An investigaion on the feasibility of peanut-hull as an adsorbent

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Recently, many researches are directed to finding low cost adsorbents for clarifying colored effluents. Agricultural residues were found to be effective adsorbents, which can be used once as such and then re-used as a fuel by combustion. In laboratory - scale studies, experimental results indicated that peanut hull has the ability to adsorb considerable amounts of basic dyes. Equilibrium modeling has been carried out using Langmuir, Freundlich and Redlich-Peterson models. The correlation between the three isotherms and experimental data is found to be better for Freundlich isotherm than those obtained from Langmuir or Redlich -Peterson ones. A simple kinetic model has been developed to explain the external mass transport of basic dye (MB) onto peanut hull and determine the external mass transfer for this under influence of a number of design variables; namely agitation speed, initial dye concentration, mass of peanut hull and initial pH value.

تتجه الأبحاث حديثا إلى إيجاد مواد مازه رخيصة لإزالة المواد الملونة المسببة للتلوث في السوائل ، وقد وجد أن البقايا الصلبة الزراعية تصلح لعمليات الامتزاز حيث تستخدم مرة واحدة للامتزاز ثم تستخدم بعد ذلك كوقود أعلى في قيمته الحرارية من المادة الأصلية وقد أثبتت التجارب المعملية أن قشر الفول السوداني يمكنه امتزاز كميات كبيرة من الصبغات القاعدية ، وعندما تم تطبيق النمذجة الرياضية للنتائج باستخدام نماذج الامتزاز الثلاثة (فروندليتش ولانجماير ورديلك بترسون) وجد أن النتائج يمثلها بدرجة أكبر نموذج فروندليتش عن غيره من النماذج، وقد تم استخدام نموذج رياضى لدراسة الخطوة المتحكمة في عملية الامتزاز و من هذا النموذج الرياضى تم ايجاد معامل انتقال المادة الخارجي (K_s) مع كافة العوامل المؤثرة وهي: سرعة التقليب، التركيز الابتدائي للصبغة وكتلة قشر الفول السوداني المستخدمة وأخيراً عامل تركيز أيون الأيدروجين الابتدائى في المحلول (pH).

Keywords: Peanut hull, Adsorption isotherms, Adsorption kinetics

1. Introduction

Wastewater from food coloring, cosmetics, paper and textile industries is polluted by dyes. When those colored effluents enter rivers or any other surface water systems, they upset biological activity. Ground-water systems are also affected by these pollutants because of leaching from the soil. Dyes can cause allergic dermatitis, skin irritation, cancer and mutation [1]. Adsorption has been found to be a successful technique for controlling the extent of water pollution due to dyes, metallic species, surfactants and other organic pollutants [2-5]. As a technique in water pollution control, adsorption requires less investment, the design of the necessary equipment is simple and such equipment can be operated easily. In these respects, adsorption is more efficient and convenient than other conventional treatment techniques. Activated carbons are conventionally used for the removal of contaminants from liquids and gases because of their structural, textural and sorption peculiarities [6-9]. However because of their high cost, activated carbons are now being replaced by other low-cost materials. In addition, activated carbons suffer losses of approximately 15 – 20 % during the regeneration process. Hence a research is being conducted for low-cost materials useful for the adsorption of dye colors [10]. Low - cost materials can be used just once and re-used as fuels of low calorific values.

A number of (non-conventional, low – cost) agricultural waste products have been tried for dye removal. These include peat, wood, sawdust, maize cob, rice hulls, banana pith, bagasse pith, orange peel and others [11-26]. The adsorption of Methylene Blue (MB), is of interest for a number of reasons: (i) the adsorption capacity of a solid adsorbent towards MB provides a measure of the decolorizing power of the adsorbent. (ii) Since MB is a bulky molecule, it is only adsorbs on the external surface of a solid and in any mesopores

which may be present. (iii) MB contain more than one adsorption center which may exhibit different modes of interaction with the solid surface.

