Carbon Dioxide (CO₂) Adsorption by Activated Carbon Functionalized with Deep Eutectic Solvent (DES)

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Abstract. In recent years, carbon dioxide (CO₂) emission has become a major concern as the amount of the emitted gas significantly increases annually. Consequently, this phenomenon contributes to global warming. Several CO₂ capture methods, including chemical adsorption by activated carbon, have been proposed. In this study, activated carbon was prepared from sea mango (Cerbera odollam), which was functionalized with deep eutectic solvent (DES) composed of choline chloride and glycerol to increase the efficiency of CO₂ capture. The samples underwent pre-carbonization and carbonization processes at 200 °C and 500 °C, respectively, with nitrogen gas and flowing several gases, namely, CO₂ and steam, and then followed by impregnation with 50% phosphoric acid (H₃PO₄) at 1:2 precursor-to-activant ratio. The prepared activated carbon was impregnated with DES at 1:2 precursor-to-activant ratio. The optimum CO₂ adsorption capacity of the activated carbon was obtained by using CO₂ gas treatment method (9.851 mgCO₂/gsol), followed by the absence of gases (9.685 mgCO₂/gsol), steam (9.636 mgCO₂/gsol), and N₂ (9.536 mgCO₂/gsol).

1. Introduction
Current atmospheric carbon dioxide (CO₂) levels are considered alarming; such levels have contributed to global environmental issues. Santos [1] reported that 70% of CO₂ emission is attributed to different forms of energy generated and used in various processes, such as burning of fossil fuels, including natural gas, oil, or coal, and industrial processes, such as cement production, oil refinery, power plant processes, and iron and steel manufacturing. Furthermore, CO₂ emission not only adversely affects climate change but also threatens human health.

Several effective methods of carbon capture and storage (CCS), such as adsorption [2], membrane separation [3], and cryogenic separation, have been proposed to reduce the amount of emitted CO₂ in the atmosphere [4]. Lee [5] demonstrated that adsorption is a promising method to remove CO₂ because it is cost effective.

Adsorption processes are generally performed using activated carbon [6], activated [7], zeolite [8], and polymeric adsorbents [9]. A few researchers [5, 10, 11] also revealed that activated carbon can capture CO₂ because it consists of a large surface area per unit volume and submicroscopic pores, in which contaminant adsorption occurs. Moreover, activated carbon is stable under acidic and basic conditions. It is also cost effective because it can be regenerated and thus suitable for organic compound removal.

Considering cost effectiveness in activated carbon production, researchers developed different precursors from abundant waste materials, such as palm shells, sea mango, cocoa pod shells, and rice
husks. For instance, Siti Noraishah [12] successfully produced activated carbon from rice husks and utilized it to remove CO₂ generated from industrial activities.

The integration of chemicals into activated carbon has shown an excellent performance in CO₂ uptake. Saad [13] and Karousos [14] demonstrated that the impregnation of activated carbon with chemicals, such as amine and ionic liquids (ILs), has increased the amount of captured CO₂. Although the immobilization of these chemicals in activated carbon assists CO₂ capture, such chemicals are difficult to prepare because they are toxic and relatively expensive [15]. Abbott [16] developed a novel green solvent known as Deep Eutectic Solvent (DES) to overcome the limitation of amine and ILs [17].

DES is used in numerous possible applications, including metal electro deposition, metal electropolishing, and synthesis applications, such as biodiesel purification and manufacturing, biotransformation, and CO₂ capture [17]. DES for CO₂ capture has been extensively investigated because of its easy preparation, biodegradability, and nontoxicity; DES can also yield results similar to amine, which is rigidly known for good CO₂ capture [18].

DES can be classified into four types: Type 1, quaternary ammonium cation + metal halide; Type 2, quaternary ammonium cation + hydrated metal halide; Type 3, quaternary ammonium cation + hydrogen bond donor; and Type 4, metal halide + hydrogen bond donor. Among these types, Type 3 is the most favorable because it is easily produced, mostly unreactive in water, biodegradable, and inexpensive [17].

In the current research, the prepared activated carbon from sea mango (Cerbera odollam) was modified to improve the CO₂ adsorption capacity by promoting DES on the surface of the activated carbon through chemical impregnation. Thus far, very few studies have focused on CO₂ capture with DES. Hence, the present work focused on the characterization and performance of CO₂ capture by using DES-functionalized activated carbon.

2. Procedure

2.1. Preparation of activated carbon

Sea mango (Cerbera odollam) was collected around Perlis and Kedah. The skin and seeds of the raw material were removed to obtain the fibrous shell. The samples were then washed and dried in an oven for 24 h at 105 °C to remove the moisture content. Afterward, the samples were crushed and sieved to obtain fine particles measuring 1 mm to 2 mm. The raw material was then subjected to semi-carbonization in a tube furnace for 30 min at 200 °C by flowing with nitrogen gas. Char was subsequently impregnated with 50 wt% H₃PO₄ at 1:2 precursor-to-activant ratio for 4 h and then dehydrated in the oven at 110 °C until dryness.

The char was weighed and placed in a tube furnace with three different gases, namely, nitrogen, carbon dioxide, and steam, for activation. One tube furnace was not filled with gases. The furnace was heated until the desired temperature of 500 °C was reached. Activation was conducted for 2 h. The samples were cooled to room temperature (25°C) and washed few times with hot distilled water to remove excess H₃PO₄.

Activated carbon was then filtered and dried in the oven until it is completely dried. The activated carbon samples for gas activation of nitrogen, carbon dioxide, steam, and absence of any gases were denoted as AC-N₂, AC-CO₂, AC-S, and AC-AAG, respectively.

