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Binary mixture sorption of basic dyes onto wheat straw

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Simultaneous adsorption of Basic Blue 3 (BB 3) and Basic Red 18 (BR 18) onto wheat straw (WS) from a binary system was studied and compared with a single dye system in a batch mode. The single-component Langmuir and Freundlich isotherm models were applied to the adsorption equilibrium data for single-component and binary-component systems. The equilibrium adsorption for the binary system was also analyzed by using multi-component modified Langmuir and Sheindorf–Rebuhn–Sheintuch (SRS) models. Equilibrium data of BB 3 in single and binary systems fitted more adequately to the Freundlich adsorption isotherm. For BR 18, the Langmuir model was the best one for fitting the adsorption equilibrium in single and binary systems. The pseudo-first order and pseudo-second order models were employed to fit the experimental data for the adsorption kinetics of BB 3 and BR 18 on WS from single- and binary-component systems. The pseudo-second-order model provided better correlation for the adsorption process in single- and binary-component systems. Adsorption results from the binary system indicated the competitive adsorption between dyes. The maximum adsorption capacities of WS for BB 3 and BR 18 dyes in single solution system were found as 90.91 mg g^{-1} and 142.86 mg g^{-1}, respectively, while in binary mixture they decreased to 76.92 mg g^{-1} and 111.11 mg g^{-1}, respectively, as a result of their antagonistic behavior.

Key words: adsorption, basic dyes, binary mixture, wheat straw, equilibrium, kinetics.

1. INTRODUCTION

Agriculture is an important sector in the world economy. However, wastes are generated as part of the cycle of harvest, preparation of crops for use and preparation of land for a subsequent crop. Although some of the crop residues are reutilized, the inadequate management of the remaining residues has been identified as a source of significant environmental threats and has contributed to serious disposal problems.

Agricultural wastes, particularly those containing cellulose, show potential sorption capacity for various pollutants. The basic components of the agricultural waste materials include cellulose, hemicellulose, lignin, lipids, proteins, simple sugars, hydrocarbons, and starch, containing a variety of functional groups. Agricultural waste materials being economic and eco-friendly due to their unique chemical composition, availability in abundance, renewable nature and low cost are a viable option for water and wastewater remediation.

There has been much interest in the use of agricultural wastes as adsorbents to prevent and remediate environmental contamination by dyes (Ahmad and Kumar [1]; Allen et al. [2]; Amin [3]; Annadurai et al. [4]; Arami et al. [5]; Franca et al. [6]; Hameed et al. [7]; Ho and McKay [8]; Garg et al. [9]; Gupta et al. [10]; Khattri and Singh [11]; Nasuha et al. [12]; Namasivayam and Kavitha [13]; Senturk et al. [14]; Sulak et al. [15].

Much of the work on the adsorption of dyes by various kinds of adsorbents has been focused on the uptake of single dyes. Since industrial effluents may contain several dyes, it is necessary to study the simultaneous sorption of two or more dyes and to quantify the interference of one dye with the sorption of the other. Thus, the studies on the equilibrium and kinetics of dyes adsorption from multi-component systems are very important. The equilibrium adsorption isotherm equations proposed for single-component adsorption have been extended and modified to represent the multi-component adsorption equilibria. However, no information is available in the literature for the simultaneous removal of BB 3 and BR 18 by WS.

The aim of the present paper was: (i) to study the feasibility of using the agricultural waste wheat straw (WS) as an adsorbent for the individual and simultaneous removal of BB 3 and BR 18 dyes from aqueous solutions, (ii) to determine the

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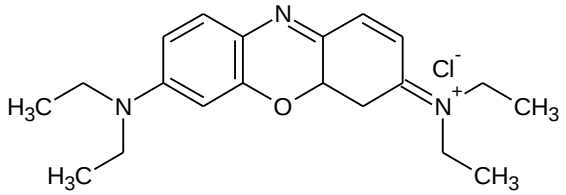
applicability of non-competitive adsorption isotherm models (i.e., Langmuir and Freundlich) for single and binary component systems, (iii) to examine the applicability of the multi-component adsorption isotherm equations to the competitive adsorption equilibria of the dyes in a binary system, and (iv) to establish which kinetic model is most suitable for describing the adsorption of BB 3 and BR 18 on WS.