In addition to the above reasons which are mainly of academic interest, another reason which is more relevant to applied and environmental requirements is the need to remove dye molecules from aqueous media. Waste water, particularly that from the effluents of dyeing and textile plants, contains dye molecules as pollutants. The removal of such dyes is important for upgrading the quality of the water and, if possible, for the recovery and recycling of the dyes concerned [27-29].

In Egypt, a vast amount of peanut hull, a waste agricultural by - product, is utilized as fuel and manure. The present investigation is undertaken to test the ability of peanut hull to be used as an adsorbent.

Isotherm studies have been undertaken to determine the maximum adsorption capacity of peanut hull for basic dye (MB). A series of contact time experiments have been undertaken in an agitated batch adsorber to assess the effect of the design variables, namely, agitation speed, initial dye concentration, mass of peanut hull and initial pH value. The external mass-transfer has been studied with four design variables.

A simple kinetic model has been developed to determine the external- mass transfer coefficient and correlated with the design variables.

2. Experimental

The adsorbent used in this investigation was Egyptian peanut hull, collected from El-Minia Governorate, Egypt. It was cut into a possible size, naturally dried by sun. It was left (for 3 days) to equilibrate to a fixed moisture content (14 ± 0.3 %) and no form of pretreatment was applied prior to sieving to obtain a border of around two millimeters particle size, (2mm). The characteristics of the used peanut hull are shown in table 1.

The dyestuff used in this study was chosen to be Methylene Blue (MB). All concentrations were measured at the wavelength corresponding to maximum absorbance, λ_{max} 661 nm, with the help of a UV -Vis spectrophotometer. Dilutions were undertaken when absorbance exceeded 0.6.

Table 1
Characteristics of raw peanut hull

Protein	6-7%
Fat	1%
Fiber	60-70%
Moisture	8-10%
Cellulose	34-45%
Lignin	27-33%
Ash	2-4 %
Bulk density	0.08-0.1 gm/cm^3
Porosity	61.70 %
Solubility in H_20	0.74 %
PH	5.6

Adsorption isotherms were determined by the bottle-point method [30]. Different masses of peanut hulls (0.125, 0.25, 0.5, 0.75 and 1.0 g) were added to bottles containing 50 ml of dye solution (different initial concentrations ranging from 5-130 ppm) for each mass adsorbent. The bottles were sealed and, together with appropriate controls, mechanically shaken for a period of 3h. (equilibrium time). Resultant solution concentrations were then determined, the equilibrium data from each of such bottles represents one point on an adsorption isotherm.

A series of contact time experiments have been undertaken in an agitated batch adsorber to assess the effect of the design variables, namely, agitation speed, initial dye concentration, mass of peanut hull and initial pH value at 30± 2 ^{o}C. The batch adsorber vessel was a baffled 2 dm^3 beaker, and the volume of dye solution used in each run was 1.7 dm^3. Constant and uniform agitation was achieved using a variable speed motor and a six – bladed (flat) stainless-steel impeller.

3. Results and discussion

3.1. Adsorption isotherm studies

Fig. 1 depicts the adsorption isotherms measured for MB at 30± 2 ^{o}C. These isotherms corroborate the marked effect of mass of peanut hull on the adsorption of MB. It can be

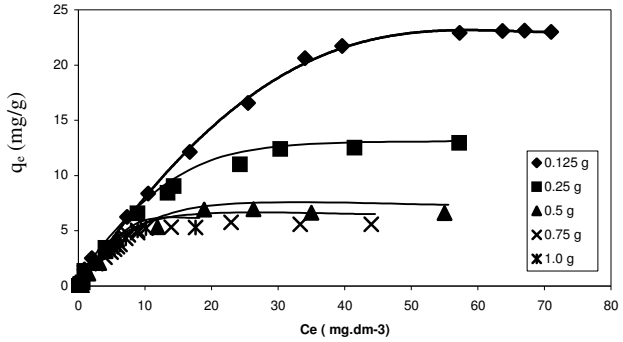


Fig. 1. Equilibrium isotherms for adsorption of methylene blue onto peanut hull at different masses.

