Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1095129

57 (2016) 19566–19571
September

Taylor & Francis
Taylor & Francis Group

Comments on the paper: a critical review of the applicability of Avrami fractional kinetic equation in adsorption-based water treatment studies

Eder C. Lima[a,*], Antonio R. Cestari[b], Matthew A. Adebayo[c]

[a] *Institute of Chemistry, Federal University of Rio Grande do Sul (UFRGS), Av. Bento Gonçalves 9500, P.O. Box 15003, 91501-970, Porto Alegre, RS, Brazil, email: eder.lima@ufrgs.br*
[b] *Department of Chemistry – CCET, Federal University of Sergipe, P.O. Box 353, 49000-000 São Cristovão, SE, Brazil*
[c] *Department of Chemistry, Federal University of Agriculture, P.M.B. 2240, Abeokuta, Ogun State, Nigeria*

Received 31 August 2015; Accepted 13 September 2015

ABSTRACT

This letter presents comments on the paper "Critical review on the applicability of Avrami fractional kinetic equation in adsorption-based water treatment studies" that was recently published in Desalination and Water Treatment by N.A. Oladoja. This author explained the misuse of Avrami-type kinetic equation in adsorption process at solid/solution interfaces and also mentioned few of the papers published in the literature that used the Avrami kinetic equation. We, therefore, decided to write this letter to make it clearer to the reader that there are no wrong or unfounded concepts in the papers cited in the review of N.A. Oladoja. We do believe that the mechanism of adsorption could only be established by several analytical techniques and a good sense of chemistry associated with the equilibrium and kinetic data. The mechanism cannot be directly assigned based on just simple kinetic experiments. In addition, the author was very selective in choosing some specific papers, which used this valuable kinetic adsorption equation, for his criticism. The kinetic equation presented at the end of Oladoja's paper is worthless and may not be a feasible equation that can be applied to adsorption from solutions.

Keywords: Avrami fractional kinetic adsorption model; Kinetics of adsorption; Interpretation of Avrami equation

Recently, Oladoja [1] published a review criticizing selectively two authors, who used the Avrami kinetic equation to evaluate the interactive parameters at solid/solution interfaces. Apparently, the main concerns of this author are related to the papers of two independent Brazilian research groups [2–15]. Among others, Oladoja stated the following considerations in his article:

(1) "The adsorption of Avrami kinetic equation for the interpretation of the time-concentration profiles of sorbate–sorbent interactions in adsorption-based water treatment operations appear to have stemmed from the report of Lopes et al. [2]."
(2) "The authors claim to have provided an alternative kinetic equation to determine time-related and/or temperature-related changes in the adsorption kinetic profiles."

---

*Corresponding author.

(3) "The use of this equation in thermal decomposition modelling is appropriate because the process involves phase transformation, which formed the basis of this kinetic equation, but in the context in which the Avrami kinetic equation was used by Lopes et al. [2], no phase change or transformation could be ascertained; hence, the applicability of this equation is questionable and, at best, unjustified."

Therefore, in this letter, we provide some explanations regarding the main aspects of such criticisms. Evidently, the concerns of Oladoja started with the work of Lopes et al. [2] in 2003, which used a kinetic equation to describe the kinetic features of Hg^{2+} on a chitosan-based material [2]. The main intention of such article was to present an alternative equation for calculating kinetic parameters of the interaction that occurred, at a glance in multi-step features, in chitosan-based materials/aqueous solutions interfaces. Secondly, the authors think that the mechanism of adsorption does not just agree with a simple kinetic equation such as pseudo-first-order, pseudo-second-order, Elovich chemisorption model, and other kinetic models [16]. A given well-established mechanism of adsorption should be certified after the use of several analytical techniques (FTIR, SEM, N_2 adsorption/desorption curves, Raman spectroscopy, TGA/DTA, DSC, NMR of ^{29}Si and ^{13}C at solid state, XRD, pH_{pzc}, CHN analysis, and solution calorimetry analysis) to support the adsorption experimental data (kinetics and equilibrium) [17–25], instead of establishing a mechanism of adsorption on a simple kinetic model [17–25], as many authors have done in the adsorption studies reported in the literature [16].