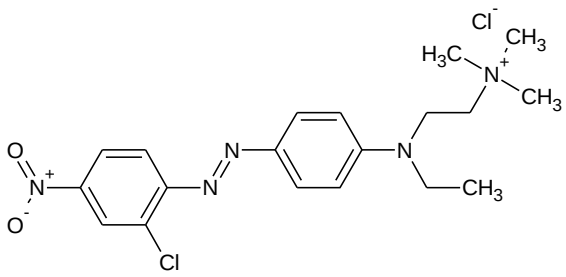
2 MATERIALS AND METHODS

2.1 Adsorbates

The dyes used as adsorbates were Basic Blue 3 (BB 3) and Basic Red 18 (BR 18), whose chemical structures and general characteristics are depicted in Fig. 1 and Table 1, respectively. Experimental solutions of desired dye concentration were obtained by dissolving accurately weighed quantities in distilled water. For binary mixture studies, desired combinations of BB 3 and BR 18 were prepared by mixing them in the test medium before adding the adsorbent.



(a)



(b)

Fig.1. Chemical structures of (a) BB 3 and (b) BR 18.

2.2 Adsorbent

Wheat straw (WS) used in this study as an adsorbent was harvested from Egyptian fields. WS was used as received without grinding or further treatment. The following chemical characteristics of WS: ash content, cellulose, hemicellulose, lignin and organic extractives were analyzed by TAPPI standard methods (Kouris [16]). The chemical composition of WS presented in Table 2 indicates that WS is composed mainly of cellulose, hemicellulose and lignin, which provides binding sites for the dyes due to the presence of functional groups such as hydroxyl, carboxyl, methoxy, phenolic, etc.

Table 1. General characteristics of BB 3 and BR 18.

Characteristics	Dye	
	BB 3	BR 18
C.I. name	Basic Blue 3	Basic Red 18
Chemical class	Monoxazine	Mono-azo
MW (g mol^{-1})	359.89	390.89
λ_{max} (nm)	610	488

Table 2. Chemical composition of WS

Constituents	%
α-Cellulose	56.2
Hemicellulose	16
Lignin	23
Extractives	3.2
Ash	1.6
Moisture	9.81

2.3 Isotherms of single and binary dye systems

The sorption studies were conducted by the batch technique. A number of stoppered 100 cm^3 Erlenmeyer flasks containing a definite volume (50 cm^3) of solutions with a desired concentration of each component were placed in a shaker at 20 °C.

For isotherm studies, 0.5 g of WS was treated with 50 cm^3 of a solution of a single or binary dye mixture with pre-determined initial dye concentrations (100-700 mg dm^{-3}). The flasks were shaken at 150 rpm for 2 days to ensure that equilibrium was reached. The supernatant solution was separated from the adsorbent by filtration using a syringe 0.2 μm filter unit (Minisart) and then the equilibrium concentrations of the dyes were measured on the spectrophotometer (Spekol 11, Carl Zeiss JENA). For the binary systems, all solutions were prepared with equimolar solutions of the two basic dyes.

The amount of dye adsorbed at the equilibrium (q_e, mg g^{-1}) was calculated according to the expression:

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

where C_0 and C_e are the initial and equilibrium dye concentrations (mg dm^{-3}), respectively, V is the solution volume (dm^3), and m is the mass of WS (g).

2.4 Kinetics of single and binary dye systems

The kinetics of BB 3 and BR 18 adsorption in single and binary adsorption systems onto FS and WS were studied at 20 °C. Experiments were carried out in a standard agitated reactor

experimental setup (a 2 dm^3 glass beaker) with a two-blade impeller to stir the dye solution using a Heidolph RZR 2100 motor.

In all adsorption experiments, a pre-selected amount of adsorbent (17 g) was dispersed in 1.7 dm^3 of dye solution of 400 mg dm^{-3} concentration (in single and binary systems) while being constantly stirred by a mechanical stirrer at a speed of 60 rpm. Samples (3-5 cm^3) were withdrawn from the mixture at regular time intervals (from 1 min up to 540 min) using a syringe, immediately filtered using a syringe filter unit (0.2 μm) and analyzed spectrophotometrically.

2.5 Analysis of dye concentration

2.5.1 Analysis in single-component systems. The concentrations of dyes in single-component systems were measured spectrophotometrically prior to (initial concentration) and following the adsorption test (residual concentration) by monitoring the absorbance changes at the wavelengths of maximum absorbance (λ_{max}) of 610 and 488 nm for BB 3 and BR 18, respectively, using standard calibration curves.

