Chlorinated phenol removal from aqueous media by tea (Camellia sinensis) leaf waste tailored activated carbon

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Abstract. In this study, activated carbons (ACs) were prepared from tea leaves by using a two-stage self-generated atmosphere method. The process was done by semi-carbonizing the precursor at 300 °C for 1 h, followed by the impregnation of the resulting char at 85 °C for 4 h and finally activation at 500 °C for 2 h. The semi-carbonised samples were impregnated with different ratios of zinc chloride (ZnCl2) and their physicochemical effect was studied. The prepared ACs underwent several aspects of both, chemical and physical characterizations, such as the percentage of yield, moisture content, ash content, pH, porosity, adsorption capacity of 2,4-dichlorophenol (2,4-DCP), surface area, porosity, morphology and surface chemistry studies. It was found that sample AC2, with an impregnation ratio of 2:1 was the best AC produced in this study. The maximum Brunauer, Emmett and Teller surface area of AC2 was found to be 695 m²/g. Langmuir, Freundlich and Temkin isotherm models were used to examine the experimental isotherms while the kinetic data was analyzed using the pseudo-first-order, pseudo-second-order and intraparticle diffusion kinetic models. The 2,4-DCP adsorption isotherm results complied well to the Langmuir isotherm for the equilibrium data while the adsorption kinetic data fitted well to the pseudo-second order model, indicating that chemisorption by valency forces via the sharing (covalent bond) or exchanging of electrons between the AC and the 2,4-DCP molecules were mainly responsible for the adsorption process. From these findings, it is concluded that tea leaves can be used as a low cost precursor for the removal of 2,4-DCP in aqueous medium.

1. Introduction
2,4-Dichlorophenol (2,4-DCP) is one of the constituent of pollutant found in wastewater and sewage. It is used in the manufacture of pesticides, germicides, resins, seed disinfectants, and antiseptics; therefore it can be found in degraded herbicides, saw mills, wood waste incinerators and hazardous waste sites [1]. The main threat of 2,4-DCP is to human health. Of the various water treatments methods have been employed to remove this toxic pollutant using chemical, biological, physicochemical and mechanical methods, adsorption using activated carbon (AC) is one of the most promising solutions due to its inert properties, low cost factor and ease of disposal of the spent carbon [2-7].

The unique characteristics of AC, such as the large surface area, highly developed porosity and high adsorption capacity makes it useful for a wide range of applications. Other than that, AC is suitable for the removal of pollutants because it is resistant to heat, acid, alkali, do not swell or shrink when expose to different pH conditions, and has good mechanical strength [8]. Due to these reasons, AC is commonly regarded as an excellent adsorbent and is more commonly used in environmental applications for removing pollutant.

The preparation of AC is considered expensive as the precursor undergoes physical and chemical treatment but produces a low yield. It requires high energy consumption during production and
subsequent thermal treatments for its regeneration while resulting in mass loss during the regeneration process (Peláez-Cid and Teutli-León 2012) [9]. Not only that, most of the commercial AC are coal based or petroleum pitch based which is a non-renewable resource and costly precursor. This limits the production and usage of AC. Other than that, it is reported that the cost of AC is expected to rise as the annual consumption of AC is growing at 9% per annum [10].

Numerous studies were done revolving around the preparation of AC from precursors which are low-cost, renewable organic by-products. Wood and coconut shells have been used to replace coal and charcoal. They have been the major precursors for AC with annual world production of 300,000 MT. The selection of precursor depends on availability, cost and purity. Precursors have to be materials with high carbon content and low ash content for a more promising yield during production (Hernández-Montoya & Bonilla-Petriciolet, 2012). Due to this factor, researchers have studied many agricultural by-products such as pistachio shell, cotton stalks, acorn shell, bagasse and rice husk, corn cob, safflower seed, press cake, elaeagnusangustifolia seeds, barley husk, nutshells, wood sawdust, jackfruit peel, orange peel, etc. for the preparation of AC [10, 12-23].

Tea leaf waste is easily available all over the world and it has a great potential to be used as a precursor to prepare AC [24 & 25]. Tea is the second largest consumed beverage after water with a worldwide per capita consumption of approximately 0.12 L/year [26]. In 2011, Food and Agriculture Organization of the United Nations ranked Malaysia as the 18th largest tea producer in Asia. Tea leaves are lignocellulosic biomass, as the cell wall of tea consists of cellulose and hemicelluloses, lignin, condensed tannins and structural proteins [27]. Tea leaves have low ash content varying from 3-8% of the tea leaf’s total weight making it suitable for preparation of AC [26].

