Do Adsorbent Pore Size and Specific Surface Area Affect The Kinetics of Methyl Orange Aqueous Phase Adsorption?

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Abstract

The kinetics of any adsorption reaction gives more information on the rate at which the adsorbate is taken up by the adsorbent, which is responsible for the residence time of an adsorbate uptake at the adsorbent-aqueous phase interface. This study was aimed at determining the effect of pore size as well as specific surface area (SSA) on the kinetics of the uptake of methyl orange (MO). The basis of the analysis was from data on kinetic models sourced from recent literature. ANOVA of the data revealed that statistical significance was achieved for SSA but not for pore size (at a significance level of 0.05). This called for a more theoretical perspective on the research data. The kinetics constant for micropores is far higher than for the two selected regimes of the mesopore. For the SSA, 100–10 m\(^2\)/g adsorbents had a higher mean \(k_2\) value. This suggested that adsorbents in the SSA range had pore sizes that favour rapid uptake. However, further studies will be needed to gain a better understanding of how SSA affects adsorption kinetics. The study also discussed the technical limitations that could arise due to the use of kinetic model linearisation.

1. Introduction

Adsorption is a very popular technique for the sequestration of pollutants such as dyes from the environment [1]. To obtain the optimum result in any adsorption study, the understanding of the following properties of the adsorbent is required; surface chemistry, hydrophilicity, physiochemical properties, proximate analysis, morphology, crystalline structure, and textural properties (pore size, pore volume, surface area, and pore surface) [2]. These characteristics are important in the selection of adsorbents for specific pollutants [3, 4]. The pore size of an adsorbent can be described as the gap or stretch of its pores. The pore size of adsorbents can be divided into three main groups as stated by the International Union of Pure and Applied Chemistry (IUPAC); micropores have pore sizes that are less than 2 nm, mesopores have pore sizes of 2–50 nm, and macropores have pore sizes more than 50 nm [5–8]. The specific surface area (SSA) is also one of the most important properties of adsorbent material as it indicates the necessary active sites for adsorption because adsorption is a surface phenomenon [9–11]. The surface area is directly proportional to the adsorptive performance of the material [12, 13].

Adsorption modelling is a very important aspect of any adsorption study as it applies adsorption models for the interpretation of experimental data to obtain useful information that would aid in the understanding of process mechanisms, process equilibrium-dynamics, predicting answers to operational condition changes and optimizing the adsorption process [14]. Common models used for understanding adsorption studies better are; thermodynamic models, isotherm models and kinetic models [15–18].

The time at which equilibrium is obtained is an important feature of any adsorption study. The kinetics of any adsorption reaction gives more information on the rate at which the adsorbate is taken up by the adsorbent, which is responsible for the residence time of an adsorbate uptake at the adsorbent-aqueous phase interface [14]. The adsorption kinetics also gives more information on the mechanism as well as a pathway for the reaction [19, 20]. The most common kinetic models used in adsorption studies which are classical models that fit adsorption data well even with non-linear methods are the pseudo-first-order (PFO) and the pseudo-second-order (PSO) models. The PFO model assumes that the adsorption process is dependent only on the concentration of adsorbate in the solution that is present at a specific time while the PSO model assumes that adsorption is a complex physico-chemical process that is dependent on the concentration of the adsorbate present in the system as well as the number of active sites on the adsorbent [21–23].

Methyl Orange (MO) (IUPAC: Sodium 4-[(4-(dimethylamino) phenyl)diazenyl] benzene-1-sulfonate) is a sulfonated azo anionic dye popularly known and used as a pH indicator in the titrations for acid and as a dye for textiles [24, 25]. It has a molecular formula C\(_{14}\)H\(_{12}\)N\(_3\)O\(_3\)NaS and a molecular weight of 327.34 g/mol. It is soluble in water and its density and melting point are 1.28 g/cm\(^3\) and > 300 °C [26, 27]. The molecular size of MO is 1.19 nm × 0.68 nm × 0.37 nm. It has a dissociation constant (pKa) of 3.47 in water at 25 °C [28–30]. MO is a toxic compound that deteriorates water quality and has been banned for use in food products because it is a carcinogen and teratogen due to the presence of aromatic and ~N = N~ groups inherent in its structure as shown in Fig. 1 [30, 31]. It usually gets into the environment in large quantities through the effluent of textile industries. Different techniques have been utilized in the removal of MO from the environment. They include electrocoagulation [32–35], ozonation [36–38], biological treatment [39], photo-degradation [40–42], membrane processes [43], and adsorption [44–46]. Due to the low cost and efficacy of adsorption, it is considered one of the best methods for the removal of MO dye from the environment [47–49].

