Kinetic studies on toluene removal from aqueous solutions using carbon nanotubes

A Kucherova*1, I Shubin1, A Yermakov1, A Gerasimova1, N Memetov1 and A Popova1

1Department “Technology and Methods of Nanoproducts Manufacturing”, Tambov State Technical University, 106 Sovetskaya Str, 392000 Tambov, Russian Federation

*1E-mail: anastasia.90k@mail.ru

Abstract. The effectiveness of Taunit-M carbon nanotubes in removing toluene from aqueous media was studied. Adsorption kinetic data were analyzed implementing the simple Weber-Morris diffusion model and very common phenomenological models (Lagergren and Ho-McKay) which simulate mass transfer processes through using formal equations for chemical kinetics. Investigating the correspondence of the experimental data to different models as regards adsorption kinetics, it can be should assumed that the toluene adsorption on the carbon nanotubes represents a two-stage process consisting of the phenomena of diffusive transfer and adsorption itself. The analysis of the temperature effect on the equilibrium sorption shows that the Gibbs free energy (ΔG°) values vary in the range typical of adsorption interactions.

1. Introduction

Volatile organic compounds (VOCs) are widely used in the manufacturing of paints, synthetic rubber, agricultural chemicals, pharmaceuticals, as well as in the oil refining and other industries. Each year, large amounts of wastewater containing these organic compounds are discharged into aquatic media from industrial, transport and target sources of disposal. Since toluene is a flammable, toxic, carcinogenic and/or mutagenic substance [1], its availability in air, water and soil is dangerous even at low levels both for human health and the environment. Thus, purifying wastewater from organic compounds that threaten the well-being of the population represents an urgent task.

To date, lots of different methods have been developed to dispose of the organic compounds. They include membrane absorption [2], condensation [3], thermal combustion method [4], catalytic and photocatalytic oxidation technologies [5], non-thermal plasma [6], phytoremediation [7], and biotechnology [8]. However, each of these purification options has certain technological and economic limitations. Among them, adsorption methods are one of the most efficient ways for the removal of low (residual) contents of VOCs, since they are more technologically and economically productive in these cases [9, 10].

Carbon nanotubes (CNTs) are among the most widely investigated carbon nanomaterials. Their hollow layered structure and high specific surface area make it possible to consider them as a promising material for the adsorption of various types of organic compounds. Studies comparing the adsorption properties of CNTs with those of activated carbons prove that the former are much more effective in removing both organic [11] and inorganic [12] compounds from wastewater.

Analysis of the scientific literature shows that functionalized CNTs with different grafted groups are usually used in studies on the removal of organic pollutants from aqueous solutions. For instance,
in the paper, [13] in order to improve the adsorption active sites for powerful connection between the adsorbent and the dye, surface modification of adsorbent was performed to create functional groups through surface oxidation of MWCNTs and zinc oxide (ZnO). At the same time, the adsorption properties of untreated (pristine) single-walled and multi-walled CNTs remain poorly investigated.

Considering the aforementioned, the purpose of this study was to study the adsorption behavior of unoxidized MWCNTs in purifying aqueous solutions from toluene.

2. Materials and methods
In the present study, Taunit-M CNTs, produced by NanoTechCenter Ltd (Tambov, Russia) were employed as an adsorbent. Before using, they were repeatedly washed with distilled water and then dried in a vacuum drying oven at 110 º C for at least 2 h.

Toluene with (purity > 99 %), purchased from Merck (Darmstadt, Germany) was used as an adsorbate. It was diluted with deionized water to the desired concentrations. Experiments were carried out in 50- mL tubes containing the sorbent and toluene solutions. The tubes were shaken at 100 rpm on BioRS-24 rotators (Biosan, Riga, Latvia). After that, the mixtures were centrifuged using a 5810 R centrifuge (Eppendorf, Hamburg, Germany) at 10670 g for 10 min to separate the phases. The results of preliminary experiments showed that the adsorption equilibrium was achieved within 60 min. The concentration of toluene solutions was determined using a UV-1201 spectrophotometer (Shimadzu, Kyoto, Japan) at 264 nm. The effects of the following factors on the adsorption process (efficiency of toluene removal) were assessed: contact time (0-80 min), adsorbent dose (0.01-0.07 g), adsorbate concentration (25-145 mg/L), and solution temperature (25-45 ºC).

