# Biosorption of Rhodamine B and Malachite green from aqueous solutions by *Tamarindus indica* fruit shells

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#### ABSTRACT

The removal of rhodamine B and malachite green from aqueous solutions was studied in batch adsorption systems using *Tamarindus Indica* fruit shells as sorbents. The well known Freundlich, Langmuir and Redlich-Peterson isotherm equations were applied to the equilibrium sorption data obtained. The sorption dynamics were found to obey the pseudo-second order rate equation and particle diffusions appear to control the overall rates. Increase of both pH and temperature resulted in increased sorption and the thermodynamic parameters like  $\Delta G$ ,  $\Delta H$  and  $\Delta S$  were evaluated.

Key words: Tamarindus indica fruit shell, malachite green.

# INTRODUCTION

Discharge of coloured wastewaters into natural water bodies is not desirable, as they are aesthetically displeasing and prevent reoxygenation in receiving waters by cutting off penetration of sunlight. In addition many dyes are toxic to aquatic organisms, mammals and humans<sup>1-5</sup>. Contamination of water resources with dyes, mainly in the surrounding areas of dyeing and textile industries, has caused great concern among environmentalists. For example, dyeing industry wastewater is one of the major environmental problems in Coimbatore district of Tamil Nadu<sup>6</sup>.

Various treatment methods have been used for the removal of dyes from aqueous solutions including chemical coagulation, ozonization<sup>7</sup>, membrane filtration<sup>8</sup>, electrolysis<sup>9</sup>, and microbial degradation<sup>10</sup>. These established technologies often unable to adequately reduce contaminants concentrations to desired and/or legislated levels<sup>11</sup> or are associated with some practical difficulties. This has initiated a search for more effective and economic treatment techniques to offer significant reduction in capital costs than for example filtration and biological processes. Adsorption is by far the most effective and widely used technique for the removal of dyes from aqueous solution. In recent years several investigators have concentrated their work on low-cost, nonconventional adsorbent materials<sup>12</sup> to achieve the economically feasible and effective treatment of wastewater containing dyes.

The present study is undertaken to evaluate the efficiency of *Tamarindus Indica* fruit shell (TIFS), for the removal of two basic dyes- Rhodamine B (RB) and Malachite Green (MG). Malachite green is a common basic dyestuff of triphenylmethane series used for dyeing silk and wool directly and cotton mordanted with tannin to deep green. Rhodamine B is also widely used in dyeing industries. *Tamarindus Indica* (tamarind tree) is one of the common and most important trees of India. A full-grown tree yields 180-225 Kg of fruit per season. On the average the pod is composed of 55% pulp, 34% seed and 11% shell and fibre<sup>13</sup>.

# **EXPERIMENTAL**

#### Adsorbent

The adsorbent used in this study was tamarind fruit shell collected from fruits of a single tree. The shells were washed with water to remove the adhered pulp and dust, air dried, ground and sieved to get particles of size 150-250  $\mu$ m.

# Analysis of dyes

The dyes were analyzed by monitoring their absorption in the visible region, 555nm for RB and 620nm for MG, using Spectronic 20D+ spectrophotometer (Spectronic Instruments, USA). Calibration graphs were prepared (1-6mg/L for RB and 1-8mg/L for MG) and concentrations of sample aliquots were established by referring to the respective calibration graph.

#### **Batch adsorption experiments**

Each equilibrium adsorption experiment comprised three replicate 100mL glass-stoppered bottles containing appropriate amount of adsorbent and 50mL of dye solutions of selected concentrations. Control flasks without the adsorbents also prepared simultaneously. Mixtures were maintained in a rotary shaker (Orbitek, Chennai, India) at constant temperature (30, 45 or 60°C). After the attainment of equilibrium the contents of each flask were filtered through a Whatmann No. 41 filter paper. The filtered samples were then analyzed for unadsorbed solutes. The equilibrium data obtained were analyzed using the following three isotherm equations, namely, Freundlich, Langmuir and Redlich- Peterson:

Freundlich

$$q_{e} = K_{F} C_{e}^{(1/n)} \qquad \dots (1)$$

Langmuir

$$q_e = K_L C_e / (1 + b C_e) = q_m b C_e / (1 + b C_e)$$
 ...(2)

**Redlich- Peterson** 

$$q_e = K_R C_e / (1 + b_R C_e^{\beta})$$
 ...(3)

where  $q_e$  is the adsorption capacity (mg/g);  $C_e$ , equilibrium concentration of the adsorbate (mg/L);  $K_F$  (mg/g) and *n*, Fruendlich constants;  $K_L$  and *b* (L/mg), Langmuir constants;  $q_m$ , Langmuir monolayer adsorption capacity (mg/g) and  $K_F$ ,  $b_F$ 

and  $\beta$  are Redlich-Peterson isotherm constants.