This study is aimed at determining the relationship between pore size as well as specific surface area (SSA) on the kinetics of the uptake of methyl orange (MO) through the PFO and PSO kinetic models. Empirical findings obtained were analysed and juxtaposed to obtain observations. The reason for using MO in our study is due to its popularity as a pH indicator as well as a textile dye [50, 51]. The results of this study would be able to enable researchers to understand the adsorption process of MO better.

2. Methodology
2.1 Data Collection and description

For our study, published works of literature on the adsorption of Methyl Orange were obtained from the Google Scholar search engine. The search was restricted to articles published in the past five years (2016–2021) and which reported the pore size of the various adsorbents used. Based on the nature of the data, adsorbent of macropores size is unavailable for MO adsorption hence the study would focus more on micropore versus mesopore. Data on SSA was also added from articles where it was reported as shown in Table 1. The kinetic models used in this study were restricted to the PFO and the PSO models. The K values of the models were reported based on which of them was best-fit from the authors’ modelling study. The most widely reported index of kinetic modelling accuracy (being the coefficient of determination, $R^2$ was also reported. The modelling techniques were reported too, L being for linear modelling and NL being for non-linear modelling.

2.2 Research Problem

To verify the effect of pore size on adsorption kinetics, the data were analysed in a variety of ways. The key goal was to evaluate how pore size and SSA relates to the kinetic constants. The kinetic constant was used as the basis of the investigation because it is in the true sense an empirical constant. Hence comparison can be made across studies using it which extricates other adsorption factors. Furthermore, only methyl orange was used because it also helps to narrow down the factors by eliminating the effects of adsorbate properties on the solution chemistry. The study will try to evaluate if there was there a relationship from empirical investigations between pore size and SSA against MO uptake kinetics. The study also discusses the influence of the modelling technique (whether linear or non-linear) on adsorption kinetics [52].
| Adsorbent Name | Average Pore Size (nm) | SSA (m²/g) | K₁ (1/min) | r² | K₂ (g/mg.min) | r² | Modelling type | Ref. |
|----------------|-----------------------|------------|------------|----|--------------|----|----------------|-----|
| ZnO nanostructure | 51.60 | 7.780 | - | - | - | - | - | [53] |
| LDH/Fe₃O₄/polyvinyl alcohol | 42.00 | 87.00 | - | - | - | 0.9750 | L | [54] |
| Chitosan/ethylene glycol diglycidyl ether biofilm | 27.62 | 0.820 | - | - | - | 0.9900 | NL | [55] |
| Goethite/chitosan beads | 26.18 | 17.81 | - | - | - | 0.9965 | - | [56] |
| Flower-like NiAl LDH | 23.30 | 133.0 | - | - | - | 0.9990 | NL | [57] |
| Starch-modified ZnMgAl LDH | 23.10 | 76.80 | - | - | - | 0.9999 | NL | [58] |
| Biochar from waste walnut shells/TiO₂ | 22.70 | 66.06 | - | - | - | - | - | [59] |
| Polyethyleneimine-modified persimmon tannin | 19.54 | 8.130 | - | - | - | 0.9994 | L | [60] |
| [Cu(L)₂(H₂O)H₂(Cu(L)₂(P₂Mo₅O₂₃)).4H₂O/Fe₃O₄ | 19.43 | - | - | - | - | - | - | [61] |
| Au/Cu₂O | 18.30 | 16.00 | - | - | - | - | - | [62] |
| Bi₂O₃/TiO₂/powdered AC | 17.60 | 83.30 | - | - | - | 5.9620 | 1.0000 | - | [63] |
| Chitosan beads | 16.69 | 10.81 | - | - | - | 0.0003 | 0.9939 | NL | [56] |
| Co₃O₄ nanocube/polyaniline | 15.57 | 43.00 | - | - | - | 0.0006 | 0.9990 | L | [64] |
| Blast furnace slag acid-alkaline precipitate | 15.40 | 3.450 | - | - | - | 0.1590 | 1.0000 | L | [65] |
| Immobilized polyaniline | 14.70 | 8.500 | - | - | - | 0.0800 | 0.9900 | L | [66] |
| Graphene oxide/NiFe LDH | 14.60 | 145.0 | - | - | - | 0.0006 | 0.9990 | NL | [67] |
| Polyaniline nano-adsorbent | 13.82 | 10.44 | - | - | - | 0.0483 | 0.9447 | NL | [68] |
| Polyanilined-based nanoadsorbent | 13.82 | 10.34 | - | - | - | - | - | [69] |
| Fly ash | 13.54 | 1.180 | - | - | - | - | - | [70] |
| Trimeric surfactant-modified NA montmorillonite | 13.41 | 7.750 | - | - | - | 1.0230 | 0.9988 | L | [71] |
| Mesoporous ZIF-67/LDH | 13.24 | 172.3 | - | - | - | 0.0002 | 0.9998 | L | [72] |
| Silver NP/zeolite X | 12.42 | 552.6 | 0.3050 | 0.9820 | - | - | L | [73] |
| Hydrotalcite-like modified bentonite | 12.13 | 83.24 | - | - | - | 0.0050 | 0.9990 | NL | [74] |
| Magnetic lignin-based CNPs | 12.00 | 82.80 | - | - | - | 0.0008 | 0.9992 | L | [75] |
| CuO NPs | 11.61 | 6.188 | - | - | - | 0.0244 | 0.9980 | L | [76] |
| NiFe LDH nanoflakes/montmorillonite | 10.70 | 103.9 | - | - | - | 0.0017 | 0.9980 | NL | [77] |
| Goethite | 10.24 | 4.370 | - | - | - | 0.0004 | 0.9953 | NL | [56] |
| Calcium ferrite/zirconia | 10.18 | 95.32 | - | - | - | 0.0001 | 1.0000 | L | [78] |
| CuO nanostructures | 9.000 | 24.10 | - | - | - | - | - | [79] |
| MgAL-LDHs nanosheets | 8.870 | 65.94 | - | - | - | - | - | [80] |
| Dimeric surfactant-modified NA montmorillonite | 8.830 | 10.72 | - | - | - | 1.4510 | 0.9889 | L | [71] |
| Date palm ash/MgAl-LDH | 8.730 | 140.7 | - | - | - | 0.0013 | 0.9990 | NL | [81] |
| Catechol/amine resin | 8.590 | 13.13 | - | - | - | 0.0007 | 0.9997 | L | [82] |
| CoFe LDH | 8.400 | 108.8 | - | - | - | - | - | [83] |
| Adsorbent Name                                      | Average Pore Size (nm) | SSA (m²/g) | K₁ (1/min) | R²     | K₂ (g/mg.min) | R²     | Modelling type | Ref. |
|----------------------------------------------------|------------------------|------------|------------|--------|---------------|--------|---------------|------|