All the tests were performed in triplicate and repeated three times, and only mean values are reported herein. The maximum deviation between parallel experiments did not exceed 3 %.

3. Results and discussion

3.1. Adsorption tests

3.1.1. Adsorbate concentration effect. The isotherm of the toluene adsorption on the Taunit-M CNTs (figure 1) belongs to the S-type, characteristic of the adsorption of sparingly water-soluble liquid compounds, according to the classification proposed by Giles and his colleagues [14]. It has a slight concave initial section, and a further increase in the adsorbate concentration leads to the formation of a plateau responsible for achieving the saturation of the adsorbent. In this case, the maximum adsorption capacity was found to be 121.7 mg/g under the following conditions: temperature – 25 ºC, C0 – 105 mg/L, and Ce – 31.98 mg/L). Therefore, the other tests were carried out under these conditions.

3.1.2. Adsorbent dose effect. The adsorbent dose is an important parameter, since it determines the adsorption capacity of the adsorbent at a given initial concentration of the adsorbate solution. The dependence of the toluene removal efficiency on the adsorbent dose (0.01-0.07 g) is presented in figure 2.
It can be seen that the maximum recovery is achieved with 0.03 g of the CNTs. The initial increase in the adsorption capacity is related to the specific surface area and the availability of active sites, as reported in [15]. However, a further increase in the dose of the adsorbent introduced does not lead to simmate changes in the toluene removal efficiency, which may be due to the adsorbent agglomeration as a result of high CNTs concentration, accompanied by partial blocking of the adsorption sites. Since no noticeable increase in the removal efficiency was observed after 0.03 g, further studies were conducted using this adsorbent dose.

3.1.3. Time effect. Kinetics plays a significant role in solute adsorption, and also represents adsorption efficiency of an adsorbent. The experimental results of studying the contact time effect on the toluene removal are shown in figure 3. From this figure, it follows that equilibrium is achieved within 60 min, and the removal rate is uniform throughout the entire period of time before the onset of equilibrium. Thus, for this study, the optimum length of time is 60 min.

3.1.4. Temperature effect. Since wastewater discharges come from the chemical industry at different temperatures, it is necessary to investigate the temperature effect on the toluene level reduction in solution using the adsorbent material considered herein. It was found that the adsorption capacity of the CNTs increases when raising the temperature from 25 to 35 °C. A further increase had the reverse impact on the adsorption capacity (figure 4). This confirms the results reported elsewhere [16].
Favorable toluene adsorption (141.8 mg/g) at a rather low temperature (35 °C) is due to intermolecular interactions between the adsorbent and the adsorbate, which increase the affinity of the adsorption sites and, in turn, increase the diffusion of organic compounds toward the adsorbent. However, a decrease in the adsorption capacity is associated with a weakening of the interaction forces between the adsorbent and the adsorbate due to desorption at elevated temperatures.

3.2. Adsorption modeling

3.2.1. Kinetics. The adsorption at the solid-solution interface with a reaction localized in the adsorbent pores is usually described by four main stages [17]:
   1) external mass transfer: from the bulk of the solution to the boundary layer – a liquid film on the adsorbent surface;
   2) film diffusion: the adsorbate penetrates through the liquid layer of the adsorbent surface;
   3) internal mass transfer: the adsorbate is transferred from the surface into the pores of the adsorbate;
   4) adsorption: the interaction between the adsorbate with the active sites.

   One (or more) of these stages can have a decisive role. The adsorption is usually the quickest step. The external diffusion is not often critical, especially when the experimental system is well mixed (agitated), as in the case considered herein. Thus, it is believed that only the intraparticle diffusion controls the adsorption kinetics [18, 19].

   Reported in 1963, the Weber-Morris (intraparticle diffusion) model has been implemented many times to describe liquid-phase adsorption [20, 21]. This model was developed for adsorbents possessing a system of pores, the size of which allows adsorbate molecules to penetrate inside and settle there, and the adsorption process involves the rate of the internal mass transfer stage, i.e. adsorbate diffusion in the adsorbent pore system.

   The model is based on earlier studies, especially the work [22], considering a theoretical approach developed for spherical adsorbent particles.