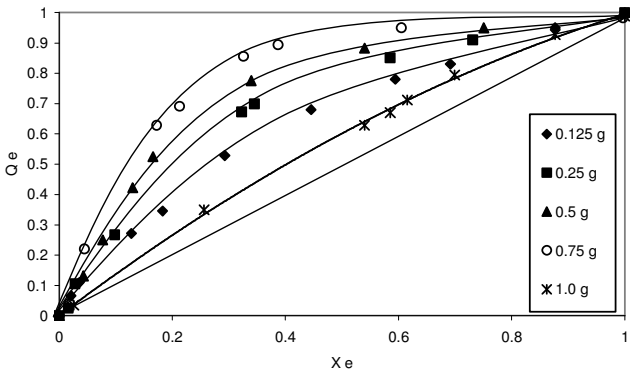


Fig. 2. Equilibrium parameter plots for the adsorption of methylene blue onto peanut hull at different masses.

seen that with an increase in mass of peanut hull the adsorption of MB decreases from 23 mg/g to 5.5 mg/g. Isotherm data were analyzed to develop an equation which both accu rately represents the results and could be used for design purposes. Several isotherm equations are available for this analysis. In this study three of these have been selected, i.e. Langmuir, Freundlich and Redlich-Peterson isotherms. The later incorporates features of both Langmuir and Freundlich equations.

The first isotherm, Langmuir, has a linear form which is represented by:

$$C_e/q_e = 1/K_L + (a_L/K_L)\, C_e. \quad (1)$$

The values of K_L at different mass massesof peanut hull have been calculated using least - squares method and tabulated in table 2. The values of K_L/a_L represent the maximum adsorption capacity, $q_{max,}$ of peanut which increases with a decrease in the mass of adsorbent.

The essential features of the Langmuir isotherm can be expressed in terms of a dimensionless constant separation factor, R [31], which is defined by:

$$R = 1/(1 + a_L\ C_o). \quad (2)$$

The R values are depicted in fig. 2, which is a plot of the dimensionless solid-phase concentration, Q_e, against the dimensionless liquid-phase concentration, X_e. The general relationship for the equilibrium parameter R, is:

$$R = X_e(1 - Q_e) / Q_e(1 - X_e), \quad (3)$$

where;

$$X_e = C_e / C_{ref}, \quad (4)$$

$$Q_e = q_e / q_{ref}, \quad (5)$$

$$R = 1/(1 + a_L\, C_{ref}). \quad (6)$$

The degree of "favourability" is generally related to the reversibility of the system giving a qualitative assessment of the methylene blue – peanut hull reactions. Indeed, the degree of reversibility of the studied system is, $0 < R < 1$, which represents that the reversible isotherm case is in the favourable range.

The Freundlich model was also used to represent the observed phenomena as given by the following equation:

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

Eq. (7) may be linearized via a logarithmic plot which enables the exponent (n) and the constant (K_F) to be determined which is:

$$\log q_e = \log K_F + (1/n) \log C_e. \quad (8)$$

Inspection of the results derived from the Freundlich analysis and depicted by eq. (8) shown that a plot of log q_e versus log C_e exhibits some curvature. Indeed, the results may be better represented by more than one straight line. The Freundlich parameters, K_F and n have been calculated using least - squares method applied to the straight lines and are listed in table 3 which shows high correlation coefficients. The magnitude of exponent, n,

gives an indication of the favourability and capacity of the adsorbent / adsorbate system.

It is generally stated [32] that values of n in the range 1-10 represent good adsorption. Another isotherm, which incorporates intermediate terms between the Langmuir and Freundlich equations, describes the isotherm better than the classical equation. The Redlich- peterson isotherm is represented by the equation

$$\log \{[(K_{RP}\, C_e) / q_e] - 1\} = \log a_{RP} - \beta \log C_e \,. \qquad (9)$$

The Redlich – Peterson parameter values at different mass of peanut hull have been calculated using the least-squares method and are tabulated in table 4.