For kinetic studies, a series of bottles with fixed amounts of adsorbent and dye solutions were taken. One bottle was taken out for the determination of unadsorbed dye at time intervals of 5, 10, 15, 20, 25, 30, 45, 60, 120 and 180 minutes. To describe the adsorption kinetics, the pseudo-fist order model proposed by Lagergren<sup>14</sup> and the pseudo-second order model proposed by Ho and McKay<sup>15</sup> were used in the following forms:

First order rate equation  

$$\log(q_e - q_t) = \log q_{e(t)} - k_t t \qquad \dots (4)$$

Second order rate equation  

$$t/q_t = (1/h) + (1/q_{e(2)})t$$
 ...(5)

where,  $q_t$  (mg/g) is the amount adsorbed at time *t* (min);  $q_{e^1}$ , amount adsorbed at equilibrium (mg/g);  $q_{e(1)}$ , adsorption capacity predicted by the I order model (mg/g);  $k_1$ , first order rate constant (min<sup>-1</sup>);  $h (=k_2/q_{e(2)})^2$ , initial sorption rate (mgg<sup>-1</sup> min<sup>-1</sup>); and  $q_{e(2)}$ , adsorption capacity predicted by the II order model (mg/g).

For determining the effect of pH on adsorption, dye solutions adjusted to different pH values using dilute NaOH or HCl solutions were taken with the chosen adsorbent dose.

### **RESULTS AND DISCUSSION**

#### Equilibrium adsorption studies

The equilibrium data obtained for each system was fitted to the three isotherm equations (for RB adsorption 0.25g and for MG adsorption 0.1g adsorbent were used per 50mL of adsorbate solutions at the solution pHs) and the isotherm constants are listed in Table 1. It is to be noted that the Langmuir monolayer adsorption capacity of the adsorbent towards MG is far greater than that of RB. This could be due to the larger molecular size the RB dye molecule, which will restrict the entry of them into micro and mesopores present in the carbon surface.

The  $q_m$  values for the dyes adsorption on TFS are quite high, it seems likely, therefore, that there could be some specific forces involved

between the dyes and TFS or that a multilayer surface coverage would have occurred. This view is also supported by the Langmuir *b* values (Table 1) that are measures of adsorbent-adsorbate interaction forces or strengths.

The *b* values determined are further used to calculate the dimensionless separation factor,  $R_{L}^{16}$  defined as

$$R_i = 1/(1 + bC_i)$$
 ...(6)

where  $C_i$  is the initial solute concentration. The magnitude of  $R_L$  value gives an idea about the

nature of adsorption equilibrium, favourable when it lies in the range 0-1.

In all the systems studied,  $R_L$  values were comprised between 0 and 1 (values listed in Table 2) indicating favourable adsorption of the dyes on TIFS.

#### Adsorption kinetics

The kinetic curves obtained (conditions: for RB adsorption 0.25g TIFS/50 mL of 25mg/L RB solution and for MG adsorption 0.10g TIFS/50mL of 50mg/L MG solution) are shown in figure 1 and the results of kinetic analyses were presented in

System Model Model parameters					
-		<i>K<sub>≓</sub></i> mg/g	1/n	n	<b>r</b> <sup>2</sup>
TFS- RB TFS- MG	Freundlich	0.3393 19.6718	0.8934 0.4738	1.1193 2.1106	0.9918 0.9990
TFS- RB TFS- MG	Langmuir	<b>К</b> _ 0.1381 228.5468	<b>b</b> 0.0024 0.1726	<b>q</b> <sub>m</sub> 57.5353 165.3926	<b>r</b> ² 0.9898 0.9912
TFS- RB TFS- MG	Redlich-Peterson	<b>K</b> <sub>R</sub> - 97.4825	<b>b</b> <sub>R</sub> - 2.0912	<b>b</b> - 0.6185	<b>r</b> ² 0.9945