   It can be assumed that the internal diffusion is the stage that limits the process rate, if the dependence is a straight line passing through the origin (C=0). However, when constructing the dependence of \( q_t \) vs. square root of \( t \), a straight section, not passing through the origin, was obtained, which may be due to the difference in the mass transfer rate at the initial and final adsorption stages [23]. Moreover, such a deviation of the straight line from the origin shows that the diffusion inside the pores is not the only stage of rate control [24]. The results show that the mechanism of the toluene adsorption on the CNTs is complex, and both the surface adsorption and the intraparticle diffusion contribute to the actual process. The \( k_{ld} \) value of the intraparticle diffusion model was found to be \( 17.9 \text{ mg/(g min}^{1/2} \). The correlation coefficient \( (R^2 \approx 0.99) \) clearly indicates that the adsorption obeys this model (table 1).

   Taking into account the complexity of quantitative description of diffusion processes through simple models, one should also analyze the possibility of implementing very common phenomenological models that simulate mass transfer processes using formal equations for chemical kinetics. This approach most often involves the implementation of the pseudo-first- and pseudo-second-order models.

   In 1898, Lagergren introduced the first-order rate equation for the adsorption of oxalic and malonic acids on carbon to explain adsorption kinetics on solid surfaces. The Lagergren (pseudo-first-order) equation is used to describe kinetic processes based on the solution concentration and the adsorption capacity of a solid [25]. It is the first rate equation developed to characterize adsorption in liquid/solid systems.

   It should be noted that the pseudo-first-order kinetic model mathematically coincides with the equation characteristic of diffusion processes, but the adsorption rate constant is used as a fixed parameter. However, in the case of diffusion, the process rate depends on the size of adsorbent particles and the film thickness. If the chemical kinetics is the limiting stage, then the adsorption rate
does not depend on the above factors, but depends only on the concentration and the temperature. Thus, when the adsorption kinetics is described by the pseudo-first-order kinetic model, the adsorption of the adsorbate is preceded by its diffusion.

The analysis of the kinetic curves constructed for the toluene adsorption on the Taunit-M CNTs in the coordinates of \( \log(q_e - q_t) \) vs. \( t \) showed that the dependence is linear \((R^2>0.9)\). The toluene adsorption capacity predicted by the Lagergren model \((q_e=139.6 \text{ mg/g})\) almost coincided with the experimentally obtained maximum adsorption capacity \((q_e=141.8 \text{ mg/g})\). The pseudo-first-order adsorption rate constant was found to be \(3.6 \times 10^{-2} \text{ min}^{-1}\) (table 1).

### Table 1. Kinetic parameters of the toluene adsorption on the Taunit-M CNTs.

| Adsorbate | Kinetic models | Weber-Morris | Lagergren | Ho-McKay |
|-----------|----------------|--------------|-----------|-----------|
|           | \( k_{1d} \) | \( R^2 \)   | \( K_q \) | \( q_e \) | \( K_2 \) | \( q_{H-M} \) | \( R^2 \) |
| Toluene   | 17.9           | 0.99         | 3.6 \times 10^2 | 139.63   | 0.97      | 1.3 \times 10^4 | 192.31  | 0.92      |

![Figure 5](image1.png)

Figure 5. Kinetic plots: (a) Weber-Morris, (b) Lagergren, (c) Ho-McKay for toluene adsorption on the Taunit-M CNTs.

The mathematical form of the pseudo-second-order equation was first proposed in 1984 by Blanchard and his colleagues to describe the adsorption kinetics of heavy metals on natural zeolites [26]. Currently, this is the most commonly used mathematical expression used to process and correlate kinetic data for solid/solution adsorption systems [27]. The classical form of this model was presented by Ho and McKay.

The applicability of this model is usually accompanied by a conclusion about the occurrence of a chemical reaction that limits the adsorption kinetics. This is obviously due to the fact that every known theoretical rationale for the pseudo-second-order model is based on the fundamental theories of surface reactions. One of the earliest theoretical interpretations of this model was proposed in 2008 by
Azizian [28]; it is based on the classical Langmuir adsorption kinetics model, in which the adsorption is considered as a chemical reaction occurring on an energetically homogeneous solid surface. A similar approach was presented in 2008 by Liu and Shen [29]. Both these works proved that the Langmuir kinetics can be reduced to the equations of either the pseudo-first- or the pseudo-second-order rate. However, there exist papers, in which the pseudo-second-order model is considered as a fairly flexible mathematical formula capable of simulating the kinetics of the internal mass transfer (diffusion) adsorption for systems with flat and spherical particles [30].