Fig. 3 shows a comparison between the experimental points and Langmuir, Freundlich and Redlich –Peterson equations , to establish which equation yields the "best fit". It is clear that the Freundlich model fits the data better than Langmuir and Redlich –Peterson models. This was supported by comparing correlation coefficients generated by linear plots performed on Langmuir, Freundlich and the Redlich-Peterson equations data. The correlation coefficients obtained from the Freundlich plots were of higher overall values (i.e closer to unity) than those obtained from the Langmuir and the Redlich-Peterson plots as shown in tables 2, 3 and 4.

Table 2
Parameters in the Langmuir model at different masses of adsorbent

Mass of peanut hull(g)	(dm^3/ g) K_L	(dm^3/mg) a_L	q_{max} (mg/g)	Correlation coefficient	R
0.125	1.44	0.053	27.1	0.8781	0.239
0.25	1.08	0.057	18.94	0.969	0.23
0.50	1.094	0.108	10.12	0.9835	0.209
0.75	1.0246	0.102	10.0	0.9412	0.151
1.0	1.003	0.111	9.04	0.8831	0.338

Table 3
Parameters of Freundlich model at different masses of adsorbent

Mass of peanut hull(g)	First section of plot		Correlation coefficient	Second section of plot		Correlation coefficient
	K_F (dm^3/g)	n (-)		K_F (dm^3/g)	n (-)	
0.125	1.633	1.374	0.9984	2.846	2.09	0.9681
0.25	1.396	1.36	0.9888	3.103	2.726	0.9213
0.5	0.938	1.182	0.932	3.435	4.149	0.9798
0.75	0.698	1.038	0.9636	3.49	6.77	0.9231
1.0	0.685	1.051	0.9952	2.72	4.003	0.9522

Table 4
Parameters of Redlich – Peterson model at different masses of adsorbent

Mass of peanut hull(g)	K_{RP} (dm^3/g)	a_{RP} (dm^3/g) $^{1/\beta}$	β (-)	Correlation coefficient
0.125	0.8679	0.1735	0.6383	0.972
0.25	1.084	0.0704	0.744	0.9355
0.50	1.94	0.0224	0.518	0.9517
0.75	1.246	0.2500	0.927	0.9376
1.0	0.946	0.4000	0.446	0.827

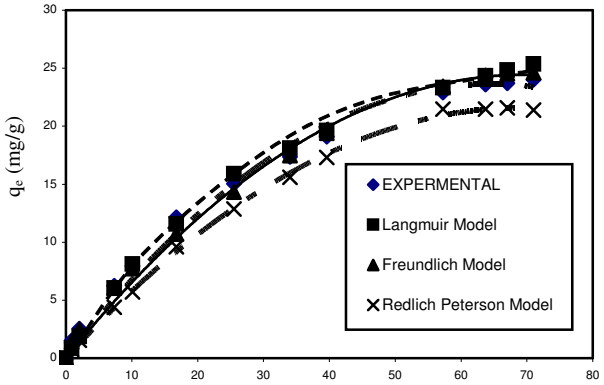


Fig. 3. Comparison between experimental and theoretical isotherms for the adsorption of methylene blue onto peanut hull.

3.2. Adsorption kinetic studies

It is necessary to study the kinetics of adsorption in batch systems in order to determine the rate – limiting step in the adsorption process. It was proposed that the mechanism of color removal from effluents involve several steps [33]:

(i) mass transfer of the dye from the bulk solution to the particle surface (external mass transfer);

(ii) adsorption at an interior site;

(iii) Intraparticle diffusion into the interior of the peanut hull.

During the establishment of the rate – limiting step, step (ii) is assumed to be rapid and hence not considered in any kinetic analysis. Consequently, the two possible rate–limiting steps considered are both external mass transfer and intraparticle diffusion. The development of models based on two such mass transport steps is quite complex, requiring a coupling equation and its subsequent solution. Initially therefore, simplifying assumptions have been made and attempts were undertaken to describe the adsorption process in terms of an external mass transfer coefficient.

The model presented for determining the external mass-transfer coefficient, K_s, is based on work of Furusawa and Smith [34]. It assumes that external mass transport of the dye from the bulk solution across the boundary layer film to the external particle surface is rate -controlling in the early stages of the adsorption process.