Therefore, in this study, tea leaves (Camellia sinensis) were used as the precursor for an alternative sorbent and experiments were conducted to determine its effect on the removal of 2,4-DCP from aqueous solution with the intention of replacing AC for water treatments commercially. The AC was produced using a two-stage self-generated atmosphere method. Zinc chloride (ZnCl₂) was used as the dehydrating agent with a fixed ratio of activating agent to precursor used. In the previous method, the precursor would be impregnated with the dehydrating agent prior to carbonisation and activation. However, in this novel method, the precursor was charred before the impregnating process and then activated in a furnace. This gave some very interesting findings which are reported here.

2. Experimental
2.1. Preparation of AC
In this study, tea leaves (1-2 mm) from Camellia sinensis species were used as a precursor to produce the activated carbon using the two-staged self-generated atmosphere method. Firstly, the tea leaves were soaked and washed with hot water several times to remove the soluble and coloured components. The washed samples were dried in an oven at 110 °C for 24 h. The dried samples were semi-carbonized at 300 °C for 1 h under self-generated atmosphere in a muffle furnace and then left to cool down to room temperature inside the muffle furnace. The semi-carbonized samples were agitated with 200 mL of aqueous solution containing varying ZnCl₂ to tea leaf (dry weight) ratio. The impregnation ratios were altered based on weight; weight of ZnCl₂: y from 1:1 to 5:1 producing samples AC1-AC5. The chemical activating agent and semi-carbonized samples were homogeneously mixed at 85 °C for 4 h. After mixing, the mixture was dried in an oven at 110 °C for 24 h. The resulted samples were then activated in a muffle furnace under self-generated atmosphere at 500 °C for 2 h, and allowed to cool to room temperature before removal for further analysis [28].

2.2. Washing Process
Traditional water-washing cannot effectively remove the chemical residues which is deep within the AC as this in turn may reduce the total pore volume. As such, acid-washing procedure was employed to wash away the chemical residue. The activated sample was soaked with a 0.01 M hydrochloric acid (HCl) solution, at 85 °C for 30 min, to eliminate excess ZnCl₂. The liquid was filtered away using filter
paper. The sample was then washed with hot distilled water several times to remove the residual acid. Finally the sample was washed with distilled water. The washed samples were dried in an oven at 110 °C for 24 h to get the final product [29].

2.3 Characterization of AC
Moisture content was determined according to the ASTM D2867–04 standard whereas ash content was determined using the ASTM D2866 – 94 standard. Details for determination of the percentage of yield, moisture content, ash content and pH were described in our previous work (Anisuzzaman et al, 2015a). Surface chemistry of the prepared carbon was analyzed using Fourier Transform Infrared (FTIR) spectroscopy (Thermo Nicolet NEXUS 670) analysis to determine the surface functional groups, where the spectra were recorded in the range of 4000-650 cm\(^{-1}\). Scanning Electron Microscope (SEM) (JEOL JSM-5610LV, Japan) at 20 kV was used to observe morphological surface structure of the ACs. The specific surface area and the pore-size distribution were determined using the Brunauer, Emmet and Teller (BET) and Barret, Joyner and Halenda (BJH) methods, respectively. The BET surface area and pore size distribution were determined from nitrogen isotherm at 77.3 K using Quanta chrome autosorb automated gas sorption instrument [2].

2.4 Adsorption capacity of 2,4-DCP
0.5g of AC sample was added into 5 different 1000 mL Erlenmeyer flask with each flask filled with 400 mL of 40 mg/L 2,4-DCP and agitated for 3h at room temperature. The solution was extracted using a syringe and then filtered using a Sterlitech 45 µm syringe filter to make the solution adsorbent free. The solution concentration was determined by using UV-Vis spectroscopy at a wavelength of 285 nm to determine 2,4-DCP uptake. The sample with best adsorption capacity was used for subsequent batch adsorption tests. Adsorption capacity was displayed as adsorption percentage, indicating the amount of 2,4-DCP adsorbed and it was calculated using the formula as below:

\[ \%e = \frac{c_i - c_t}{c_i} \times 100 \]  \hspace{1cm} (1)

where \( c_i \) is the Initial concentration of adsorbate solution, mg L\(^{-1}\) and \( c_t \) is the concentration of adsorbate solution at time \( t \), mg L\(^{-1}\).