Similarly, Lima et al. [16] reported that the authors attribute wrongly ca. 99% of the mechanism of adsorption just based on one of the four forms of the linearized pseudo-second-order kinetic model [16]. Of course, there is no direct correlation between chemisorption and the experimental data to simply follow one of the linearized pseudo-second-order kinetic equations [16]. Considering the criticism used by Oladoja [1], in his review that the usage of the Avrami kinetic equation in adsorption kinetic experiments does not correlate with the phase change/thermal decomposition or crystallization of a specie as earlier proposed in the original works of Avrami [26–28], and therefore, the mechanism of adsorption cannot be established based on this kinetic equation. We do affirm that the majority of the adsorption kinetic data described in the literature, where the linearized pseudo-second-order kinetic models were used, cannot also be correlated with chemisorption. Therefore, the fitting of data using a kinetic or isotherm model should be complemented with other experimental evidences using several analytical techniques as well as chemical knowledge about the nature of the adsorbate and adsorbent, surface of adsorbent, and chemical or physical interaction of the adsorbent with the adsorbate.

An example of the scenario in which pseudo-second-order kinetic models cannot be ascribed to chemical sorption: Oladoja et al. [29] reported the adsorption of methylene blue dye (MB) onto castor seed shell using only the values of coefficient of determination (R^2), which the authors erroneously denominated as correlation coefficient [29] (see Fig. 1 [29]). Perusing at Fig. 1, mainly 200 and 300 mg/L MB, the curves depicted on the graph were not obtained by nonlinear fitting. Similarly, at these higher concentrations, the experimental points fall outside the predicted curve. On visualizing Fig. 1, it is seen that the points were poorly fitted by the predicted curve compared to Table 1, when the kinetic data were linearized to the pseudo-second-order, the R^2 values were ca. 0.99. As Lima et al. [16] have reported, therefore, irrespective of the kinetic data obtained, practically all the kinetic adsorption data when linearized will follow the linearized pseudo-second-order kinetic model. Consequently, this observation will make researchers to state that the mechanism of adsorption will be chemisorption. However, the conclusion drawn by Oladoja et al. [29] was the same pattern followed by the majority of the researchers working in the field

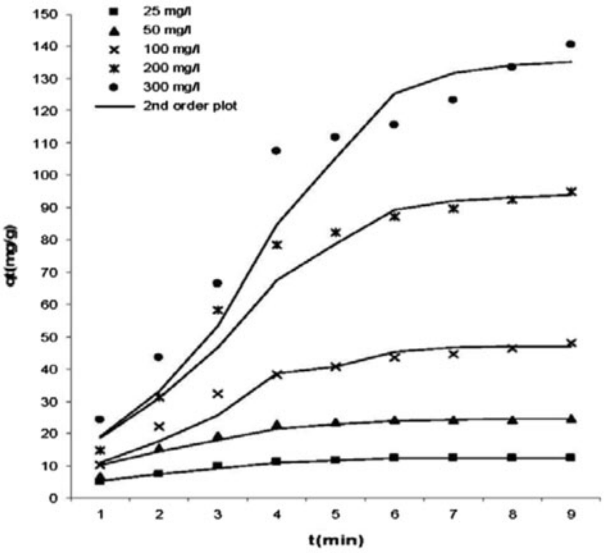

Fig. 1. Plot of the amount of MB sorbed vs. time at various initial MB concentrations [29].

Table 1
Pseudo-second-order and intraparticle diffusion parameters for the sorption of MB on CSS at various initial concentrations of MB [29]

Initial conc. (mg/l)	q_e (mg/g)	k (g/mg min) × 10^{-3}	h_0 (mg/g min)	R^2	k^{id} (mg/g in$^{1/2}$)	I (mg/g)
25	12.55	110.03	17.33	1.000	0.0324	12.13
50	24.69	55.608	33.90	0.9999	0.0868	23.617
100	47.85	11.228	25.71	0.9991	0.8135	38.802
200	95.24	5.057	45.87	0.9995	1.4122	79.118
300	138.89	2.254	43.48	0.9964	4.6518	88.989

of adsorption, and this conclusion is completely wrong, and biased.

