the adsorption of these elements.

The results for the change in entropy ( $\Delta S^{\circ}$ ) for the adsorption of heavy elements on plant residues showed positive values, ranging between 0.0982 and -0.1855 kJ mol<sup>-1</sup> (Table 2). A positive  $\Delta S^{\circ}$  value indicates an increase in the randomness of the interaction between the surface and the solution during adsorption, likely due to the exchange of heavy element ions with more mobile ions on the exchange surfaces. This exchange would increase  $\Delta S^{\circ}$ . It is noted that most, if not all, of the  $\Delta S^{\circ}$  values mentioned earlier fall within the range of physical adsorption (physisorption). The liberation of water molecules from hydrated ions or surface-bound water molecules during adsorption may contribute to the increased randomness of the interaction (**Ünlu & Ersoz, 2006**).

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**Table 2.** Thermodynamic parameters of adsorption of elements on the studied plant residues under different temperatures

Dlant		$\Delta \mathbf{G}^{\circ}$				A TTO	1 50
Flant	Metals	KJ mol <sup>-1</sup>					Δ3 <sup>-</sup> KLmal-1
residues		303k	313k	323k	343k	KJ MOI	KJ IIIOI -
	Fe	-15.3402	-16.9631	-18.5859	-21.8315	33.83109	-0.162282
Sidr nabak	Mn	-15.6887	-17.5444	-19.4002	-23.1117	40.54024	-0.185574
	Zn	-14.2347	-15.2762	-16.3177	-18.4008	17.32299	-0.104151
	Fe	-15.8953	-17.0766	-18.2578	-20.6202	19.8958	- 0.118123
Sebesten	Mn	-18.0316	-19.2203	-20.4091	-22.7867	17.98874	- 0.118879
	Zn	-15.7063	-16.6895	-17.6728	-19.6392	14.0854	- 0.098322
Rachis Base	Fe	-15.5593	-17.0691	-18.5788	-21.5984	30.18738	- 0.150979
	Mn	-14.6483	-16.6801	-18.712	-22.7758	46.91816	- 0.203189
	Zn	-15.3398	-16.3222	-17.3046	-19.2694	14.42699	- 0.09824

## 4. Adsorption kinetics

The results presented in Figs. (4, 5, 6), which illustrate the relationship between the adsorbed amount (mg  $g^{-1}$ ) of heavy elements and time (minutes), reveal a clear variation in the adsorbed amount depending on the heavy elements and plant residues. The zinc ion exhibited the highest adsorbed amount over time across the various plant residues compared to the other heavy elements. In contrast, the lowest adsorbed amount during the studied time period was observed for the iron ion with Sidr nabak leaves, Bamber leaf branches, and palm frond base.



**Fig. 4.** The amount of heavy metals absorbed (Mg g-1) on the surfaces of Sidr leaves with different periods



**Fig. 5.** The amount of heavy metals absorbed (Mg  $g^{-1}$ ) on the surfaces of Bamber leaves with different periods



**Fig. 6.** The amount of heavy metals absorbed (Mg g-1) on the surfaces of Palm frond base leaves with different periods

The results also revealed that the adsorption of zinc and manganese on the surfaces of all plant residues reached its maximum within approximately 10 minutes. This indicates that the studied time range (10–60 minutes) did not show a significant difference in the adsorbed amount compared to the initial 10 minutes. This suggests that the adsorption of these two elements on the plant residues occurred predominantly within the first 10 minutes, highlighting a rapid adsorption process. As shown in Table (3), the percentage of the adsorbed amount of the zinc ion on the surfaces of the studied plant residues ranged between 77.70 and 77.79% after 10 minutes, while it increased to 84.92–94.02% after 160 minutes. Similarly, for manganese, the adsorption percentage after 10 minutes ranged between 67.43 and 74.86%, increasing to 73.25–90.29% after 160 minutes. These findings indicate that most of the adsorption sites on the plant residue surfaces were occupied by these two elements within the first 10 minutes. This rapid adsorption may be attributed to the properties of these elements, such as particle diameter

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and the affinity between the element ions and the active sites distributed on the surfaces of the plant residues, among other factors.

Plant residues	Metals	Vibrating time(Time)				
		10	20	40	80	160
Sidr nabak	Fe	53.6	54.93	58.94	62.34	62.63
	Mn	67.76	68.18	69.57	69.86	70.11
	Zn	69.53	70.19	74.13	76.25	76.39
Sebesten	Fe	53.88	54.57	59.64	60.44	61.12
	Mn	67.97	68.42	76.46	83.41	84.87
	Zn	77.70	77.91	80.48	84.45	84.92
Rachis Base	Fe	54.76	54.83	59.21	59.86	60.43
	Mn	67.43	67.57	71.56	72.75	73.25
	Zn	74.84	74.89	77.73	78.24	79.75

**Table 3.** Percentage of the removed elements (iron, zinc, and manganese) on the plant residues under study, depending on the shaking time

When the data—the amount of heavy elements adsorbed on the surfaces of plant residues over time—were applied to kinetic models (Elovich, Fractional Power, Zero Order, First Order, Pseudo-First Order, Second Order, Pseudo-Second Order I, Pseudo-Second Order II, Pseudo-Second Order II, Pseudo-Second Order II, and Intraparticle Diffusion), the goal was to study the adsorption rate. The kinetic system of adsorption, which is time-dependent, is crucial for understanding the adsorption mechanism (**Ho**, **2006**). As shown in Table (4) (tables of constants and determination values, R<sup>2</sup>), all the studied kinetic models provided a good description of the amount of heavy elements adsorbed over time, as evidenced by the coefficient of determination (R<sup>2</sup>).