2.5.2 Analysis in binary-component systems. Suppose that there is no interaction between the two dyes in binary-component systems, the total absorbance for a mixed dye solution is equal to the sum of the absorbances of each dye (Skoog et al. [17]). This is represented in Eq. (2).

To determine whether the presence of one dye affected the adsorption of another dye, the adsorption capacities of each dye in mixed solutions are computed using Eqs. (3) and (4).

$$A_\lambda = A_{BB} + A_{BR} \quad (2)$$

$$A_{\lambda 1} = \varepsilon_{1BB} l C_{BB} + \varepsilon_{1BR} l C_{BR} \quad (3)$$

$$A_{\lambda 2} = \varepsilon_{2BB} l C_{BB} + \varepsilon_{2BR} l C_{BR} \quad (4)$$

where: A_λ, $A_{\lambda 1}$ and $A_{\lambda 2}$ are the absorbances at wavelengths λ, λ_1 and λ_2, respectively; A_{BB} and A_{BR} are the absorbances of BB 3 and BR 18 at a wavelength λ, respectively; ε_{1BB} and ε_{2BB} are the molar absorptivities of pure BB 3 at wavelengths λ_1 and λ_2, respectively; ε_{1BR} and ε_{2BR} are the molar absorptivities of pure BR 18 at wavelengths λ_1 and λ_2, respectively; C_{BB} and C_{BR} are the concentrations of BB 3 and BR 18 in the mixed solutions; l is the cell width (1 cm); λ_1 (610 nm) is the wavelength of maximum absorbance for BB 3; and λ_2 (488 nm) is the wavelength of maximum absorbance for BR 18. The concentrations C_{BB} and C_{BR} are determined from Eqs. (3) and (4) and then used to obtain the adsorption capacity for each dye in the mixed solutions.

3. ADSORPTION ISOTHERM MODELS

3.1 Single-component models

Isotherm models such as Langmuir [18] and Freundlich [19] were often used to fit the data with a view to understand the adsorption process and to obtain the information needed for scaling up to a larger system.

3.1.1 Langmuir isotherm. The Langmuir model assumes monolayer coverage of adsorbate on an energetically identical homogeneous adsorbent surface. The Langmuir equation and its linearized form may be written as:

$$q_e = \frac{q_m b C_e}{1 + b C_e} \quad (5)$$

$$\frac{C_e}{q_e} = \frac{1}{q_m b} + \frac{C_e}{q_m} \quad (6)$$

where: q_e is the dye uptake at equilibrium (mg g^{-1}), C_e is the concentration of the solution at equilibrium (mg dm^{-3}), while b (dm^3 g^{-1}) and q_m (mg g^{-1}) are related to the affinity and maximum sorption capacity, respectively.

3.1.2 Freundlich isotherm. The Freundlich isotherm is derived by assuming a heterogeneous surface with a non-uniform distribution of heat of adsorption over the surface.

The Freundlich adsorption isotherm equation and its linear form can be written as follows:

$$q_e = K_F C_e^{1/n} \quad (7)$$

$$\log q_e = \log K_F + {}^1/_n \log C_e \quad (8)$$

where: K_F is the Freundlich constant representing the adsorption capacity (dm^3 g^{-1}), and n is the Freundlich exponent depicting the adsorption intensity.

3.2 Multi-component models

When several components are present, there is interference and competition between the different components for the adsorption sites. The isotherm models for a single-component system are thus inapplicable. A multi-component system requires a more complex mathematical isotherm model.

3.2.1 Modified Langmuir model. The modified Langmuir model assumes that all adsorbate ions or molecules compete for energetically identical adsorption sites and it can be written for N

components in the mixture as follows (McKay and Al Duri [20]):

$$q_{e,i} = \frac{q_{m,i} b_i C_i}{1 + \sum_{j=1}^{N} b_j C_j} \quad (9)$$

where: C_i and C_j are the concentrations of the adsorbates *i* and *j* remaining in liquid at equilibrium (mg dm^{-3}), $q_{e,i}$ is the equilibrium uptake of the adsorbate *i* in the multi-component system (mg g^{-1}). b_i and b_j are the Langmuir adsorption constants of the adsorbates (dm^3 g^{-1}) and $q_{m,i}$ is the Langmuir adsorption capacity of the adsorbate *i* (mg g^{-1}) that can be estimated from the fitting of the experimental data by the corresponding individual Langmuir isotherm equation.