Certainly, researchers could try to check experimentally how a molecule of MB will form a chemical covalent bond with the ligno-cellulosic material, the chemical composition of castor seed shell. Unfortunately, in the literature of adsorption field, almost all researchers will base their kinetic judgment only on a simple linearized kinetic model. Obviously, this situation is not the only one and will not be the last error of analysis found in the literature, regarding the kinetic data associated with adsorption [29].

On the basis of these numerous errors of adsorption kinetic data using linearized pseudo-first-order and pseudo-second-order, Lopes et al. [2] tried to use an uncommon kinetic equation to explain some specific kinetic data. However, this approach is indeed a difficult task since the use of non-linearized Avrami equations [2–16] has brought to the adsorption literature that different mechanisms of adsorption could take place. However, in order to establish a more correct mechanism, other analytical techniques should be employed to elucidate confident data. This has been researched in our research groups in Brazil [2–16].

In addition, it is noteworthy that the application of the Avrami equation to study sorption phenomena occurring at solid/solution interfaces was firstly reported by Knezevic et al. [30] in 1998. In this manuscript, the authors named the kinetic equation as Kolmogorov–Erofeev–Kazeeva–Avrami–Mampel equation [30], and the equation was used to study the kinetics of adsorption of lipase enzyme on Y zeolite. Afterwards, this material was used to hydrolyze palm oil in a lecithin/isooctane system [30]. In this situation, also, no changes in the crystallization or thermal decomposition of the adsorbent were stated or cited by the authors of the article. However, Oladoja [1] neglected the occurrence of this paper, and many others, in his review. Therefore, the work of Lopes et al. [2] was used in a very specific field of adsorption from solution using a chitosan-based material, and it is not the first paper in literature that employed the Avrami kinetic equation in the adsorption from solution.

Recently, Lima et al. [16] classified the Avrami kinetic model as an empiric model applied to kinetic data of adsorption studies. Therefore, it is not expected from the readers that the parameters earlier attributed to the Avrami equation [26–28] will have the same meaning as the kinetic adsorption equations used in the papers selectively chosen by Oladoja for his criticism [2–15], because this equation was also used to evaluate kinetics of adsorption, instead of only phase transformation or thermal degradation phenomenon of synthesis and/or degradation of the solid-state materials [26–28].

Making a very fast and non-exhaustive revision, of the literature, of the use of the Avrami equation as an empiric equation in the adsorption field, it is noted that Oladoja [1] did not cite in his review at least 31 papers [30–61]. In these references [30–61], the Avrami kinetic equation was used to obtain valuable kinetic parameters for adsorption from the solution systems. Moreover, it is pertinent to highlight that the majority of these articles do not cite any of the publications of Cestari group and/or Lima group, since the use of the Avrami kinetic equation for adsorption studies from solutions is of public domain, at least since 1998 [30].

A detailed description of kinetic models for adsorption at solid/solution interfaces was recently published by Haerifar and Azizian [62] and can be used by the readers or researchers, who are interested to know specific outstanding aspects of kinetic sorption phenomena. Briefly, the main features of the Avrami kinetic model applied to interactive phenomena occurring at solid/solution interfaces are given by this general equation:

$$\frac{\mathrm{d}_q}{\mathrm{d}_t} = k_n t^{M-1} (q_\mathrm{e} - q)^n$$

where q and q_e are amount of adsorbate per unit mass of adsorbent at a given time t and at equilibrium, respectively; and k_n is the rate constant, while the value of n reflects the pseudo-order of the reaction. It is noteworthy to mention that for $M = 1$ and $n = 1$ or 2, the final equation is converted to the respective pseudo-first-order or pseudo-second-order kinetic models, which are the main kinetic equations for calculating kinetic parameters of adsorption process taking place at solid/solution interfaces [62].