Like in the previous case with the pseudo-first-order model, the analysis of the kinetic curves obtained for the toluene adsorption on the Taunit-M material in the coordinates of \( t/ q_t \) vs. \( t \) showed that the dependence is also linear \( (R^2>0.9) \) (figure 5). However, the adsorption capacity predicted by the Ho-McKay model \( (q_{H,M}=192.3 \text{ mg/g}) \) differed from the experimentally obtained maximum adsorption capacity \( (q_c=141.8 \text{ mg/g}) \). The pseudo-first-order adsorption rate constant was found to be \( 1.3 \times 10^{-4} \text{ g/(mg min)} \) (table 1).

3.2.2. Thermodynamics. To study the temperature effect on the equilibrium adsorption, the following Gibbs equation was used:

\[
\Delta G^o = -RT \ln K_e
\]  (1)

where \( \Delta G^o \) is the Gibbs free energy (kJ/mol), \( R \) is the universal gas constant equal to 8.314 J/(mol K), \( T \) is the absolute temperature (K), and \( K_e \) is the thermodynamic equilibrium constant, which can be estimated as follows:

\[
\ln K_e = \frac{\Delta S^o}{R} - \frac{\Delta H^o}{RT}
\]  (2)

where \( \Delta H^o \) is the enthalpy (kJ/mol), and \( \Delta S^o \) is the entropy (J/mol K).

The analysis of the dependence of \( \ln K_e \) vs. \( 1/T \) showed that it is linear \( (R^2>0.9) \), thereby making it possible to determine the \( \Delta H^o \) and \( \Delta S^o \) values, and then the \( \Delta G^o \) values at different temperatures (table 2).

| Adsorbate | Thermodynamic parameters | \( R^2 \) |
|-----------|-------------------------|----------|
|           | \( \Delta G^o \) at     | \( \Delta S^o \) | \( \Delta H^o \) |
| Toluene   | 298.15 K | 303.15 K | 308.15 K | 151.81 | 41.77 | 0.99 |

The negative \( \Delta G^o \) values, varying from -46.74 to -45.21 kJ/mol, indicate the spontaneity of the process and correspond to the range of values typical of physical adsorption. The standard enthalpy shows the energy change in the system. Its positive \( \Delta H^o \) value evidences the endothermic process. The positive \( \Delta S^o \) value stands for a change in the structure of the Taunit-M CNTs in the toluene adsorption process, leading to an increase in system disorder. The similar results were reported in the paper [31].

4. Conclusion

The adsorption efficiency of the Taunit-M CNTs was assessed regarding toluene. The maximum toluene adsorption capacity of this material was found to be 141.8 mg/g, which exceeds the adsorption capacity of analogous materials given in table 3.
Table 3. Comparison between the adsorption studies performed using different adsorbents.

| Adsorbent                        | Toluene adsorption capacity (mg/g) | Conditions                        | Reference |
|---------------------------------|------------------------------------|-----------------------------------|-----------|
| NaOCl-oxidized single-walled CNTs | 103.2                              | pH: 7, T: 25 °C, C₀: 20mg/L        | 1         |
| HCl-oxidized multi-walled CNTs   | 60.0                               | pH: 7, T: 25 °C, C₀: 20mg/L        | 32        |
| H₂SO₄-oxidized multi-walled CNTs | 36.7                               | pH: 7, T: 20 °C, C₀: 200 mg/L      | 32        |
| NaOCl-oxidized multi-walled CNTs | -                                  | -                                 | 33        |
| NaOCl-oxidized multi-walled CNTs | 99.9                               | pH: 7, T: 35 °C, C₀: 200 mg/L      | 34        |
| Powdered activated carbon       | 40.0                               | pH: 6.4, T: 23 °C, C₀: 50 mg/L     | 35        |
| HNO₃/30-% NaOCl-oxidized multi-walled CNTs | 59.5               | pH: 7, T: 20 °C, C₀: 200 mg/L      | 36        |
| KOH-oxidized multi-walled CNTs   | 63.3                               | pH: 7, T: 25 °C, C₀: 20mg/L        | 37        |
| Taunit-M CNTs                   | 141.8                              | pH: 7, T: 35 °C, C₀: 25mg/L        | Present work |

The adsorption kinetic data were analysed using the simple Weber-Morris diffusion model and very common phenomenological models which simulate mass transfer processes using formal equations for chemical kinetics — the Lagergren and Ho-McKay models. As a result of processing the data, it was shown that the considered models are suitable, regardless of the adsorption process stage, i.e. intraparticle diffusion (Weber-Morris equation) or surface reaction (Lagergren equation). As noted in the literature, there is no consensus on the interpretation of formal equations for chemical kinetics.