| CuAl LDH                                           | 7.358                  | -          | -          | -      | -             | -      | L             | [84] |
| Cetyltrimethylammonium bromide/H₂O₂-clay           | 6.804                  | 21.16      | -          | -      | 0.0250        | 0.9999 | L             | [85] |
| Bismuth nitrate NP                                 | 5.850                  | 5.290      | -          | -      | -             | 0.9998 | L             | [86] |
| Chitosan/Fe(OH)₃ beads                             | 5.710                  | 10.20      | -          | -      | 0.0068        | 0.9998 | L             | [87] |
| Manganese(l) ions-based MOF                       | 5.619                  | -          | -          | -      | -             | -      | -             | [88] |
| Mesoporous carbon                                  | 5.300                  | 2944       | -          | -      | 0.0002        | 1.0000 | L             | [89] |
| TiO₂/aluminosilicate zeolite (ZSM-5)               | 5.200                  | 1151       | -          | -      | -             | 0.9994 | L             | [90] |
| Mesoporous carbon nanofibers                       | 5.000                  | 392.3      | -          | -      | 0.0002        | 0.9967 | L             | [91] |
| ZnO/polyaniline                                    | 5.000                  | 63.17      | -          | -      | 0.0012        | 0.9990 | L             | [92] |
| γ-Fe₂O₃/2C nanocomposites                          | 4.965                  | 394.1      | -          | -      | 0.0024        | 0.9996 | NL            | [93] |
| MOF-derived nanoporous carbon                      | 4.770                  | 1731       | -          | -      | 0.0011        | 0.9937 | NL            | [94] |
| Cd-zeolite imidazolate framework (Cd-ZIF-8)        | 4.700                  | 1281       | -          | -      | 0.0080        | 0.9900 | NL            | [95] |
| Nitrogen-doped mesoporous carbon                   | 4.200                  | 1259       | -          | -      | -             | -      | -             | [96] |
| Porous ZnO spheres                                 | 4.150                  | 114.6      | -          | -      | -             | -      | -             | [97] |
| Al-doped CNTs                                      | 3.820                  | 118.8      | -          | -      | 0.0044        | 0.9990 | NL            | [98] |
| Stone-like NiAl LDH                                | 3.800                  | 90.00      | -          | -      | 0.0015        | 0.9900 | NL            | [57] |
| Nanoporous carbon                                  | 3.700                  | 814.0      | -          | -      | 0.1490        | 0.0760 | L             | [99] |
| NiO NPs                                            | 3.492                  | 78.37      | -          | -      | 0.0002        | 0.9900 | L             | [76] |
| AC from sugarcane mills boiler residue             | 3.372                  | 1073       | -          | -      | 0.0001        | 0.9923 | L             | [100]|
| CoAl/Cl LDH                                        | 3.344                  | 19.70      | -          | -      | 0.0002        | 0.9890 | NL            | [101]|
| Mesoporous MCM-41                                  | 3.280                  | 1451       | -          | -      | 0.0057        | 0.9995 | L             | [102]|
| p-CNTs/N,N-diethylethanol ammonium chloride        | 3.009                  | 169.7      | -          | -      | 0.0001        | 0.9900 | L             | [103]|
| Nitrogen-doped mesoporous carbon                   | 3.000                  | 968.0      | -          | -      | -             | -      | -             | [104]|
| NDA88 MOF/Cu                                       | 2.990                  | 370.4      | -          | -      | -             | -      | -             | [105]|
| Calcined organic matter-rich clays from Egypt       | 2.988                  | 48.32      | -          | -      | 0.0370        | 0.9999 | L             | [106]|
| Organic matter-rich clays from Egypt               | 2.930                  | 59.14      | -          | -      | 0.0940        | 1.0000 | L             | [106]|
| Fe₂O₃/Mn₃O₄ magnetic nanocomposites                | 2.870                  | 178.3      | -          | -      | 0.0003        | 0.9998 | L             | [107]|
| Copper sulphide NPs/AC                             | 2.840                  | 1286       | -          | -      | 0.0300        | 0.9900 | L             | [108]|
| Magnetic nanoporous Fe/MCM-41                      | 2.840                  | 1216       | -          | -      | 0.0057        | 0.9995 | L             | [102]|
| Ni-Co/S/hexadecyltrimethyl ammonium bromide        | 2.780                  | 12.73      | -          | -      | 0.0237        | 0.9962 | NL            | [109]|
| Fe₃O₄/AC                                           | 2.750                  | 1200       | -          | -      | 18.950        | 0.9999 | NL            | [110]|
| Organosilica                                       | 2.700                  | 10.00      | -          | -      | 0.0001        | 0.9860 | NL            | [111]|
| AC from popcorn                                     | 2.580                  | 3291       | -          | -      | -             | -      | -             | [112]|
| AC from coconut shell                              | 2.520                  | 1640       | -          | -      | 0.2266        | 0.9959 | L             | [113]|
| AgGaO₂ nanocomposites                              | 2.500                  | 23.35      | -          | -      | -             | -      | -             | [114]|
| p-CNTs/chlorine chloride                           | 2.413                  | 197.8      | -          | -      | 0.00003       | 0.9900 | L             | [103]|