Batch adsorption tests were carried out with differing adsorbent dosage (0.1, 0.3 and 0.5 g), pH (3, 7 and 9) and initial 2,4-DCP concentration (10, 20, 30 and 40 mg/L).

2.5 Adsorption isotherms
The resulting data was analysed using Langmuir, Freundlich and Temkin isotherm models. Linearized form of the model equations are shown as below:

\[ \frac{c_e}{q_e} = \frac{1}{q_m} + \frac{1}{q_m K_L} c_e \]  \hspace{1cm} (2)

\[ \log q_e = \log K_F + \frac{1}{n} \log C_e \]  \hspace{1cm} (3)

\[ q_e = \frac{RT}{b} \ln K_T + \frac{RT}{b} \ln c_e \]  \hspace{1cm} (4)

where, \( q_m \) is the Langmuir constant (mg g\(^{-1}\)); \( K_L \) is the Langmuir rate constant (L mg\(^{-1}\)); \( K_F \) is the Freundlich rate constant; \( K_T \) is the Temkin rate constant or adsorption potential (L mg\(^{-1}\)); \( b \) is the heat of adsorption (kJ mol\(^{-1}\)); \( R \) is the gas constant; \( T \) is the absolute temperature (K). A plot of \( c_e/q_e \) against \( c_e \); \( \log q_e \) against \( \log c_e \) and \( q_e \) against \( \ln c_e \) was done for Langmuir isotherm; Freundlich isotherm and for Temkin isotherm respectively.
2.6 Adsorption kinetics

For adsorption kinetics, pseudo-first-order, pseudo-second-order and intraparticle diffusion model were used to analyse the experimental data. Linearized form of the model equations are shown as below:

\[ \log(q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \]  
\[ \frac{t}{q_t} = \frac{1}{q_e} + \frac{1}{k_2 q_e^2} \]  
\[ q_t = k_{id} t^{0.5} + C \]

where, \( q_e \) and \( q_t \) is the amount of 2,4-DCP adsorbed by AC at equilibrium and time \( t \) respectively (mg g\(^{-1}\)); \( t \) is time (min); \( k_1 \) is the rate constant for pseudo-first-order (min\(^{-1}\)); \( k_2 \) is the rate constant for pseudo-second-order (g mg\(^{-1}\) min\(^{-1}\)); \( k_{id} \) is the rate constant for intraparticle diffusion (mg g\(^{-1}\) min\(^{0.5}\)); \( C \) is the plot intercept. A plot of \( \log(q_e - q_t) \) against \( t \); \( t/q_t \) against \( t \) and \( q_t \) against \( t^{0.5} \) was done for pseudo first-order model, pseudo-second-order model and intraparticle diffusion model respectively.

3. Results and discussion

3.1 Physical Characterization

The yield percentage, moisture and ash content along with pH of AC1-AC5 are shown in Table 1. It can be seen that the total yield percentage increased in proportional to the increased ZnCl\(_2\) impregnation ratio with the exception of AC5, which reduced to 50.015%. The moisture content of ACs also showed a gradual increment when ZnCl\(_2\) impregnation ratio increases. Ash content of ACs range from 13.989\% to 28.398\% with AC2 having the lowest ash content whereas AC5 having the highest ash amount. Ash content does not show any trend with the increasing ZnCl\(_2\) impregnation ratio. pH of ACs did not show drastic changes as it stayed between 5.80 and 5.95. When compared to the work done by Gundogdu et al. [24] the moisture content showed a better result while the yield and the ash content of this work was less favourable.

Table 1. ACs with their relative yield percentage, moisture, ash and pH

| Sample | Yield, (%) | Moisture content (%) | Ash content (%) | pH |
|--------|------------|----------------------|----------------|----|
| AC1    | 22.568     | 3.629                | 28.226         | 5.85 |
| AC2    | 30.271     | 4.537                | 13.989         | 5.95 |
| AC3    | 43.832     | 4.742                | 17.938         | 5.87 |
| AC4    | 64.327     | 4.790                | 15.968         | 5.83 |
| AC5    | 50.015     | 5.477                | 28.398         | 5.80 |