#### Table 1: Isotherm parameters for the adsorption of dyes at 30°C

# Table 2: R<sub>L</sub> values for adsorption of dyes at 30°C

Dye	C <sub>i</sub> , mg/L	R
RB	10	0.9785
	20	0.9579
	30	0.9381
	40	0.9191
	50	0.9009
	60	0.8834
MG	20	0.2432
	40	0.1384
	50	0.1139
	60	0.0967
	80	0.0744
	100	0.0604



Fig. 1. Kinetics curves for the adsorption of dyes on TIFS

tables 3 and 4. The high correlation coefficients and the good agreement between the theoretical  $q_e$  and experimental  $q_e$  values for the II order model suggest that the sorptions are better described by this model. Such a betterment of the II order model over I order model has been observed for many adsorption processes.<sup>15</sup>

Attempt has been made to find whether film or particle diffusion of the dye molecules determine the overall order assuming them ions. According to Boyd *et al.*<sup>17</sup> film diffusion will be ratedetermining if a graph of time versus  $\ln(1-F)$  yields a straight line and particle diffusion control the overall adsorption rate if a plot of  $t^{0.5}$  against *F* (expressed in equation 7) produces a straight line. Such linear relationships do exist for the systems under study (figures not shown) and an additional quantitative treatment proposed by Boyd<sup>17</sup> and Reichenberg<sup>18</sup> as adapted others<sup>19,20</sup> was followed. The sorption dynamics can be represented by the following expressions:

$F = q_t / q_e$	(7)
$F = 1 - 6/\pi^2 \sum_{n=1}^{\infty} 1/n^2 \exp(D_i t \pi^2 n^2 / r^2)$	(8)
$F = 1 - 6/\pi^2 \sum_{n=1}^{\infty} 1/n^2 \exp(-n^2 Bt)$	(9)

# Table 3: Pseudo- first order parameters for adsorption of dyes at 30°C

Dye	Equilibri uptake m	Equilibrium uptake mg/g		first r² >,
	<b>q</b> <sub>e(1)</sub>	$q_{_{e(exp)}}$	<i>k</i> , min <sup>-1</sup>	
RB	1.7923	2.750	0.0131	0.9920
MG	15.2511	20.320	0.0083	0.9968

where,

 $B = D_{i}\pi^{2} r^{2} = \text{time constant} \qquad \dots (10)$ 

F = fractional attainment of equilibrium at time t $D_i$  = effective diffusion coefficient of the ions in the adsorbent phase

r = adsorbent particle radius

 $n = 1,2,3,\frac{1}{4}$  are the integers defining the infinite series solution obtained by a Fourier type of analysis.

Bt values were derived for each F value by the use of Reichenberg's table.<sup>18</sup> A plot of *t* versus Bt was employed to assess the contributions of film and particle diffusion on rates of adsorption. Both the *t* versus Bt plots were linear (presented in Fig. 2). Examination over figure 2 reveals that dye adsorptions under study pass near the origin indicating that the rate-limiting step for these processes are predominately governed by particle diffusion constraints.

The effective particle diffusion coefficient values ( $D_i$ 's) are calculated by equation (10) where B is the slope of the t versus Bt plots. Since in the present study, adsorbents of particle sizes ranging



Fig. 2. t vs Bt for the adsorption of dyes on TIFS

Table 4: Pseudo- second order parameters for adsorption of dyes at 30°C

Dye	Equilibrium u q <sub>e(2)</sub>	otakemg/g q <sub>e(exp)</sub>	Pseudo- second order constant, <i>k</i> <sub>2</sub> , gmg <sup>-1</sup> min <sup>-1</sup>	Initial sorption rate, <i>h</i> mgg <sup>-1</sup> min <sup>-1</sup>	r²
RB	3.0544	2.750	0.0229	0.2136	0.9980
MG	23.3645	20.320	2.6426	1.4426	1.0000

130

from 150 - 250  $\mu$ m were used, the average of them, 200  $\mu$ m was taken as the mean particle diameter, which would give 100 × 10<sup>4</sup> cm as the mean particle radius (*r*). The *B* and *D<sub>i</sub>* values calculated are listed in Table 5.

Increase in the pH of the dye solutions lead to increased adsorption for both the dyes Fig. 3. This is as expected for the exchange of any cationic dye. Increase of solution pH increases the surface charge of any adsorbent which will eventually result in greater tendency to attract positively charged species like MG and RB.