In a well agitated batch adsorber, the concentration of adsorbate in the liquid phase (C_t) and the concentration of adsorbent particles in the liquid (m_s) are assumed to be uniform throughout the vessel. Consequently, m_s, may be determined from the measured mass of adsorbent (m) and the volume of particle – free liquid (v) according to the equation:

$$m_s = \frac{m}{v}. \quad (10)$$

The change in dye solution concentration (C_t) with time is related to the fluid - particle mass-transfer coefficient by the equation:

$$d\,C_t / dt = - K_s\ S_s\ (C_t - C_s), \quad (11)$$

where $C_t = C_o$ at $t = 0$.

Since C_s approaches zero and C_t approaches C_o as $t \rightarrow 0$, eq. (11) becomes:

$$[d\,(C_t / C_o)/\ dt]_{t=0} = - K_s\ S_s. \quad (12)$$

The external (outer) surface area of the particles, S_s, can be obtained from m_s by assuming that the particles are spherical of diameter dp; hence:

$$S_s = \frac{6m_s}{d_p \rho_t \cdot (1-\varepsilon_P)}. \quad (13)$$

Eq. (12) can be used for obtaining K_s from the slope of plot of (C_t / C_o) versus time but is only strictly valid for time $t = 0$.

The value of K_s may be expressed by an equation of the general form:

$$K_s = X\ (\text{variable})^Y, \quad (14)$$

or in the logarithmic form

$$\log K_s = \log\ X + Y \log\ (\text{variable}). \quad (15)$$

The variables investigated include: agitation speed initial dye concentration, mass of peanut hull and initial pH value.

3.2.1. Effect of agitation

Fig. 4 shows the experimental results obtained from a series of contact time studies for the adsorption of MB onto peanut hull at the concentration of 85 mg/l, pH ≈ 6, 2 mm parti-

cle diameter and temperature 30 ± 2°C in which the degree of agitation was varied from 200 to 600 rpm .The curves are shown in fig. 4 as a plot of (C_t / C_o) against time. The initial gradients $(d(C_t/C_o)/dt)_{t=0}$ of the various curves have been determined which are equal to ($-K_s S_s$). From such slopes, K_s can be extracted. The results indicate that the removal of dye increases with the increase in the speed of agitation, the increase in the extent of removal can be explained by being due to decrease in the boundary layer resistance to mass transfer in the bulk solution [35].

The, K_s, values have been determined for different impeller speeds as before and the data have been plotted in fig. 5 as log K_s versus log rpm on the basis of eq. (15). Linear variation was nearly observed and the values of constants X and Y associated with eq. (15) have subsequently been determined using the least-squares method and are listed in table 5. The data in table 5, indicate that the external adsorption of MB onto peanut hull is controlled by the degree of agitation (since the plot in fig. 5 is considered linear) and that the effect of increasing agitation is to decrease the boundary layer resistance to mass transfer.

The equation relating K_s to agitation speed in the range 200-600 rpm for the adsorption of MB onto peanut hull is:

$$K_s = 6.9 \times 10^{-4} (rpm)^{0.57}. \quad (16)$$

The correlation coefficient of the agitation data is 0.997.

3.2.2. Effect of initial concentration

The influence of initial dye concentration has also been studied and the experimental results obtained are depicted in fig. 6 as a plot of (C_t/C_o) against time for the adsorption of MB onto peanut hull. It has been observed that at high concentrations the lines lie close together and fractional adsorption is low. However, for low concentrations the initial uptake of MB is rapid. Consequently, the concentration of MB in solution shows high effect on the extent and rate of MB uptake on peanut hull.

The external mass-transfer coefficient K_s have been determined at different initial dye concentrations and tabulated in table 5. The

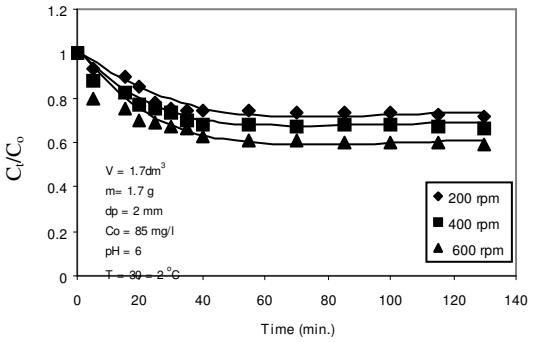


Fig. 4. Effect of agitation on the adsorption of methylene blue onto peanut hull.