For a binary system, the modified Langmuir isotherms can be written as:

$$q_{e,1} = \frac{q_{m,1} b_1 C_1}{1 + b_1 C_1 + b_2 C_2} \quad (10)$$

$$q_{e,2} = \frac{q_{m,2} b_2 C_2}{1 + b_1 C_1 + b_2 C_2} \quad (11)$$

where: the subscripts 1, 2 represent the two solutes (BB 3 and BR 18) in the binary system used in the present study.

3.2.2 Sheindorf–Rebuhn–Sheintuch (SRS) model. Sheindorf et al. [21] derived a Freundlich-type multi-component adsorption isotherm, the Sheindorf–Rebuhn–Sheintuch (SRS) equation, to represent experimental data. The assumptions incorporated in the derivation are: (i) each component individually obeys the Freundlich isotherm; and (ii) for each component in a multi-component adsorption system, there exists an exponential distribution of site adsorption energies.

The general SRS equation for a component *i* in an *N*-component system is given as:

$$q_i = K_i C_i \left(\sum a_{ij} C_j \right)^{n_i - 1} \quad (12)$$

where: q_i is the adsorption capacity of component *i* (mg g^{-1}); C_i and C_j are the concentrations of *i* and *j* in the equilibrium solution (mg dm^{-3}); K_i (dm^3 g^{-1}) and n_i are the Freundlich constants obtained for *i* in a single-component system; and a_{ij} is the competition coefficient for the adsorption of component *i* in the presence of component *j*.

The bicomponent isotherm can be written as:

$$\frac{C_1}{C_2} = \frac{\beta_1}{C_2} - a_{12} \quad (13)$$

and

$$\frac{C_2}{C_1} = \frac{\beta_2}{C_1} - a_{21} \quad (14)$$

with

$$\beta_1 = \left(\frac{K_1 C_1}{q_1} \right)^{1/(1-n_1)} \quad (15)$$

and

$$\beta_2 = \left(\frac{K_2 C_2}{q_2} \right)^{1/(1-n_2)} \quad (16)$$

If both concentrations vary during the experiment, then plotting C_1/C_2 vs β_1/C_2 yields a straight line of unity slope and the competition coefficient could be determined from the intercept.

4. ADSORPTION KINETICS MODELS

The applicability of the pseudo-first-order kinetics (Lagergen [22]) and the pseudo-second order kinetics (Ho&McKay [23]) was tested for the adsorption kinetics of BB 3 and BR 18 on WS from single- and binary-component systems.

4.1 The Pseudo-first order kinetic model

Assuming pseudo-first order kinetics, the rate of the adsorptive interactions can be evaluated using the simple Lagergren equation:

$$\frac{dq_t}{dt} = k_1 (q_e - q_t) \quad (17)$$

Integrating Eq. (17) for the boundary conditions, $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_t$, the linear form of the equation becomes:

$$\ln(q_e - q_t) = \ln q_e - k_1 t \quad (18)$$

where: q_e and q_t are the values of amount adsorbed per unit mass at equilibrium and at any time *t*, respectively, and k_1 is the pseudo-first order rate constant (min^{-1}).

The values of k_1 and calculated equilibrium adsorption capacity, q_e, can be obtained from the slope and intercept, respectively, of the linear plot of $\ln(q_e - q_t)$ versus *t*.

4.2 The Pseudo-second order kinetic model

If the rate of adsorption follows a second order mechanism, the pseudo-second order kinetic rate equation is expressed as:

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \quad (19)$$

where: k_2 is the second order rate constant (g mg $^{-1}$ min^{-1}).

For the boundary conditions, $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_t$, the integrated linear form of the equation is written as:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \left(\frac{1}{q_e}\right)t \quad (20)$$

The plot of t/q_t versus t gives a linear relationship, which allows computation of k_2 and predicted q_e.