# Effect of Temperature and Thermodynamics

Equilibrium adsorption studies were conducted at two more temperatures, namely 45 and 60°C apart from room temperature. The adsorptions increased with increase in the operating temperature suggesting that the processes are endothermic. This is also seen in the trends of

Table 5: Effective pore diffusion coefficients for adsorption of dyes

Dye	C <sub>i</sub> mg/L	<i>B</i> min⁻¹	<i>D<sub>i</sub></i> ×10⁻⁵ cm²min⁻¹	r <sup>2</sup>
RB	25	0.0284	2.8775	0.9895
MG	50	0.0175	1.7731	0.9980

Langmuir  $q_m$  and  $K_L$  values. The former increases but the latter decreases with increase in temperature (Tables 6 and 7). The increased adsorption at higher temperatures can be due to acceleration of some originally slow step(s),<sup>21</sup> creation of some new activation sites on the adsorbent surface<sup>22</sup> or decrease in the size of the adsorbing species as desolvation may occur at high temperatures.

Thermodynamic parameters such as Gibbs's free energy change ( $\Delta$ G), enthalpy change ( $\Delta$ H) and entropy change ( $\Delta$ S) were calculated using the following expressions:

$K_{c} = C_{ae} / C_{e}$	(11)
$\Delta G = -RT \ln K_{o}$	(12)

$$\label{eq:G} \begin{split} \Delta G &= - \mbox{ RT In } K_{\rm C} & ...(12) \\ & \log K_{\rm C} = [\Delta S/\ 2.303 \mbox{ R}] - [DH/\ 2.303 \mbox{ RT}] & ...(13) \\ & \mbox{where,} \end{split}$$

 $K_c$  = equilibrium constant for the distribution of dyes



Fig. 3. Effect of pH on the adsorption of dyes on TIFS

System	Model		ameters		
		<i>K<sub>F</sub></i> ,mg/g	1/n	n	r <sup>2</sup>
TFS- RB	Freundlich	0.4466	0.7421	1.3475	0.9918
TFS- MG		15.9440	0.6394	1.5640	0.9932
		K,	b	q	r <sup>2</sup>
TFS- RB	Langmuir	0.2500	0.0109	22.9358	0.9982
TFS- MG		9.7073	0.0376	258.1729	0.9898
		Kp	bp	b	r <sup>2</sup>
TFS- RB	Redlich-	1.3485	2.2608	0.2991	0.9998
TFS- MG	Peterson	-	-	-	-

# Table 6: Isotherm constants for adsorption of Dyes at 45°C

System	Model	Model parameters			
		<i>K<sub>F</sub></i> ,mg/g	1 <i>/n</i>	п	r <sup>2</sup>
TFS- RB	Freundlich	0.7625	0.6451	1.5501	0.9911
TFS- MG		35.3132	0.4738	2.1106	0.9990
		κ <sub>L</sub>	b	q <sub>m</sub>	$r^2$
TFS- RB	Langmuir	0.3805	0.0211	18.0332	0.9953
TFS- MG		28.5515	0.1556	183.4929	0.9912
		K <sub>R</sub>	b <sub>R</sub>	b	r <sup>2</sup>
TFS- RB	Redlich-	0.3428	0.0065	1.2493	0.9956
TFS- MG	Peterson	-	-	-	-

Table 7: Isotherm constants for adsorption of Dyes at 60°C

Table 8: Thermodynamic parameters for adsorption of dyes on TIFS

Dye	C, mg/L		-∆G kJ mol <sup>-1</sup>		ΔH	ΔS
		30°C	45°C	60°C	kJmol <sup>-1</sup>	JK <sup>-1</sup> mol <sup>-1</sup>
	20	0.9013	2.1990	2.9276	19.6595	68.1332
	30	-1.1657	1.8445	2.9926	43.4820	140.5860
RB	40	-0.5284	1.5643	2.3726	30.0472	98.0621
	50	-0.4344	1.4048	2.2370	27.5871	90.1160
	20	6.4927	8.1080	1.1779	46.5666	174.0916
	40	5.7434	7.2166	10.2587	39.6067	148.8901
MG	60	5.5538	6.3455	9.0491	29.4362	114.5286
	80	4.7161	6.4707	8.0426	30.8844	117.5635
	100	4.3539	5.9075	7.4273	26.6976	102.5004