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| Adsorbent Name | Average Pore Size (nm) | SSA (m²/g) | K₁ (1/min) | R² | K₂ (g/mg.min) | R² | Modelling type | Ref. |
|----------------|-----------------------|------------|-------------|----|---------------|----|---------------|------|
| Nickel hydroxide catalysts | 2.400 | 87.00 | - | - | - | - | - | [115] |
| Nano ZnO/mesoporous silica | 2.176 | 849.0 | 0.0182 | 0.9931 | - | - | L | [116] |
| Chitosan/Al₂O₃/Fe₃O₄ | 2.122 | 21.87 | - | - | 0.0173 | 0.9977 | L | [117] |
| Non-functionalized CNTs (p-CNTs) | 2.049 | 123.5 | - | - | 0.00004 | 0.9900 | L | [103] |
| TiO₂/slag-made calcium silicate | 2.030 | 149.0 | - | - | - | - | - | [118] |
| Carbon nanostructure from Bengal gram bean husk | 1.940 | 1710 | - | - | 0.00243 | 1.0000 | L | [119] |
| Pomelo peel-derived porous carbon | 1.920 | 1892 | - | - | 0.0022 | 0.9939 | L | [120] |
| Polyaniline/AC | 1.840 | 36.00 | - | - | 0.0002 | 0.9996 | L | [121] |
| Polyvinylene fluoride/PEDOT mats | 1.807 | 5.691 | - | - | 0.0004 | 0.9990 | NL | [122] |
| Mg NP/modified nanosized Si₃N₄-Al₂O₃ | 1.800 | 410.0 | - | - | 0.1960 | 0.9990 | NL | [123] |
| NiFe LDH | 1.800 | 17.85 | - | 0.9998 | - | - | L | [124] |
| Nitrogen-doped nanoporous carbon | 1.730 | 1152 | - | - | 0.0810 | 0.9980 | L | [125] |
| Uio-66 MOF | 1.700 | 1276 | - | - | 0.0062 | 0.9990 | L | [126] |
| Fe₂O₃/biochar | 1.700 | 15.30 | - | - | 12427 | 0.9990 | L | [127] |
| Ag-N-ZnO/coconut husk AC | 1.350 | 472.0 | - | - | 0.0037 | 0.9862 | NL | [128] |
| TiO₂/pure calcium silicate | 1.340 | 126.0 | - | - | - | - | - | [118] |
| Tungstosilicic acid/zeolites | 1.000 | 26.0 | - | - | - | - | - | [129] |
| Activated biochar from pomelo peel waste | 0.940 | 75.32 | - | - | 0.0007 | 0.9840 | L | [130] |
| Al-doped MOF/graphene oxide | 0.600 | 139.0 | - | - | 0.0060 | 1.000 | NL | [131] |
| Cd-based MOF | 0.246 | 384.0 | - | - | 200.00 | 0.9990 | L | [132] |
| N-acyl thiolated chitosan | 0.214 | 10.00 | - | - | 0.0150 | 0.9999 | NL | [133] |
| Salecan polysacharides | 0.109 | - | - | - | - | - | 0.9941 | L | [134] |
| Mesoporous MCM-41/microfiltration membrane | 0.0002 | 1451 | - | - | 0.0078 | 0.9998 | L | [135] |