The so-called Avrami's exponent (n) has been described to be related to the interaction mechanism and the region in which a given kinetic process takes place, because different paths for adsorption on adsorbent may appear [62]. Some authors state that the rate constants (k) obtained are the sum of all possible rate constants [62]. Specifically, the numerical values of the Avrami parameter n can be used to state whether the reaction kinetics is governed by diffusion or surface interactions with random nucleation or both [62]. However, the analysis of the mechanistic meaning of the Avrami kinetic parameters k and n is not a trivial task, and we have clearly pointed out this aspect in proposing mechanistic features in our recent publications [2–15]. The statement of Abraham et al. [63] seems to describe properly the real sense of the findings of the Avrami equation: "The Avrami model gives only a phenomenological description of the adsorption kinetics without revealing much information about molecular details." Indeed, as stated earlier in this letter, such specific molecular details should be provided using characterization techniques. On the other hand, despite the limited citations of the Avrami-type kinetic equation, which was not created by Lopes et al. [2], the equation has been considered to be useful and attractive [30–62].

In Oladoja´s review [1], one can find a description of an alternative F–W model for modeling kinetic sorption parameters in adsorption from solutions. However, such an equation seems to be valid by solely taking into account the general chemical reactions, $A \rightarrow B$ (Nucleation) and $A + B \rightarrow 2B$ (autocatalytic growth), which are not clearly stated and cannot occur for all interactions occurring at solid/solution interfaces. These statements should be properly and obviously proved by Oladoja using physicochemical characterization and other analytical techniques. In addition, such F–W equation seems to be valid only in the liquid phase, and this feature strongly limits (even prevents) comparisons of F–W model with the Avrami equation discussed in the article of Oladoja and this letter.

Unfortunately, the review of Oladoja was performed using a few literature data of only two research groups in Brazil [2–15]. In this sense, the lack of a deeper historical background found in the Oladoja´s review, concerning the earlier applications and foundations of the Avrami kinetic equation in adsorption from solution field is really disappointing. We recommend that Oladoja or other interested researchers should provide other reviews with additional and individual deeper criticisms of works of several authors described in the literature [30–62], who claim that such an Avrami kinetic equation was successfully used to describe the adsorption systems occurring at solid/solution interfaces.

Acknowledgments

The authors are grateful to CNPq, Brazil for financial support and sponsorship.

References

[1] N.A. Oladoja, A critical review of the applicability of Avrami fractional kinetic equation in adsorption-based water treatment studies, Desalin. Water Treat. (2015), doi: 10.1080/19443994.2015.1076355.

[2] E.C.N. Lopes, F.S.C. dos Anjos, E.F.S. Vieira, A.R. Cestari, An alternative Avrami equation to evaluate kinetic parameters of the interaction of Hg(II) with thin chitosan membranes, J. Colloid Interface Sci. 263 (2003) 542–547.

[3] A.R. Cestari, E.F.S. Vieira, E.C.N. Lopes, R.G. da Silva, Kinetics and equilibrium parameters of Hg(II) adsorption on silica–dithizone, J. Colloid Interface Sci. 272 (2004) 271–276.

[4] A.R. Cestari, E.F.S. Vieira, G.S. Vieira, L.E. Almeida, The removal of anionic dyes from aqueous solutions in the presence of anionic surfactant using aminopropylsilica—A kinetic study, J. Hazard. Mater. 138 (2006) 133–141.

[5] E.F.S. Vieira, A.R. Cestari, E.C.N. Lopes, L.S. Barreto, G.S. Lázaro, L.E. Almeida, Determination of kinetic parameters from isothermal calorimetry for interaction processes of pyrimethamine with chitosan derivatives, React. Funct. Polym. 67 (2007) 820–827.

[6] J.C.P. Vaghetti, E.C. Lima, B. Royer, N.F. Cardoso, B. Martins, T. Calvete, Pecan nutshell as biosorbent to remove toxic metals from aqueous solution, Sep. Sci. Technol. 44 (2009) 615–644.