Considering this, more studies are required to elucidate the toluene adsorption mechanisms. However, the analysis of the temperature effect on the equilibrium adsorption showed that the Gibbs free energy values vary in the range characteristic of physical sorption. Besides, these values were identified as negative, therefore the spontaneity of the adsorption process was established. The enthalpy and entropy values were found to be positive, thereby evidencing the endothermic process and showing an increase in randomness at the solid/solution interface after the toluene adsorption on the surface of the Taunit-M CNTs.

Thus, the results obtained can be useful in the development of adsorption technology for the purification of natural and waste water from toluene using CNTs.

Acknowledgment

The research was funded by the Ministry of Science and Higher Education of the Russian Federation under Project No. 16.1384.2017/PCh.

References

[1] Wibowo N, Setyadhi L, Wibowo D, Setiawan J and Ismadji S 2007 Adsorption of benzene and
toluene from aqueous solutions onto activated carbon and its acid and heat treated forms: influence of surface chemistry on adsorption J. Hazard. Mater. 146 237

[2] Al-Gharabli S, Kujawski W, El-Rub Z A, Hamad E M and J. Kujawa 2018 Enhancing membrane performance in removal of hazardous VOCs from water by modified fluorinated PVDF porous material J. Membr. Sci. 556 214

[3] Farrell E S and Pacey E S 2010 Rapid removal of selected volatile organic compounds from gaseous mixtures using a new dispersive vapor extraction technique: a feasibility study Talanta 82 739

[4] Cloirec P Le, Pré P, Delage F and Giraudet S 2012 Visualization of the exothermal VOC adsorption in a fixed-bed activated carbon adsorber Environ. Technol. 33 285

[5] environment air purification: the state-of-the-art Appl. Catal. B 203 247

[6] Feng X, Liu H, He C, Shen Z and Wang T 2018 Synergistic effects and mechanism of a non-thermal plasma catalysis system in volatile organic compound removal: a review Catal. Sci. Technol. 8 936

[7] Kim J, Khalekuzzaman M, Suh J N, Kim H J, Shagol C, Lagergren H – H and Kim H J Kim 2018 Phytoremediation of volatile organic compounds by indoor plants: a review Hortic. Environ. Biotechnol. 59 143

[8] Cheng Y, He H, Yang C, Zeng G, Li X, Chen H and Yu G 2016 Challenges and solutions for biofiltration of hydrophobic volatile organic compounds Biotechnol. Adv. 34 1091

[9] Aditya D, Rohan P and Suresh G 2011 Nano-adsorbents for wastewater treatment: a review Res. J. Chem. Environ. 15 1033

[10] Mohmood I, Lopes C B, Lopes I, Ahmad I, Duarte A C and Pereira E 2013 Nanoscale materials and their use in water contaminants removal—a review Environ Sci Pollut R. 20 1239

[11] Hosseini S J, Kokhdan S N, Ghaedi A M and Moosavian S S 2011 Comparison of multiwalled carbon nanotubes and activated carbon adsorbs for efficient removal of methyl orange: kinetic and thermodynamic investigation Fresenius Environ Bull. 20 219

[12] Li Y-H, Dinga J, Luoan Z, Di Z, Zhua Y, Xua C, Wua D and Weic B 2013 Competitive adsorption of Pb\(^{2+}\), Cu\(^{2+}\) and Cd\(^{2+}\) ions from aqueous solutions by multiwalled carbon nanotubes Carbon 41 2787

[13] Seyed Arabi S M, Lalehloo R S, Olyai M R T B; Ali Gomaa AM, Sadegh, H 2019 Removal of congo red azo dye from aqueous solution by ZnO nanoparticles loaded on multiwall carbon nanotubes Physica E. 106 150

[14] Rashid A, Bhatti H N, Iqbal M and Noreen S 2016 Fungal biomass composite with bentonite efficiency for nickel and zinc adsorption: A mechanistic study Ecol. Eng. 91 459