 Table 9: Comparison of removal efficiency of TIFS towards RB and MG with other adsorbents reported in the literature

Dye	Adsorbent	Adsorption capacity	Reference
22			
RB	poly(γ-glutamic acid),a natural biopolymer	390.25 mg/g	23
RB	Waste banana pith	8.5 g/g	24
RB	Unburned carbon in fly ash	9.7 × 10⁻⁵ mol/g	25
RB	Activated carbon	536 mg/g	26
RB	TIFS	27.57mg/g(57.57µmole/g)	Present work
MG	Jack fruit peel carbon	166.37 mg/g	27
MG	Fly ash – GAC blend	25 mg/g	28
MG	Jute fiber carbon	136.58 mg/g	29
MG	A fresh water algae	117.647 mg/g	30
MG	TIFS	0.36 mg/g (0.99 μmole/g)	Present work

between the two phases

 $C_{ae}$  = solid phase dye concentration, mg/L  $C_{e}$  = liquid phase dye concentration, mg/L T = absolute temperature, °K

R = gas constant

Equation (13) was used to construct Van't Hoff plots and  $\Delta H$  and  $\Delta S$  were calculated from the slope and intercept of the Van't Hoff plot respectively. Thermodynamic parameters evaluated for varied dye concentrations are listed in Table 8.

The negative values of  $\Delta G$  obtained for the adsorptions reflect the spontaneity. The positive values of  $\Delta H$  indicate the endothermic nature and

the positive values of  $\Delta S$  indicate increased randomness at the interface. The rather large  $\Delta S$ values speak for the large size of the species that are being adsorbed; a single dye molecule displaces a lot of water molecules from the adsorbent surface.

# Comparison of removal efficiency of TIFS with other adsorbents

Finally an attempt has been made to compare the removal efficency of TIFS with other adsorbents reported in literature (Table 9). It is found that the capacity of TIFS in removing the dyes selected in this study is comparable to other adsorbents reported.

### REFERENCES

- 1. Srivastava, S., Sinha, R., and Roy, D., Toxicological effects of malachite green. *Aquat. Toxicol.* **66**(3): 319-329 (2004).
- Culp, S. J., Blankenship, L. R., Kusewitt, D. F., Doerge, D. F., Mulligan, L. T., and Beland, F. A., Toxicity and metabolism of malachite green and leucomalachite green during short-term feeding to Fischer 344 rats and B6C3F1 mice. *Chem.-Biol. Interact.* **122**(3): 153-170 (1999).
- Lewis, I. L., Patterson, R. M., and McBay, H. C., The effects of Rhodamine B on the chromosomes of Muntiacus muntjac. *Mutat. Res., Genet. Toxicol.* 88(2): 211-216 (1981).
- Toshiyuki Kaji., Tomotsugu Kawashima., Michiko Sakamoto., Youichi Kurashige., and Fumitomo Koizumi., Inhibitory effect of rhodamine B on the proliferation of human lip fibroblasts in culture. *Toxicology* 68(1): 11-20 (1991).
- Annalaura Stammati., Carlo Nebbia., Isabella De Angelis., Alessandra Giuliano Albo., Monica Carletti., Claudia Rebecchi., Franco Zampaglioni., and Mauro Dacasto., Effects of malachite green (MG) and its major metabolite, leucomalachite green (LMG), in two human cell lines. *Toxicol. in Vitro* 19(7): 853-858 (2005).

- Suguna Devi, S R., Sathish Kumar, M., Shanthi, K., Kadirvelu, K., and Pattabhi, S., Removal of direct-T-blue-R from aqueous solution onto carbonized sugarcane bagasse waste. *Ind. J. Env. Protect.* **22**(5): 500-505 (2002).
- Huseyin Selcuk., Decolorization and detoxification of textile wastewater by ozonation and coagulation processes. *Dyes and Pigm.* 64(3): 217-222 (2005)
- Buckley, C. A., Membrane technology for the treatment of dye house effluents. *Water Sci. Technol.* 22, 265-274 (1992).
- Lin, S. H., and Peng, C. F., Continuous treatment of textile wastewater by combined coagulation, electrochemical oxidation and activated sludge. *Water Res.* **30**: 587-592 (1996).
- Banat, I. M., Nigam, P., Datel Singh and Roger Marchant, Microbial decolorization of textile-dye containing effluents: A review. *Bioresour. Technol.* 58(3): 217-227 (1996).
- Lambert, S. D. *et al.*, Evaluation of organic adsorbents for the removal of problematic textile dyes and pesticides. *Water Technology* 36: 173-180 (1997).
- Gregorio Crini., Non-conventional low-cost adsorbents for dye removal: A review. *Bioresour. Technol.* 97(9): 1061-1085 (2006)