5. RESULTS AND DISCUSSION

5.1 Adsorption of dyes in single and binary systems

Single-component models of Langmuir and Freundlich were each applied to adsorption data from single and binary systems. In adsorption in binary solutions, these models were applied to each dye neglecting the possible interference by the other dye. The possible reduction in dye adsorption capacity onto WS in binary mixtures was evaluated by comparing the maximum adsorption capacity from single dye solutions to that of binary dye solutions for each particular dye. Such comparisons should only be made if the initial conditions are identical in single and binary dye solution systems. As illustrated in section 2.3, the adsorption isotherms data in this study were determined under identical experimental conditions.

It should be noted that equilibrium adsorption for a binary system was also analyzed by using multi-component modified Langmuir and Sheindorf–Rebuhn–Sheintuch (SRS) models which describe competitive adsorption. Moreover, single-component models have been used to simulate competitive adsorption systems (Allen and Brown [24]; Allen et al. [25]; Martin and Al-Bahrani [26]).

The results of fitting Eqs. (6) and (8) to the adsorption data of single and binary systems are presented in Table 3.

Table 3 shows the maximum adsorption capacity (q_m) of WS for basic dyes from single and binary solutions. The maximum adsorption capacities of WS for BB 3 and BR 18 dyes in a single solution system were found as 90.91 mg g^{-1} and 142.86 mg g^{-1}, respectively, while in a binary mixture they decreased to 76.92 mg g^{-1} and 111.11 mg g^{-1}, respectively, as a result of their competitive behavior. Although the maximum adsorption capacities of WS for BB 3 and BR 18 dyes decreased in binary mixture, simultaneous removal of these dyes is still possible owing to the high adsorption capacities obtained in the binary system.

Table 3. Parameters of Langmuir and Freundlich isotherms for single (S) and binary (B) systems for WS.

System	Langmuir		Freundlich	
	q_m(mg g^{-1})	b(dm^3 g^{-1})	K_F (dm^3 g^{-1})	n
BB 3 (S)	90.91	0.054	7.89	0.579
BB 3 (B)	76.92	0.115	11.75	0.482
BR 18 (S)	142.86	0.010	2.01	0.816
BR 18 (B)	111.11	0.038	5.71	0.700

In the application of adsorption for purification of wastewater the solution will normally be a mixture of many compounds rather than a single one. The interactions of these compounds may mutually enhance or mutually inhibit adsorption capacity (Ho and McKay [27]). In general, a mixture of different adsorbates may exhibit three possible types of behavior: synergism, antagonism and non-interaction (Srivastava et al. [28]). In this study, the binary solution exhibited inhibitory (antagonistic) adsorption for each dye, thereby resulting in a lower q_m.

Generally, the adsorption capacities of each individual dye proportionally decrease in the presence of another solute. This can be attributed mainly to the competitive interaction between the dyes on the solid surface. Other factors may include the electrical repulsion of a dye from the adsorbent surface by the other adsorbed dye of similar charge. In addition, the dye with the higher saturation value may effectively occupy most of the active sites hindering further adsorption of the other dye possessing a lower affinity (Porter [29]).

Allen et al. [25] considered the competitive adsorption of three basic dyes. Their results showed that the adsorption capacity of an individual dye decreased in the presence of a second or a third dye. They reported that reduced capacities could be attributed to a combination of a number of factors. These include: (i) interaction between dyes in solution; (ii) change in the adsorbent surface charge due to adsorption; (iii) competitive adsorption between dyes for active sites on the adsorbent surface where displacement effects replace the other dyes from the adsorption sites.

5.2 Fitting adsorption data to adsorption models

The single-component Langmuir and Freundlich isotherm models were applied to the adsorption equilibrium data for a single-component and a binary mixture. Equilibrium adsorption for the binary system was also analyzed by using multi-component modified Langmuir and Sheindorf–Rebuhn–Sheintuch (SRS) models.

The sum of the squares of the errors (*SSE*) function was used to test the adequacy and accuracy of the fit of the four isotherm models with the experimental data:

$$SSE = \sum_{i=1}^{N} \left(q_{e,cal} - q_{e,exp}\right)_i^2 \quad (21)$$

where: the subscripts '*exp*' and '*cal*' indicate the experimental and calculated values, respectively and *N* is the number of measurements.

The best fitting model is determined on the basis of the lowest *SSE* values. Table 4 summarizes the values of *SSE* for single-component and multi-component isotherms models. Equilibrium data of BB 3 in single and binary systems fitted more adequately to the Freundlich adsorption isotherm. For BR 18, Langmuir model was the best one for fitting the adsorption equilibrium in single and binary systems.