3.2 Surface Functional Group of AC

FTIR spectras of the tea leaves and ACs are shown in Fig. 1 and Fig 2. The band at 3400, 2923, 2851, 2366 and 1628.18 cm\(^{-1}\) were contributed by OH stretching vibration in hydroxyl group, asymmetric C-H, symmetric C-H, saturated C-H stretching and aromatic ring vibration (vibration mode of olefinic C=C bonds) respectively. The bands around 1383.44 cm\(^{-1}\) and 1436.84 cm\(^{-1}\) consists carboxylic-carbonate groups, C=O and nitrate groups, N=O. The band present around 1156-1103 cm\(^{-1}\) indicates C-C, C-O-H and C-O-C stretch in primary and secondary alcohol. The bands at 876.14 and 609.15 cm\(^{-1}\) were contributed by C-C stretching and -C-C- group respectively. The band at 2923, 2851 and 876.14
cm$^{-1}$ disappeared in the FTIR spectra of ACs but is present in FTIR spectra of the tea leaves. Comparison of tea leaves and AC samples showed that the intensities were stronger in tea leaves and was weakened after the precursor was carbonized and activated. The combined FTIR of AC1-5 is shown in Fig. 2. As shown in Fig. 2 that intensities decrease as impregnation ratios increased.

![Figure 1. FTIR of tea leaves](image1)

![Figure 2. FTIR of combined AC1-5](image2)

### 3.3 Morphological Study of AC

SEM was used to compare the morphology of tea leaves and AC. It was also used to compare the morphology of AC of different impregnation ratio. The micrographs are shown in Fig. 3 (a-f). Before activation, it can be seen that there are plenty fibres on the surface of tea leaves and pores cannot be found on the surface. Other than that, it can also be observed that with each different impregnation ratio, the surface morphology also changes as there are no similarities among the five activated carbon samples. Among the five different AC samples, porosity in AC1 and AC3 were not displayed well, however pore channels still can be observed. Photos of AC2 and AC4 are able show large pores clearly. Micrograph of AC2 with magnification of shows the pores are attached to the pore channels. The pore structures in AC4 closely resemble those of sponge-like structures and the pores have an opening larger than 10µm. In the micrograph of AC5, pores can be seen however the surface looks damaged. In overall, the ACs show some form of irregularities which is probably caused by impurities or the ZnCl$_2$ residue.
3.4 Specific Surface Area and Pore-distribution

Table 2 contains the porous and surface characteristics data of tea leaves. Fig. 4 shows the isotherms from N$_2$-sorption measurements of the Tea leaves which contain specific information on the porosity of the particles at the temperature of liquid nitrogen. Type I isotherm with no hysteresis loop was observed for the selected adsorbent, AC$_2$. This type of isotherm pattern is identified as a single-molecule adsorption process. The characteristic of this isotherm is demonstrated by a continuous increase in the adsorption volume until the relative pressure reaches and exceeds a certain value. This isotherm corroborate with the calculated Langmuir isotherm model which indicates monolayer coverage with chemisorption properties due to the compliance with the pseudo-second-order reaction kinetics. This type of corroboration is typical for adsorption in microporous solids (Anisuzzaman et al., 2015a).

![Figure 3. SEM micrographs at magnification of x1000 for (a) tea leaves, (b) AC1, (c) AC2, (d) AC3, (e) AC4 and (f) AC5](image-url)
Table 2. ACs with their relative yield percentage, moisture, ash and pH

| Surface area                                      |          |
|--------------------------------------------------|----------|
| Langmuir surface area, m$^2$/g                   | 6.95x10$^2$ |
| BJH method cumulative adsorption surface area, m$^2$/g | 6.13x10$^2$ |
| BJH method cumulative desorption surface area, m$^2$/g | 6.52x10$^2$ |

| Pore volume                                      |          |
|--------------------------------------------------|----------|
| BJH method cumulative adsorption pore volume, cc/g | 0.22x10$^{-2}$ |
| BJH method cumulative desorption pore volume, cc/g | 0.23x10$^{-2}$ |

| Pore size                                         |          |
|--------------------------------------------------|----------|
| Average pore diameter, Å                          | 25.70    |
| BJH method adsorption pore diameter (mode), Å     | 8.82     |
| BJH method desorption pore diameter (mode), Å     | 9.09     |