2.3 Data analysis

Statistical analysis of the data was done using one-way analysis of variance (ANOVA) and descriptive statistics such as coefficient of variance (CV), coefficient of determination (R²) and root mean square error (RMSE). This analysis was done using Origin Pro 2017 (OriginLab Co., Wellesley, MA, USA). Other analyses for the determination of means was done using Microsoft excel 2016 (Microsoft Inc., Redmond, WA, USA).

3. Results And Discussion

3.1 Statistical analysis of the data

From Table 1, the pseudo-second-order kinetics was best-fit in most of the cases. Hence its kinetics constant (k₂) is the selected basis for this investigation. Firstly, before the data can be used for this analysis, we first need to verify if there is any statistical relationship between the pore size and specific surface area against the kinetic constant. This was done by the one-way ANOVA and descriptive statistics such as CV, R² and RMSE. From Table 2, statistical significance (at a threshold of Prob > F being 0.05) was achieved for SSA but not for pore size. What this simply means is that a holistic consideration of the data revealed specific trends between SSA and the kinetics constant while this was not so for the case of pore size. It is also unsurprising that the descriptive statistics are also correspondingly poorer for pore size. This does not however...
invalidates the data since the statistical significance only verifies if the results in the dataset are due to chance or some specific factors. A more theoretical perspective will be needed to properly consider the data.

| Result                              | SSA          | Pore size |
|-------------------------------------|--------------|-----------|
| F – value (One-way ANOVA)           | $4.33 \times 10^{10}$ | 0.04761   |
| Prob > F (One-way ANOVA)            | $2.31 \times 10^{-11}$ | 1.000     |
| Coefficient of determination ($R^2$) | 1.000        | 0.4919    |
| Coefficient of variance (CV)        | $3.79 \times 10^{-5}$ | 25.57     |
| RMSE                                | 0.00752      | 5073      |