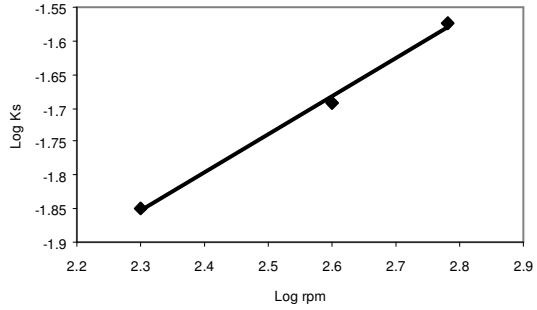


Fig. 5. Plot of log Ks versus log rpm for the adsorption of methylene blue onto peanut hull.

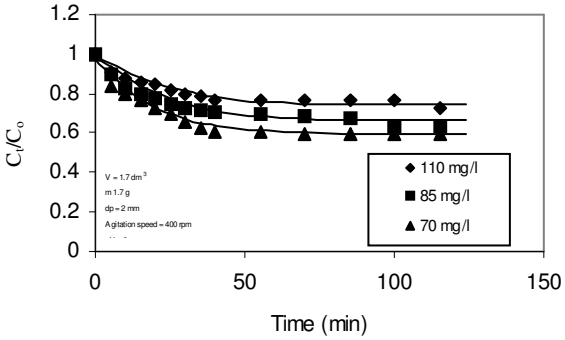


Fig. 6. Effect of initial dye concentration on the adsorption of methylene blue onto peanut hull.

driving force for mass transfer (based on the difference between the bulk liquid concentration and the particle surface liquid concentration) is timedependent. This concentration difference, relative to C_o, will affect the way in which external mass transfer coefficient varies with dye concentration. Thus, the external

mass transfer coefficients are decreasing as C_o increases for MB being adsorbed onto peanut hull . the equation relating K_s to initial dye concentration is:

$$K_s = 4.13 \text{ X } 10^{-2} (C_o)^{-0.43}. \quad (17)$$

The correlation coefficient of the initial concentration data is 0.94.

3.2.3. Effect of peanut hull mass

The effect of peanut hull mass on the adsorption rate has also been studied keeping the other experimental conditions constant. Fig. 7 depicts plots for the adsorption of MB onto peanut hull on the basis of eq. (12). The results show an increase in the rate of MB uptake as the mass of peanut hull increased. The initial gradients of the various curves allow the determination of K_s values for different masses and the results have been plotted as log K_s versus log m.

The external mass-transfer coefficient depends on the driving force per unit area and in this case, since C_o is constant, increasing the mass of peanut hull increases the surface area for adsorption and hence, the rate of dye removal increases. Since the particle size range is constant, the surface area will be directly proportional to the mass of peanut in the system.

The K_s values listed in table 5 indicate a small dependence on mass, with K_s decreasing by increasing the mass of peanut hull. This effect is probably due to the fact that for small masses a small amount of external surface is subjected to the dye and therefore there is large driving force from the dye per unit surface area of peanut hull [36]. The constants X and Y are also listed in table 5. The K_s values are correlated in terms of mass of peanut hull (m) for the adsorption of MB by the eq. (18) in the range of 0.85-3.4 *g*.

$$K_s = 1.27 \text{ x } 10^{-3} \ (m)^{-0.49} . \quad (18)$$

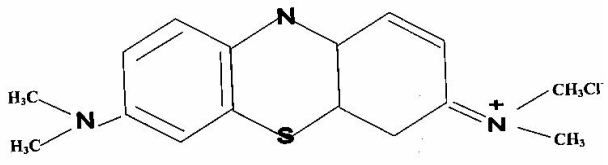
The correlation coefficient on the mass data is 0.909.