Figure 4. Nitrogen adsorption-desorption isotherm for tea leaves

3.5 Adsorption capacity of the ACs

The adsorption capacity data are presented in Table 3 and it shows that AC2 has the highest adsorption capacity among the different ratio impregnated ACs. AC2 was capable of removing up to 95% while AC5 gave the lowest adsorption capacity, with only 75% of the target pollutant removed from the solution. This can be explained by comparing the ash content of AC1 and AC5. AC2 shows a high removal percentage of 2,4-DCP due to the lowest ash content and a fairly low moisture content. Since AC2 gave the best adsorption capacity, it was used to carry out the batch adsorption tests, adsorption
kinetics and adsorption isotherm analysis. For batch adsorption studies, the adsorption dosage is related to the removal efficiency. As such, it can be seen that using 0.5 g of AC2 effectively removed up to 95% of 2,4-DCP from the solution as compared to 43.5 % and 67% of 0.1 and 0.3g of AC2, respectively. Therefore to effectively remove the pollutant from an aqueous solution, a sufficient amount of AC is required to ensure the optimum adsorption removal. The pH of the solution is one of the important parameters affecting adsorption efficiency. Removal of 2,4-DCP was optimal under acidic condition. At pH 3, the adsorption percentage reached 95.25 % however under neutral condition, the percentage reaches 94.25 % whereas under basic condition, the percentage only reaches 93.50 %. The adsorption percentage only reduced when the solution pH shifted away from acidic to basic medium. It can explained that at high pH, 2,4-DCP anions will be formed, which will repel the negatively charged activated carbon thus reducing the adsorption efficiency. This concludes that in order to remove 2,4-DCP from a solution using AC, the solution pH should be adjusted to acidic condition to allow for optimal removal.

Table 3. Adsorption test result for (a) adsorption capacity, (b) AC dosage, (c) pH and (d) initial 2,4-DCP concentration

| Parameters                  | Adsorption percentage, % |
|-----------------------------|---------------------------|
| Adsorption capacity         |                           |
| AC1                         | 83.00                     |
| AC2                         | 95.00                     |
| AC3                         | 92.75                     |
| AC4                         | 90.00                     |
| AC5                         | 75.00                     |
| Adsorbent dosage, g         |                           |
| 0.1                         | 43.50                     |
| 0.3                         | 67.00                     |
| 0.5                         | 95.00                     |
| pH                          |                           |
| 3                           | 95.25                     |
| 7                           | 94.25                     |
| 9                           | 93.50                     |
| Initial adsorbate concentration, mg L⁻¹ |                   |
| 10                          | 98.00                     |
| 20                          | 97.50                     |
| 30                          | 96.33                     |
| 40                          | 95.00                     |

Altering the initial concentration of 2,4-DCP gave varying results. When the solution had low initial concentration, the available surface and pores for adsorption was abundant but at higher initial concentration, these properties became the limiting factor and as a result, the removal percentage decreases. At 10 mg/L, 0.5 g of AC2 can remove the pollutant up to 98 % whereas in 40 mg/L, only 95% was removed. Although the differences are small, it can be concluded that the initial pollutant concentration in the solution has to be evaluated prior to determining the suitable amount of AC to be used in the treatment process.

3.6 Adsorption Isotherms of the ACs

The plot for Langmuir, Freundlich and Temkin are shown in Fig. 5 whereas the data is shown in Table 4. \( R_L \) for Langmuir isotherm was found to be 0.023; which was in between 0 and 1, indicating that the adsorption was favourable for monolayer adsorption process. The maximum adsorption capacity, \( q_m \) was calculated from the plot was capable of adsorbing 44.25 mg of 2,4-DCP per gram of AC2. The value of \( 1/n \) obtained from Freundlich isotherm is less than 1, indicating that the adsorption was a normal adsorption process while \( n = 1.7058 \), indicates that it was a favourable adsorption (multi-layer
adsorption process). $K_F$ shows a fairly large value which shows that there was an adsorption intensity during the adsorption process. The heat of adsorption, $b$ obtained from Temkin isotherm equalled to 0.2528 kJ mol$^{-1}$ indicating a physical adsorption process. Compliance with all three isotherms indicated that the adsorbate (2,4-DCP) can bind to more than one surface on the adsorbent. When compared among the three adsorption isotherm models, Freundlich had a lower $R^2$ of 0.9852 whereas Temkin had a higher $R^2$ value of 0.9939 but Langmuir has the highest $R^2$ of 0.997. Although both Freundlich and Temkin have high $R^2$ value, Langmuir isotherm showed the best fitting. This indicates that the adsorption of 2,4-DCP taking place with the AC was mainly monolayer.

![Figure 5](image)

**Figure 5.** (a) Langmuir plot, (b) Freundlich plot (c) Temkin plot

Figure 6 (a) shows the uptake rate of 2,4-DCP for 3 h of period. It can be observed that at 90 min onward when adsorption percentage reached 90%, the uptake process was slowed down and stayed around 95%. The calculated $q_e$ and rate constant for both the pseudo-first-order and pseudo-second-order was calculated from the intercept and slope of the plot.