Table 4. *SSE* values for single-component and multi-component isotherms models for WS**.**

System	Langmuir	Freundlich	Modified Langmuir	SRS model
BB 3 (S)	296.07	219.35		
BB 3 (B)	187.47	97.23	642.11	6E+13
BR 18 (S)	184.12	450.02		
BR 18 (B)	76.67	169.54	4109.35	4.6E+11

Table 5. Kinetic parameters for the adsorption of BB 3 and BR 18 on WS in single and binary systems.

Dyes	Adsorption system	q_e, exp. (mg g^{-1})	Pseudo-first order kinetic model			Pseudo-Second order kinetic model		
			q_e, cal. (mg g^{-1})	K_1 (min^{-1})	R^2	q_e, cal. (mg g^{-1})	K_2 (g mg^{-1} min^{-1})	R^2
BB 3	BB 3-S	39.33	7.34	0.012	0.961	40	0.009	0.999
	BB 3-B	38.07	12.9	0.010	0.961	38.46	0.004	0.999
BR 18	BR 18-S	40.66	6.64	0.016	0.881	41.67	0.014	1
	BR 18-B	39.02	8.46	0.008	0.925	40	0.005	0.999

5.3 Kinetics modeling

The study of adsorption kinetics in wastewater treatment is important since it provides valuable insights into reaction pathways and mechanism of adsorption process.

Figs. 2 and 3 show the effect of the contact time on the amounts of dyes adsorbed in single and binary dye systems for BB 3 and BR 18, respectively. As contact time increases, dye uptake initially increases and then becomes almost stable, denoting attainment of equilibrium. These changes in dye uptake may be due to the fact that, initially, all adsorbent sites were vacant and the solute concentration was high. After that period, only a very low increase in the dye uptake was observed because there are few free surface active sites on WS.

As can also be seen from the figures, the adsorption capacities decreased for both dyes after adsorption in binary systems, indicating their competitive behavior. The pseudo-first order and pseudo-second order models were employed to fit the experimental data for the adsorption kinetics of BB 3 and BR 18 on WS from single- and binary-component systems.

Plots of pseudo-first order and pseudo-second order models are demonstrated in Figs. 4 and 5, respectively. Modeling of kinetics models and parameters obtained from the pseudo-first-order and pseudo-second-order models are given in Table 5. It can be seen that the correlation coefficients,

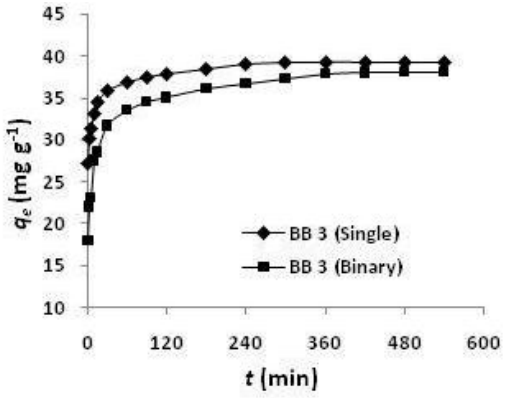


Fig. 2. Effect of contact time on the amounts of BB 3 adsorbed on WS in single and binary systems.

R^2, of the pseudo-second order model are close to 1 while correlation coefficients for the pseudo-first order kinetics model range from 0.881 to 0.961.

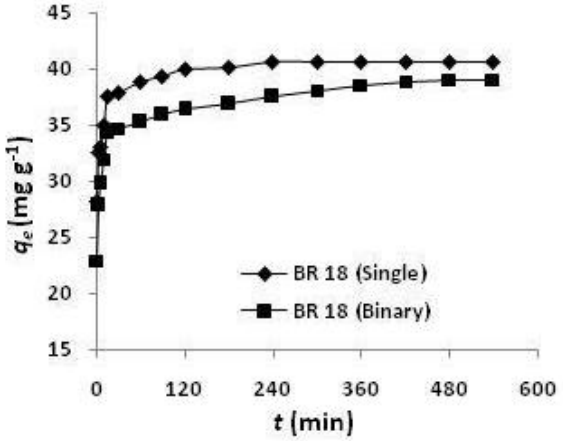


Fig. 3. Effect of contact time on the amounts of BR 18 adsorbed on WS in single and binary systems.