[7] J.C.P. Vaghetti, E.C. Lima, B. Royer, B.M. da Cunha, N.F. Cardoso, J.L. Brasil, S.L.P. Dias, Pecan nutshell as biosorbent to remove Cu(II), Mn(II) and Pb(II) from aqueous solutions, J. Hazard. Mater. 162 (2009) 270–280.

[8] B. Royer, N.F. Cardoso, E.C. Lima, J.C.P. Vaghetti, N.M. Simon, T. Calvete, R.C. Veses, Applications of Brazilian pine-fruit shell in natural and carbonized forms as adsorbents to removal of methylene blue from aqueous solutions—Kinetic and equilibrium study, J. Hazard. Mater. 164 (2009) 1213–1222.

[9] T. Calvete, E.C. Lima, N.F. Cardoso, S.L.P. Dias, F.A. Pavan, Application of carbon adsorbents prepared from the Brazilian pine-fruit-shell for the removal of Procion Red MX 3B from aqueous solution—Kinetic, equilibrium, and thermodynamic studies, Chem. Eng. J. 155 (2009) 627–636.

[10] B. Royer, N.F. Cardoso, E.C. Lima, V.S.O. Ruiz, T.R. Macedo, C. Airoldi, Organofunctionalized kenyaite for dye removal from aqueous solution, J. Colloid Interface Sci. 336 (2009) 398–405.

[11] B. Royer, N.F. Cardoso, E.C. Lima, T.R. Macedo, C. Airoldi, A useful organofunctionalized layered silicate for textile dye removal, J. Hazard. Mater. 181 (2010) 366–374.

[12] B. Royer, N.F. Cardoso, E.C. Lima, T.R. Macedo, C. Airoldi, Sodic and acidic crystalline lamellar magadiite adsorbents for the removal of methylene blue from aqueous solutions: Kinetic and equilibrium studies, Sep. Sci. Technol. 45 (2010) 129–141.

[13] T. Calvete, E.C. Lima, N.F. Cardoso, J.C.P. Vaghetti, S.L.P. Dias, F.A. Pavan, Application of carbon adsorbents prepared from Brazilian-pine fruit shell for the removal of reactive orange 16 from aqueous solution: Kinetic, equilibrium, and thermodynamic studies, J. Environ. Manage. 91 (2010) 1695–1706.

[14] D.S.F. Gay, T.H.M. Fernandes, C.V. Amavisca, N.F. Cardoso, E.V. Benvenutti, T.M.H. Costa, E.C. Lima, Silica grafted with a silsesquioxane containing the positively charged 1,4-diazoniabicyclo[2.2.2]octane group used as adsorbent for anionic dye removal, Desalination 258 (2010) 128–135.

[15] N.F. Cardoso, R.B. Pinto, E.C. Lima, T. Calvete, C.V. Amavisca, B. Royer, M.L. Cunha, T.H.M. Fernandes, I.S. Pinto, Removal of remazol black B textile dye from aqueous solution by adsorption, Desalination 269 (2011) 92–103.

[16] E.C. Lima, M.A. Adebayo, F.M. Machado, Kinetic and equilibrium models of adsorption, in: C.P. Bergmann, F.M. Machado (Eds.), Carbon Nanomaterials as Adsorbents for Environmental and Biological Applications, Springer, Heidelberg, 2015, pp. 33–69, doi: 10.1007/978-3-319-18875-1_3.

[17] L.G. da Silva, R. Ruggiero, P.M. Gontijo, R.B. Pinto, B. Royer, E.C. Lima, T.H.M. Fernandes, T. Calvete, Adsorption of Brilliant Red 2BE dye from water solutions by a chemically modified sugarcane bagasse lignin, Chem. Eng. J. 168 (2011) 620–628.

[18] M.A. Adebayo, L.D.T. Prola, E.C. Lima, M.J. Puchana-Rosero, R. Cataluña, C. Saucier, C.S. Umpierres, J.C.P. Vaghetti, L.G. da Silva, R. Ruggiero, Adsorption of Procion Blue MX-R dye from aqueous solutions by lignin chemically modified with aluminum and manganese, J. Hazard. Mater. 268 (2014) 43–50.