When comparing these kinetic models to identify the best model that describes the interaction between the heavy element ions and the plant residues during the study period and determines the adsorption rate, it was found that the pseudo-second-order kinetic model (in its various forms) achieved the highest  $R^2$  values. This model best described the data for most of the relationships between the heavy elements and the plant residues under study.

Kinetic model	Plant residues	<b>R</b> <sup>2</sup>
Elovich	Sidr nabak	0.943
	Sebesten	0.916
	Rachis Base	0.872
Fractional power	Sidr nabak	0.945
	Sebesten	0.935
	Rachis Base	0.892
Zero-order	Sidr nabak	0.795
	Sebesten	0.965
	Rachis Base	0.980
First order	Sidr nabak	0.778
	Sebesten	0.945
	Rachis Base	0.972
Pseudo first order	Sidr nabak	0.968
	Sebesten	0.975
	Rachis Base	0.981
Second order	Sidr nabak	0.762
	Sebesten	0.919
	Rachis Base	0.960
Pseudo second order I	Sidr nabak	0.990
	Sebesten	0.991
	Rachis Base	0.993
Pseudo-second order II	Sidr nabak	0.619
	Sebesten	0.678
	Rachis Base	0.671
Pseudo-second order III	Sidr nabak	0.823
	Sebesten	0.669
	Rachis Base	0.588
Pseudo-second order IV	Sidr nabak	0.823
	Sebesten	0.669
	Rachis Base	0.588
	Sidr nabak	0.898
Intraparticle diffusion	Sebesten	0.974
	Rachis Base	0.960

Table 4. Constants and values of the coefficient of determination  $(R^2)$  in the linear form of the kinetic adsorption models of iron ions on the studied plant residues

Kinetic model	Plant residues	$\mathbf{R}^2$
	Sidr nabak	0.737
Elovich	Sebesten	0.827
	Rachis Base	0.885
	Sidr nabak	0.754
Fractional power	Sebesten	0.834
	Rachis Base	0.882
	Sidr nabak	0.954
Zero-order	Sebesten	0.713
	Rachis Base	0.979
	Sidr nabak	0.961
First order	Sebesten	0.810
	Rachis Base	0.705
	Sidr nabak	0.968
Pseudo first order	Sebesten	0.975
	Rachis Base	0.981
	Sidr nabak	0.967
Second order	Sebesten	0.807
	Rachis Base	0.698
	Sidr nabak	0.994
Pseudo second order I	Sebesten	0.997
	Rachis Base	0.999
	Sidr nabak	0.659
Pseudo-second order II	Sebesten	0.634
	Rachis Base	0.606
	Sidr nabak	0.588
Pseudo-second order III	Sebesten	0.597
	Rachis Base	0.769
	Sidr nabak	0.441
Pseudo-second order IV	Sebesten	0.597
	Rachis Base	0.769
	Sidr nabak	0.872
Intraparticle diffusion	Sebesten	0.855
	Rachis Base	0.826

**Table 5.** Constants and values of the coefficient of determination  $(R^2)$  in the linear form of the kinetic adsorption models of manganese ion on the studied plant residues

Kinetic model	Plant residues	$\mathbf{R}^2$
Elovich	Sidr nabak	0.947
	Sebesten	0.873
	Rachis Base	0.927
Fractional power	Sidr nabak	0.946
	Sebesten	0.877
	Rachis Base	0.926
Zero-order	Sidr nabak	0.823
	Sebesten	0.792
	Rachis Base	0.834
First order	Sidr nabak	0.811
	Sebesten	0.788
	Rachis Base	0.826
Pseudo first order	Sidr nabak	0.968
	Sebesten	0.975
	Rachis Base	0.981
Second order	Sidr nabak	0.698
	Sebesten	0.785
	Rachis Base	0.818
Pseudo second order I	Sidr nabak	0.999
	Sebesten	0.999
	Rachis Base	0.999
Pseudo-second order II	Sidr nabak	0.616
	Sebesten	0.615
	Rachis Base	0.612
Pseudo-second order III	Sidr nabak	0.799
	Sebesten	0.683
	Rachis Base	0.755
Pseudo-second order IV	Sidr nabak	0.799
	Sebesten	0.683
	Rachis Base	0.755
	Sidr nabak	0.916
Intraparticle diffusion	Sebesten	0.867
	Rachis Base	0.912

**Table 6.** Constants and values of the coefficient of determination  $(R^2)$  in the linear form of the kinetic adsorption models of zinc ion on the studied plant residues

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