3.2.4. Effect of starting pH value

The effect of initial pH value on the adsorption of MB onto peanut hull was studied by evaluating the adsorption rate at pH_0 4,6 and 9. The pH_0 was adjusted using HCl or NaOH. The experimental results are shown in fig. 8 as a plot of C_t / C_o against time.

The initial gradients of various curves in fig. 8 allow the determination of the K_s values for the different pH values and the results have been plotted as log K_s versus log pH. The resulting linear graph indicated that K_s varies with pH of solution in a logarithmic manner. The data listed in table 5 demonstrate that an increase in the (pH) value results in an increase in the external mass-transfer coefficient, K_s. This may be explained due to at alkaline pH values some oily/ greasy constituents are removed from raw peanut hull during the adsorption process. Partial scouring of such impurities is affected in alkaline solution forming saponified, dispersed and /or hydrolysed derivatives. Removal of the forementioned impurities from the adsorbant surface and pores enhance adsorption. Some of the formed impurities, acting as wetting agents, together with wettability gained by the parent adsorbeant, are positive factors for better adsorption. Subsequent increase in absorbancy of peanut hulls increases the chance of adsorption by producing a hydrophilic surface.

It is observed that there is an uptake increase in range of pH values exceeding neutrality. This may be attributed to the basic cationic nature of the dye molecule which when dissolved in water (or in a neutral solution) gives rise to zwitterions possessing acidic and basic centers. On increasing the pH from 4 to 9, the solubility of MB in water decreases. Another point of view may be ellustrated as: the basic dyes are generally used as halide salts. The form in which the dye is able to form the ion- association compound is its singly-charged cation.



The acidity of the aqueous phase can vary over a wide range, from moderately concentrated mineral acid solution to pH 3-5, de-

pending mainly on the dye used. As long as the aqueous phase pH exceeds 7 (in the alkaline region), the basic character of the free amine present in the dye molecule may prevail. Thus the salt composition of the dyestuff molecule changes, reflecting its effect on decreasing its solubility in the dye-bath. Since competition may occur between the solute and the solvent for sites on the solid adsorbent, it is reasonable to expect that the maximum adsorption would occur at the minimum solubility [37].

The relation between K_s and pH values were correlated by eq. (19) in the range of pH values from 4-9 of the aqueous phase:

$$K_s = 1.45 \times 10^{-3} \ (pH)^{-0.5} . \quad (19)$$

The correlation coefficient of the pH data is 0.9.

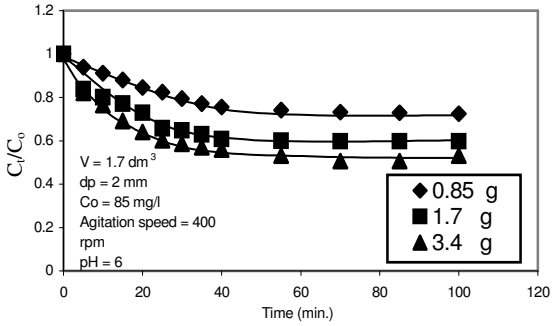


Fig. 7. Effect of peanut hull mass on the adsorption of methylene blue onto peanut hull.

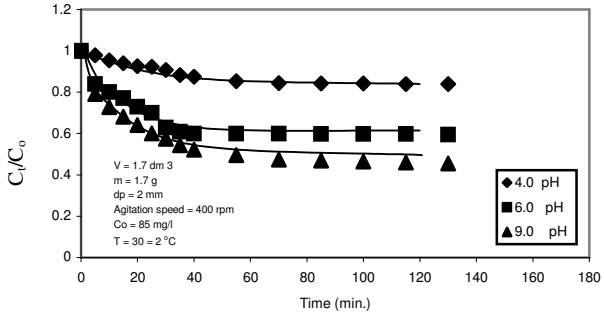


Fig. 8. Effect of pH of the adsorption of methylene blue onto peanut hull.