[19] D.C. dos Santos, M.A. Adebayo, S.F.P. Pereira, L.D.T. Prola, R. Cataluña, E.C. Lima, C. Saucier, C.R. Gally, F.M. Machado, New carbon composite adsorbents for the removal of textile dyes from aqueous solutions: Kinetic, equilibrium, and thermodynamic studies, Korean J. Chem. Eng. 31 (2014) 1470–1479.

[20] M.C. Ribas, M.A. Adebayo, L.D.T. Prola, E.C. Lima, R. Cataluña, L.A. Feris, M.J. Puchana-Rosero, F.M. Machado, F.A. Pavan, T. Calvete, Comparison of a homemade cocoa shell activated carbon with commercial activated carbon for the removal of reactive violet 5 dye from aqueous solutions, Chem. Eng. J. 248 (2014) 315–326.

[21] F.M. Machado, C.P. Bergmann, E.C. Lima, B. Royer, F.E. de Souza, I.M. Jauris, T. Calvete, S.B. Fagan, Adsorption of Reactive Blue 4 dye from water solutions by carbon nanotubes: Experiment and theory, Phys. Chem. Chem. Phys. 14 (2012) 11139–11153.

[22] J.A. Mota, R.A. Chagas, E.F.S. Vieira, A.R. Cestari, Synthesis and characterization of a novel fish scale-immobilized chitosan adsorbent—Preliminary features of dichlorophenol sorption by solution calorimetry, J. Hazard. Mater. 229–230 (2012) 346–353.

[23] J.A. Mota, E.S. Silva, E.F.S. Vieira, E.M. Sussuchi, A.R. Cestari, A highly efficient adsorbent synthesized by reactive depositions of chitosan layers on fish scale collagen—Hydrodynamic swelling and dichlorophenol derivative sorption evaluated by continuous long-term solution microcalorimetry, J. Environ. Chem. Eng. 1 (2013) 480–485.

[24] V. Kuroki, G.E. Bosco, P.S. Fadini, A.A. Mozeto, A.R. Cestari, W.A. Carvalho, Use of a La(III)-modified bentonite for effective phosphate removal from aqueous media, J. Hazard. Mater. 274 (2014) 124–131.

[25] A.R. Cestari, E.F.S. Vieira, G.S. Vieira, L.P. da Costa, A.M.G. Tavares, W. Loh, C. Airoldi, The removal of reactive dyes from aqueous solutions using chemically modified mesoporous silica in the presence of anionic surfactant—The temperature dependence and a thermodynamic multivariate analysis, J. Hazard. Mater. 161 (2009) 307–316.

[26] M. Avrami, Kinetics of phase change. I General theory, J. Chem. Phys. 7 (1939) 1103–1112.

[27] M. Avrami, Kinetics of phase change. II Transformation-time relations for random distribution of nuclei, J. Chem. Phys. 8 (1940) 212–224.

[28] M. Avrami, Granulation, phase change, and microstructure kinetics of phase change. III, J. Chem. Phys. 9 (1941) 177–184.

[29] N.A. Oladoja, C.O. Aboluwoye, Y.B. Oladimeji, A.O. Ashogbon, I.O. Otemuyiwa, Studies on castor seed shell as a sorbent in basic dye contaminated wastewater remediation, Desalination 227 (2008) 190–203.

[30] Z. Knezevic, L. Mojovic, B. Adnadjevic, Palm oil hydrolysis by lipase from *Candida cyhdracea* immobilized on zeolite type Y, Enzyme Microb. Technol. 22 (1998) 275–280.

[31] Y.K. Chang, L. Chu, J.C. Tsai, S.J. Chiu, Kinetic study of immobilized lysozyme on the extrudate-shaped NaY zeolite, Process Biochem. 41 (2006) 1864–1874.

[32] G. Crini, Kinetic and equilibrium studies on the removal of cationic dyes from aqueous solution by adsorption onto a cyclodextrin polymer, Dyes Pigm. 77 (2008) 415–426.