[15] Giles C H, MacEwan T H, Nakhwa S N and Smith D 1960 Studies in adsorption: A system of classification of solution adsorption isotherms J. Chem. Soc. 3 3973

[16] Dehghani M H, Mostofi M, Alimohammadi M, McKay G, Yetilmsezsoy K, Albadarin A B, Heibati B, AlGhouti M., Mubarak N M and Sahu J N 2016 High-performance removal of toxic phenol by single-walled and multi-walled carbon nanotubes: Kinetics, adsorption, mechanism and optimization studies J. Ind. Eng. Chem. 35 63

[17] Yang J Y, Jiang X Y, Jiao F P and Yu J G 2017 The 2018 oxygen-rich pentaerythritol modified multi-walled carbon nanotube as an efficient adsorbent for aqueous removal of alizarin yellow R and alizarin red S Appl. Surf. Sci. 436 198

[18] Knappe D and Rudiger U 1996 Predicting the removal of atrazine by powdered and granular activated carbon, PhD thesis, University of Illinois at Urbana-Champaign, 1996.

[19] McKay G 1998 Application of surface diffusion model to the adsorption of dyes on bagasse pith Adsorption 4 361

[20] Cook D, Newcombe G and Sztabnik P 2001 The application of powdered activated carbon for MIB and geosmin removal: predicting PAC doses in four raw waters Water Res. 35 1325

[21] Schwaab M, Steffani E, Barbosa-Coutinho E and Júnior J B S 2017 Critical analysis of adsorption/diffusion modelling as a function of time square root Chem. Eng. Sci. 173 179
[22] Pandey P K, Sharma S K and Sambi S S 2015 Removal of lead (II) from waste water on zeolite-NaX. *J. Environ. Eng.* 3 2604
[23] Boyd G E, Adamson A W and Myres L S 1947 Kinetics of ionic exchange adsorption processes *J. Am. Chem.* 69 2836
[24] Pandey K K, Prasad G and Singh V N 1986 Mixed adsorbent for Cu(II)removal from aqueous solutions *Environ Technol. Lett.* 50 547
[25] Poots V J P, McKay G and Healy J J 1978 Removal of basic dye from effluent using wood as an adsorbent *J. Water Poll.* 50 926
[26] Lagergren S 1898 About the theory of so-called adsorption of soluble substances *Kungliga Svenska Vetenskapsakademiens Handlingar* 24 1
[27] Blanchard G, Maunaye M and Martin G 1984 Removal of heavy metals from waters by means of natural zeolites *Water Res.* 18 1501
[28] Ho Y S and McKay G 1998 Sorption of dye from aqueous solution by peat *Chem. Eng. J.* 70 115
[29] Azizian S 2008 Comments on “Biosorption isotherms, kinetics and thermodynamics” review *Sep. Purif. Technol.* 63 249
[30] Liu Y and Shen L 2008 From Langmuir kinetics to first- and second-order rate equations for adsorption *Langmuir* 24 11625
[31] Plazinski W, Dziuba J and Rudzinski W 2013 Modeling of sorption kinetics: the pseudo-second order equation and the sorbate intraparticle diffusivity *Adsorption* 19 1055
[32] Lu C, Su F and Hu S 2008 Surface modification of carbon nanotubes for enhancing BTEX adsorption from aqueous solutions *Appl. Surf. Sci.* 254 7035
[33] Chen W, Duan L and Zhu D 2007 Adsorption of polar and nonpolar organic chemicals to carbon nanotubes *Environ. Sci. Technol.* 41 8295
[34] Lu C, Chung Y.L and Chang K F 2005 Adsorption of trihalomethanes from water with carbon nanotubes *Water Res.* 39 1183
[35] Koh S-M and Dixon J B 2001 Preparation and application of organo-minerals as sorbents of phenol, benzene and toluene *Appl. Clay Sci.* 18 111
[36] Pourzamani H, Hajizadeh Y and Fadaye S 2015 Efficiency enhancement of multi-walled carbon nanotubes by ozone for benzene removal from aqueous solution *Int. J. Environ. Health Eng.* 4 29
[37] Abbas A, Abussaud B A, Al-Baghlani A, Redhwi H H and Zheng J 2017 Adsorption of toluene and paraxylene from aqueous solution using pure and iron oxide impregnated carbon nanotubes: kinetics and isotherms study *Bioinorg. Chem. Appl.* 2017 2853925