Table 5
External mass-transfer coefficient, K_s, for various system variables (A,B,C,D)

A. Agitation speed (C_0=85 mg/dm^3, m=1.7 g and pH_0=6)

Agitation speed (rpm)	200	400	600	X	Y	C.F.
Ks*10^2(cm/sec)	1.4	2.03	2.66	6.9x10^{-4}	0.57	0.996

B. Initial concentration (Agitation speed=400 rpm , m= 1.7 g and pH_0=6)

Initial conc. C_0 (mg/dm^3)	70	85	110	X	Y	C.F.
Ks*10^2(cm/sec)	3.22	2.03	1.82	4.13 x10^{-3}	-0.43	0.94

C. Mass of peanut hull (Agitation speed=400 rpm ,C_0=85 mg/dm^3 and pH_0=6)

mass of peanut hull m(g)	0.85	1.7	3.4	X	Y	C.F.
Ks*10^2(cm/sec)	3.38	2.03	0.36	1.27 x10^{-3}	-0.49	0.909

D. Initial pH value (Agitation Speed=400 rpm ,C_0=85 mg/dm^3 and m= 1.7g)

pH_0	4	6	9	X	Y	C.F.
Ks*10^2(cm/sec)	0.42	2.03	4.18	1.45 x10^{-3}	-0.5	0.99

4. Conclusions

1. The preliminary studies show that peanut hull has the ability to adsorb considerable amounts of basic dyes (methylene blue for example).
2. Adsorption isotherms have been determined and the data obtained were analyzed using Langmuir, Freundlich and Redlich-Peterson isotherms. The correlation coefficients obtained from the Freundlich were higher than those obtained from the Langmuir and Redlich-Peterson plots.
3. The external mass – transfer process has been studied with certain system variables; namely agitation speed, initial dye concentration, mass of peanut hull, and starting pH value. The external mass transfer coefficient K_s has been determined and used to correlate the experimental data against the design variables. The K_s has been found to vary linearly with design variables according to the general correlation:
$K_s = X$ (variable $)^Y$.
The kinetic studies indicated that the external mass transfer is the rate - limiting step in the early stages of the adsorption process.

Nomenclature

a_L Parameter of Langmuir isotherm (dm^3/mg),
a_{RP} Parameter of Redlich-Peterson isotherm[$(dm^3/mg)^{1/\beta}$],
C_e Equilibrium liquid-phase concentration (mg/dm^3),
C_o Initial liquid-phase concentration (mg/dm^3),
C_{ref} Reference liquid-phase concentration (mg/dm^3),
C_s liquid-phase dye concentration at particle surface (mg/dm^3),
C_t liquid-phase dye concentration at time t (mg/dm^3),
d_p Average particle diameter (mm),
K_F Parameter of Freundlich isotherm (dm^3/g),
K_L Parameter of Langmuir isotherm (dm^3/g),
K_{RP} Parameter of Redlich-Peterson isotherm (dm^3/g),
K_s External mass transfer coefficient (cm/s),
m Mass of particle- free liquid in the adsorber (g),
m_s Mass of adsorbent particles per unit volume of particle-free dye (g/dm^3),
n Freundlich exponent (dimensionless),
q_e Equilibrium solid-phase concentration (mg/g),
Q_e Dimensionless solid-phase concentration at equilibrium($=q_e/q_{ref}$),
q_{ref} Equilibrium solid-phase concentration co-existing with C_{ref} ($mg\text{-}g^{-1}$),
q_t Solid- phase concentration at time t (mg/g),
R Dimensionless equilibrium parameter, defined by eq. (3),
S_s Outer surface area of peanut hull per unit volume of particle-free liquid (cm^{-1}),
t Time (min),
v Volume of particle free liquid in the adsorber (dm^3),
X Pre-exponential constant, defined by eq. (14),
X_e Dimensionless liquid-phase concentration at equilibrium ($=C_e/C_{ref}$), and
Y Exponential factor, defined by eq. (14).

Greek symbols

β Redlich-Peterson exponent (dimensionless),
ε_p Porosity of particles (dimensionless), and
ρ_t True density (g/cm^3).

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