[33] G. Crini, P.M. Badot, Application of chitosan, a natural aminopolysaccharide, for dye removal from aqueous solutions by adsorption processes using batch studies: A review of recent literature, Prog. Polym. Sci. 33 (2008) 399–447.

[34] C.E. Zubieta, P.V. Messina, C. Luengo, M. Dennehy, O. Pieroni, P.C. Schulz, Reactive dyes remotion by porous TiO_2-chitosan materials, J. Hazard. Mater. 152 (2008) 765–777.

[35] G. Bascialla, A.E. Regazzoni, Immobilization of anionic dyes by intercalation into hydrotalcite, Colloids Surf., A: Physicochem. Eng. Aspects 328 (2008) 34–39.

[36] R. Serna-Guerrero, A. Sayari, Modeling adsorption of CO_2 on amine-functionalized mesoporous silica. 2: Kinetics and breakthrough curves, Chem. Eng. J. 161 (2010) 182–190.

[37] A.M.M. Vargas, A.L. Cazetta, M.H. Kunita, T.L. Silva, V.C. Almeida, Adsorption of methylene blue on activated carbon produced from flamboyant pods (*Delonix regia*): Study of adsorption isotherms and kinetic models, Chem. Eng. J. 168 (2011) 722–730.

[38] A.H. Gorji, A. Sayari, CO_2 capture on polyethylenimine-impregnated hydrophobic mesoporous silica: Experimental and kinetic modeling, Chem. Eng. J. 173 (2011) 72–79.

[39] L.G. Wang, G.B. Yan, Adsorptive removal of direct yellow 161 dye from aqueous solution using bamboo charcoals activated with different chemicals, Desalination 274 (2011) 81–90.

[40] M.A. Hossain, H.H. Ngo, W.S. Guo, T. Setiadi, Adsorption and desorption of copper(II) ions onto garden grass, Bioresour. Technol. 121 (2012) 386–395.

[41] J. Wang, L.A. Stevens, T.C. Drage, J. Wood, Preparation and CO_2 adsorption of amine modified Mg–Al LDH via exfoliation route, Chem. Eng. Sci. 68 (2012) 424–431.

[42] A.M.M. Vargas, A.L. Cazetta, A.C. Martins, J.C.G. Moraes, E.E. Garcia, G.F. Gauze, W.F. Costa, V.C. Almeida, Kinetic and equilibrium studies: Adsorption of food dyes Acid Yellow 6, Acid Yellow 23, and Acid Red 18 on activated carbon from flamboyant pods, Chem. Eng. J. 181–182 (2012) 243–250.

[43] C. Djilani, R. Zaghdoudi, A. Modarressi, M. Rogalski, F. Djazi, A. Lallam, Elimination of organic micropollutants by adsorption on activated carbon prepared from agricultural waste, Chem. Eng. J. 189–190 (2012) 203–212.

[44] L. Wang, Application of activated carbon derived from 'waste' bamboo culms for the adsorption of azo disperse dye: Kinetic, equilibrium and thermodynamic studies, J. Environ. Manage. 102 (2012) 79–87.

[45] V.K. Gupta, R. Kumar, A. Nayak, T.A. Saleh, M.A. Barakat, Adsorptive removal of dyes from aqueous solution onto carbon nanotubes: A review, Adv. Colloid Interface Sci. 193–194 (2013) 24–34.

[46] S. Rangabhashiyam, N. Anu, N. Selvaraju, Sequestration of dye from textile industry wastewater using agricultural waste products as adsorbents, J. Environ. Chem. Eng. 1 (2013) 629–641.

[47] T.S. Anirudhan, T.A. Rauf, Lysozyme immobilization via adsorption process using sulphonic acid functionalized silane grafted copolymer, Colloids Surf., B: Biointerfaces 107 (2013) 1–10.

[48] L. Stevens, K. Williams, W.Y. Han, T. Drage, C. Snape, J. Wood, J. Wang, Preparation and CO_2 adsorption of diamine modified montmorillonite via exfoliation grafting route, Chem. Eng. J. 215–216 (2013) 699–708.