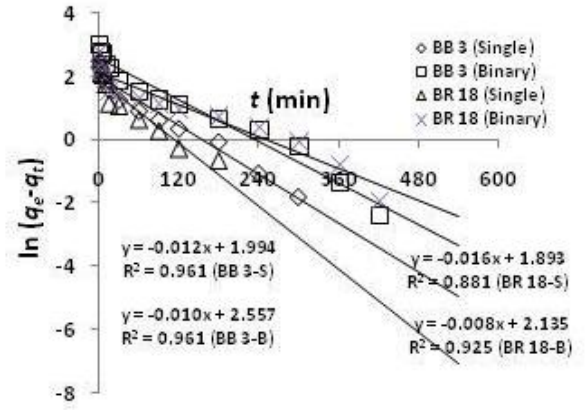


Fig.4 Pseudo-first order kinetics for adsorption of BB 3 and BR 18 on WS in single and binary systems.

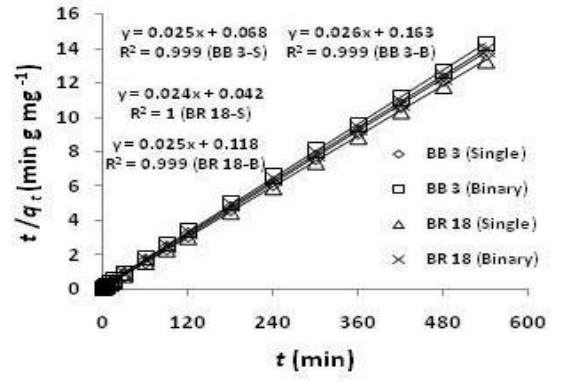


Fig.5. Pseudo-second order kinetics for adsorption of BB 3 and BR 18 on WS in single and binary systems.

Adsorption capacities calculated (q_e, cal.) by the pseudo-second order were also close to those obtained from experiments (q_e, exp.). Hence, the pseudo-second-order model provides better correlation for the adsorption process of BB 3 and BR 18 on WS in single- and binary component systems**.**

6. CONCLUSIONS

The agricultural waste, wheat straw, displayed a high adsorption capacity for basic dyes (BB 3 and BR 18) from single and binary solutions. It was found that the maximum adsorption capacities decreased in a binary system as compared to single dye systems.

Although the maximum adsorption capacities of WS for BB 3 and BR 18 dyes decreased in a binary mixture, simultaneous removal of these dyes is still possible due to the high adsorption capacities obtained in the binary system (76.92 mg g^{-1} and 111.11 mg g^{-1} for BB 3 and BR 18, respectively).

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ДВУКОМПОНЕНТНА АДСОРБЦИЯ НА ОСНОВНИ БАГРИЛА ВЪРХУ ПШЕНИЧЕНА СЛАМА

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(Резюме)

Изследвана е едновременната адсорбция на основно синьо 3 (BB 3) и основно червено 18 (BR 18) върху пшеничена слама (WS) и е сравнена с еднокомпонентните им системи. Приложени са моделите на Лангмюир и Фройндлих за описание на равновесието на едно- и двукомпонентните системи. Адсорбционното равновесие на двукомпонентната система е анализирано чрез използването на модифицирания за многокомпонентни системи модел на Лангмюир и този на Sheindorf-Rebuhn-Sheintuch. Равновесните данни за BB 3 в моно- и двукомпонентна системи се описва адекватно с адсорбционната изотерма на Фройндлих. За BR 18 моделът на Лангмюир е по-подходящ за моно- и двукомпонентна смес. За описание на адсорбционната кинетика на BB 3 и BR 18 върху WS за моно- и двукомпонентни системи са използвани моделите от псевдо-първи и псевдо-втори порядък. По-добра корелация предоставя моделът от псевдо-втори порядък. Резултатите при двукомпонентната система показват конкуриращa се адсорбция на багрилата. Максималните адсорбционни капацитети на WS за еднокомпонентни системи на BB 3 и BR 18 са съответно 90.91 mg g^{-1} и 142.86 mg g^{-1}, докато за двукомпонентните смеси те намаляват съответно до 76.92 mg g^{-1} и 111.11 mg g^{-1} в резултат на антагонистичното поведение на багрилата.