### 3.2 Theoretical consideration of the effect of pore size on MO adsorption kinetics

Empirical evidence cannot be summarily dismissed due to a lack of statistical relationship. Statistics try to evaluate trends based on a holistic computation of the dataset. This does not consider some known theoretical understanding of adsorption. For this case, we are considering the 2 nm pore size threshold. This will be used to differentiate between the micropore and the mesopore. Based on this, we can then summarise the data as shown in Table 3. Considering magnitudes, it is observed that the kinetics for micropores is far higher than for the two selected regimes of the mesopore. We believe this is a bias induced by the uncharacteristic results obtained by Chaukura, Murimba [127] for Fe$_2$O$_3$/biochar adsorption of MO. If this value is excluded, we still obtain a mean $k_2$ value of 34.1 which is still significantly higher than for mesopores. The molecular size of MO is 1.19 nm × 0.68 nm × 0.37 nm. This dimension suggests that it would quickly fill up a pore of the average diameter of 2 nm as opposed to larger mesopores. This quickness is what is captured by the rate constant.

| Regime | Pore size (nm) | Mean $k_2$ (g/mg.min) |
|--------|----------------|------------------------|
| Mesoporous | 50–10         | 0.3659                 |
| Mesoporous | 10–2          | 0.6788                 |
| Microporous | <2            | 919.3                  |

### 3.3 Theoretical consideration of the effect of SSA on MO adsorption kinetics

In this section, we investigate the possible effects of SSA on MO adsorption kinetics. A simple summary of the results is presented in Table 4. For the SSA, 100–10 m$^2$/g adsorbents had a higher mean $k_2$ value. This suggests that adsorbents in the SSA range had pore sizes that favour rapid uptake (which we have already earlier observed to be micropores). The SSA of a material is only closely related to its total pore volume. Pore diameters are controlled more by the method and parameter of adsorbent preparation and on the intrinsic nature of the feedstock. Hence, further studies will be needed to gain a better understanding of how SSA affects the adsorption kinetics (if at all it does).

| SSA (m$^2$/g) | Mean $k_2$ (g/mg.min) |
|---------------|------------------------|
| 3000–1000     | 17.49                  |
| 1000–100      | 12.52                  |
| 100–10        | 460.5                  |
| 10–0          | 0.1616                 |
3.4 Technical issues with kinetics modelling

In this section, we discuss the technical issues around the modelling of adsorption kinetics, albeit from a mathematical perspective. In Table 1, we reported the technique used by various studies for modelling adsorption. A majority of the studies used the linear modelling technique while others employed non-linear modelling. Tran, You [2] explained that the kinetics of adsorption can be very rapid. In some cases, over 90% of the adsorbate can be removed within the first 5 minutes of the process. Most experiments usually employed a protracted contact time because the adsorption process becomes significantly less rapid as equilibrium is approached. Simonin [136] has explained that serious biases that favour the PSO model are created because of this extended portion of the contact time when kinetics is slow and equilibrium is close. Such vast differences in adsorption kinetics can be difficult to capture by a linearised model. This led to the issues raised by Lima, Sher [137]. Lima, Sher [137] observed that researchers seem too confident in employing linear techniques because of their perceived similarity with non-linear modelling when comparing their R^2 and adjusted R^2. This did not take into cognisance the dissimilarities and inconsistencies in the obtained rate constants [138, 139]. In some scenarios, studies with PFO as best-fits were erroneously assigned as having PSO as best-fit. It is by consequence not surprising that most of the studies in Table 1 have the PSO as best-fit. Besides the use of just the R^2 for determining goodness of fit, Aniagor, Igwegbe [22] recommended including other accuracy statistics in making this decision (which are still not commonly employed in literature in this respect). Increment in the degree of freedom of a given kinetics data set will unfairly favour the model fit. Hence this suggestion.

4. Conclusion

Some unique observations were derived in this study, albeit MO adsorption. ANOVA of the data revealed that statistical significance (at a threshold of Prob > F being 0.05) was achieved for SSA but not for pore size. This does not however invalidate the data since the statistical significance only verifies if the results in the dataset are due to chance or some specific factors thereby requiring a more theoretical perspective. It was observed that the kinetics for micropores is far higher than for the two selected regimes of the mesopore. Based on the molecular size of MO, the compound would quickly fill up a pore of the average diameter of 2 nm as opposed to larger mesopores. This quickness is what is captured by the rate constant. For the SSA, 100–10 m^2/g adsorbents had a higher mean k_2 value. This suggested that adsorbents in the SSA range had pore sizes that favour rapid uptake (which we have already earlier observed to be micropores). However, further studies will be needed to gain a better understanding of how SSA affects the adsorption kinetics (if at all it does).

Declarations

Disclosure statements

Conflict of Interest: The authors declare that there are no conflicts of interest.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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Figures
Figure 1

Chemical structure of methyl orange