The plot for pseudo-first-order, pseudo-second-order and intraparticle diffusion is shown in Fig. 6 (b), (c) and (d) respectively whereas the data is shown in Table 5. The $q_e$ from experiment and the $q_e$
calculated from the pseudo-first-order showed a large difference. The experimental $q_e$ is more similar to the one calculated from pseudo-second-order model. Not only that, the coefficient of correlation shows that the data does not fit well to pseudo-first order model with $R^2$ of only 0.9681 when compared to pseudo-second-order with a $R^2$ of 0.9998 which is closer to 1.

For the intraparticle diffusion plot, two slopes were observed. The slope does not pass through the origin, indicating that the adsorption was not controlled solely by intraparticle diffusion. The first slope suggest rapid uptake of the target pollutant by the boundary layer or adsorption on the solid surface. The less steep, second slope suggests adsorption occurs by slow diffusion inside the particles. This is the step where intra-particle diffusion within the pores is the rate-limiting step. Using the second slope as the comparison, the correlation of coefficient, $R^2$ was 0.9227. This value is lower compared to the $R^2$ value for the pseudo-second-order. This indicates that the adsorption of 2,4-DCP did not follow the pseudo-first-order reaction kinetic but fitted well to the pseudo-second-order model more. The rate determining step for the adsorption process was most probably a chemisorption process, which was restricted to monolayer adsorption on the surface. In chemisorption, 2,4-DCP reacted with the AC surface to form a chemical bond with the carbon matrix.
Figure 6. 2,4-DCP adsorption, (b) pseudo-first-order plot, (c) pseudo-second-order plot and (d) intraparticle diffusion plot

Table 4. Adsorption isotherm data using AC2

| Sample | Langmuir model | Freundlich model | Temkin model |
|--------|----------------|-----------------|--------------|
|        | $K_L$ | $q_m$ | $R^2$ | $K_F$ | $n$ | $R^2$ | $K_T$ | $b$ | $R^2$ |
| AC2    | 1.0610 | 44.25 | 0.9970 | 21.3698 | 1.7058 | 0.9852 | 10.3588 | 0.2528 | 0.9939 |

Table 5. Adsorption kinetics data

| $k_1$ (min$^{-1}$) | $q_{e,exp}$ (mg g$^{-1}$) | $q_{e,cal}$ (mg g$^{-1}$) | $R^2$ | $k_2$ (g mg$^{-1}$ min$^{-1}$) | $q_{e,cal}$ (mg g$^{-1}$) | $R^2$ | $k_{id}$ (mg g$^{-1}$ min$^{-0.5}$) | $C$ (mg g$^{-1}$) | $R^2$ |
|-------------------|--------------------------|---------------------------|-------|-------------------------------|---------------------------|-------|---------------------------------|----------------|-------|
| pseudo-first order |                          |                           |       | pseudo-second order           |                           |       | Intraparticle diffusion          |                 |       |
| 0.2326            | 30.4                     | 18.2348                   | 0.9681| 3.8297 x 10$^{-4}$            | 32.4675                   | 0.9998| 0.6107                          | 22.354         | 0.9227 |

4. Conclusion
In this study, AC was successfully prepared from tea leaves using a two-stage self-generated atmosphere method. The yield percentage ranged from 22.568 to 50.015 % while moisture content showed a low percentage ranging from 3.629 to 5.477 %. On the contrary, ash content ranged from 13.989 to 28.398 % indicating an undesirable result due to the impregnation ratio. The FTIR analysis showed that changes occur when AC was prepared from tea leaves. From the SEM micrographs, morphological changes on the ACs surfaces were observed. Comparison of tea leaves and ACs showed that pores were formed from a non-porous surface. Comparison of the different impregnation ratio AC showed that each impregnation ratio produced a different effect on the activated carbon. The maximum Brunauer, Emmett and Teller (BET) surface area of the best produced AC was found to be 695 m$^2$/g. Adsorption capacity showed that AC2 had the highest capacity among the other ACs. The theoretical maximum adsorption capacity of AC2 was found to be 44.25 mg g$^{-1}$. Multi-linearity in intraparticle diffusion plot suggested that the intraparticle diffusion was not the only rate limiting step. Adsorption kinetics showed that pseudo second-order fitted more when compared to pseudo first-order. Experimental results are in good agreement with Langmuir, Freundlich and Temkin isotherm with Langmuir giving the best compliance. The data suggested that adsorption rate was limited by chemisorption and the adsorption process was mostly a monolayer adsorption process.
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