[49] T.S. Anirudhan, T.A. Rauf, Adsorption performance of amine functionalized cellulose grafted epichlorohydrin for the removal of nitrate from aqueous solutions, J. Ind. Eng. Chem. 19 (2013) 1659–1667.

[50] T.S. Anirudhan, T.A. Rauf, Silane graft copolymer modified with sulphonic acid functional groups used for immobilization of trypsin from aqueous solutions via adsorption process, J. Ind. Eng. Chem. 20 (2014) 1901–1910.

[51] V.O. Njoku, Biosorption potential of cocoa pod husk for the removal of Zn(II) from aqueous phase, J. Environ. Chem. Eng. 2 (2014) 881–887.

[52] R. George, S. Sugunan, Kinetics of adsorption of lipase onto different mesoporous materials: Evaluation of Avrami model and leaching studies, J. Mol. Catal. B: Enzym. 105 (2014) 26–32.

[53] N. Sivarajasekar, R. Baskar, Adsorption of Basic Magenta II onto H_2SO_4 activated immature *Gossypium hirsutum* seeds: Kinetics, isotherms, mass transfer, thermodynamics and process design, Arabian J. Chem. (2014), doi: 10.1016/j.arabjc.2014.10.040.

[54] A.C. Martins, O. Pezoti, A.L. Cazetta, K.C. Bedin, D.A.S. Yamazaki, G.F.G. Bandoch, T. Asefa, J.V. Visentainer, V.C. Almeida, Removal of tetracycline by NaOH-activated carbon produced from macadamia nut shells: Kinetic and equilibrium studies, Chem. Eng. J. 260 (2015) 291–299.

[55] X. Wang, Q. Guo, T. Kong, Tetraethylenepentamine-modified MCM-41/silica gel with hierarchical mesoporous structure for CO_2 capture, Chem. Eng. J. 273 (2015) 472–480.

[56] M. Arabloo, M.H. Ghazanfari, D. Rashtchian, Spotlight on kinetic and equilibrium adsorption of a new surfactant onto sandstone minerals: A comparative study, J. Taiwan Inst. of Chem. Eng. 50 (2015) 12–23.

[57] S. Mondal, K. Sinha, K. Aikat, G. Halder, Adsorption thermodynamics and kinetics of ranitidine hydrochloride onto superheated steam activated carbon derived from mung bean husk, J. Environ. Chem. Eng. 3 (2015) 187–195.

[58] P.F. de Sales, Z.M. Magriotis, M.A.L.S. Rossi, R.F. Resende, C.A. Nunes, Comparative analysis of tropaeolin adsorption onto raw and acid treated kaolinite: Optimization by response surface methodology, J. Environ. Manage. 151 (2015) 144–152.

[59] P. Pornaroonthama, N. Thouchprasitchai, S. Pongstabodee, CO_2 adsorption on diatomaceous earth modified with cetyltrimethylammonium bromide and functionalized with tetraethylenepentamine: Optimization and kinetics, J. Environ. Manage. 157 (2015) 194–204.

[60] J.O. Gonçalves, G.L. Dotto, L.A.A. Pinto, Cyanoguanidine-crosslinked chitosan to adsorption of food dyes in the aqueous binary system, J. Mol. Liq. 211 (2015) 425–430.

[61] N. Chalal, H. Bouhali, H. Hamaizi, B. Lebeau, A. Bengueddach, CO_2 sorption onto silica mesoporous materials made from nonionic surfactants, Microporous Mesoporous Mater. 210 (2015) 32–38.

[62] M. Haerifar, S. Azizian, Fractal-like adsorption kinetics at the solid/solution interface, J. Phys. Chem. 116 (2012) 13111–13119.

[63] T. Abraham, S. Giasson, J.F. Gohy, R. Jérôme, B. Müller, M. Stamm, Adsorption kinetics of a hydrophobic−hydrophilic diblock polyelectrolyte at the solid−aqueous solution interface: A slow birth and fast growth process, Macromolecules 33 (2000) 6051–6059.