- The Wealth of India, Raw Materials Volume X, Publications and Information Directorate, CSIR, New Delhi, pp 115-122 (1976).
- Ho, Y S., McKay, G., A comparison of chemisorption of kinetic models applied to pollutant removal on various sorbents. *IChemE. Part B* 76: 332-340 (1998).
- Ho, Y. S., McKay, G., Pseudo-second order model for sorption processes. *Process Biochem.* 34: 451-465 (1999).
- Weber, T.W., Chakkravorti, P., Pore and solid diffusion models for fixed-bed adsorbers. *AIChEJ* 20: 228-236 (1974).
- Boyd, G. E., Adamson, A. W., and Myers, L. S., The exchange adsorption of ions from aqueous solutions by organic zeolites–II. Kinetics. *J. Am. Chem. Soc.* 69: 2836 2848 (1947).
- Reichenberg, D., Properties of ion- exchange resins in relation to their structure. III. Kinetics of exchange. *J. Am. Chem. Soc.* **75**: 589 -597 (1953).
- Kelleher, B. P., Marguerite N O' Callaghan, Leahy, M. J., Thomas F O' Dwyer., and Leahy, J. T., The use of fly ash from the combustion of poultry litter for the adsorption of chromium(III) from aqueous solution. *J. Chem. Technol. Biotechnol.* 77: 1212-1218 (2002).
- Gupta, V. K., Mohan, D., and Sharma, S., Removal of lead from wastewater using bagasse fly ash- A sugar industry waste material. *Sep. Sci. Technol.* 33(9): 1331-1343 (1998).
- Khalid, N., Ahmed, S., Kiani, S. N., and Ahmed, J., Removal of lead from aqueous solutions using rice husk. Sep. Sci. Technol.33(15): 2349 - 2362 (1998).
- Khalid N, Ahmed S, Kiani S N and Ahmed J, Removal of mercury from aqueous solutions by adsorption onto rice husks. *Separation Science and Technology* 34(16): 3139 - 3153

(1999).

- Stephen Inbaraj, B., Chien, J. T., Ho, G. H., Yang, J., and Chen, B. H., Equilibrium and kinetic studies on sorption of basic dyes by a natural biopolymer poly(β-glutamic acid). *Biochemical Engineering Journal.* **31**(3): 204-215 (2006).
- Namasivayam, C., Kanchana, N., and Yamuna, R. T., Waste banana pith as adsorbent for the removal of Rhodamine B from aqueous solutions. *Waste Management* 13: 89-95 (1993).
- Shaobin Wang., and Huiting Li., Dye adsorption on unburned carbon: Kinetics and equilibrium *J. H. Mater.* **126**(1-3): 71-77 (2005).
- Kannan, N., and Meenakshi Sundaram, M., Kinetics of adsorption of dyes on activated carbon: A comparative study. *Ind. J. Env. Protect.* 22(1): 9-16 (2002).
- Stephen Inbaraj, B., and Sulochana, N., Basic dye adsorption on a low-cost carbonaceous sorbent-Kinetic and equilibrium studies. *Ind. J. Chem. Technol.* 9(5): 201-208 (2002).
- Kannan, N., and Jeya Ganesh, R.V., Studies on the removal of malachite green from aqueous solutions by mixed adsorbent. *Ind. J. Env. Protect.* **20**(2): 127-133 (2000).
- Porkodi, K., and Vasanth Kumar, K., Equilibrium, kinetics and mechanism modeling and simulation of basic and acid dyes sorption onto jute fiber carbon: Eosin yellow, malachite green and crystal violet single component systems. *J. H. Mater.* 143(1-2): 311-327 (2007).
- Vasanth Kumar, K., Sivanesan, S., and Ramamurthi, V., Adsorption of malachite green onto Pithophora sp., a fresh water algae: Equilibrium and kinetic modeling. *Process Biochem.* 40(8): 2865-2872 (2005).