2.2. Preparation of DES

Choline chloride and glycerol (1:2) were added at 80 °C under stirring. The mixture was stirred for approximately 1 h, and the resulting solution was clear and homogeneous.

2.3. Functionalization of activated carbon with DES

Each type of activated carbon was impregnated by using DES with a 1:2 ratio of activated carbon to DES for 4 h by using the vacuum impregnation method with a vacuum pressure of −0.5 bar. The activated carbon was completely dried at 150 °C. The impregnated activated carbon samples for AC-N₂, AC-CO₂, AC-S, and AC-AAG were denoted as AC-N₂-D, AC-CO₂-D, AC-S-D, and AC-AAG-D, respectively.

2.4. Carbon dioxide adsorption

The experimental set-up employed in this study is as shown in figure 1. The adsorption column was made of glass with 1 cm inner diameter and 30 cm long, enclosed with an insulator to retain a constant
temperature throughout the whole experiments. The glass column was vertically installed and implanted within a glass water jacket with inlet and outlet connections. The activated carbon (3 g) was inserted into this column with a piece of cotton wool at the top and bottom for breakthrough study. During the experiments, the gas flow was in an up-flow manner at 5 ml/min.

A Guardian NG CO\textsubscript{2} analyzer with measuring a range of 0-30% CO\textsubscript{2} (Edinburgh Instruments Ltd, Chorley, Lancashire, England) was used to measure the concentration of CO\textsubscript{2} exiting the adsorption bed. The CO\textsubscript{2} analyzer displays a value when the adsorption column is saturated with CO\textsubscript{2} and thus causes the gas to break through out of the column. The breakthrough time was recorded for every sample.

The gases flow from the gas cylinders was regulated using gas regulators Weldmark provided by (Weldmarks’s Corporate, Indianapolis, Indiana, United State). A set of gas flow controller (Brooks Instrument, PA, USA) model SLA 5850 and model 0254 Secondary Electronics were used to accurately measure and control the gas flow rate. The gases, purified N\textsubscript{2} and 15 % CO\textsubscript{2} (balance N\textsubscript{2}) were obtained from The Linde Group (Munich, Germany).

![Figure 1. Experimental Setup.](image)

2.5. Characterization of activated carbon
The surface area of the activated carbon was determined using a BELSORP-Mini machine. Fourier transform infrared (FTIR-KBR) with the obtained spectra between 450 and 4000 cm\textsuperscript{-1} was used to determine the surface properties and functional groups. Surface morphology and element composition analyses were performed using a field emission scanning electron microscope (FESEM), and the total ash content of the adsorbent was determined in accordance with ASTM standard D2866 – 11[19].

3. Results and Discussion

3.1. Characterization results

3.1.1. BET surface area and pore characteristics. Table 1 shows the BET surface area and characteristics for all the samples. Different gas treatments showed varying surface areas. The highest surface area of the non-functionalized activated carbon was obtained from the absence of any gas treatment at 882.71 m\textsuperscript{2}/g, whereas the lowest surface area from steam treatment was 842.25 m\textsuperscript{2}/g.

After impregnation with DES was conducted, the surface area of all of the gas treatments reduced almost to half at 435.63, 426.40, 423.99, and 455.18 m\textsuperscript{2}/g for AC-AAG-D, AC-S-D, AC-N\textsubscript{2}-D, and AC-CO\textsubscript{2}-D, respectively. This result is attributed to the deposition of DES on the surface and inside the pore, which reduced the surface area of the activated carbon [20].
Table 1. Total surface area and pore volume of different types of activated carbon.

| Sample   | Total surface area [m² g⁻¹] | \(V_{\text{micropore}}\) [cm³ g⁻¹] | \(V_{\text{mesopore}}\) [cm³ g⁻¹] | Total pore volume [cm³ g⁻¹] | Main type of pore |
|----------|-----------------------------|---------------------------------|---------------------------------|-----------------------------|-----------------|
| AC-AAG  | 882.71                      | 0.4539                          | 0.1520                          | 0.4696                      | Micropore       |
| AC-S    | 842.25                      | 0.4556                          | 0.1543                          | 0.4696                      | Micropore       |
| AC-N₂   | 852.06                      | 0.4318                          | 0.1475                          | 0.4445                      | Micropore       |
| AC-CO₂  | 880.39                      | 0.4438                          | 0.1516                          | 0.4603                      | Micropore       |
| AC-AAG-D | 435.63                     | 0.2197                          | 0.0733                          | 0.2276                      | Micropore       |
| AC-S-D  | 426.40                      | 0.2129                          | 0.0693                          | 0.2191                      | Micropore       |
| AC-N₂-D | 423.99                      | 0.2125                          | 0.0713                          | 0.2195                      | Micropore       |
| AC-CO₂-D | 455.18                     | 0.2263                          | 0.0722                          | 0.2334                      | Micropore       |

3.1.2. FTIR Spectra. FTIR is an adaptable technique that can be applied to determine surface chemistry. In particular, chemical bonding was observed in the sample. The following chemical bonds (table 2) were observed in all of the samples: OH-stretch, H-bonded, and C-H stretch interactions. These bonds were possibly ascribed to the cerebrin structure of sea mango. The N-H bonds from the primary amine group only existed in the DES-functionalized activated carbon because the presence of choline chloride in the activated carbon contributed to the N-H bond. Figure 2 shows the suggested attachment of DES on the surface of the activated carbon. The elemental N which is believed to assist in CO₂ capture into the substrate was successfully attached on the surface of the activated carbon as per illustrated in figure 3 [21]. The C-C stretch from the aromatic group was present in the raw and non-functionalized activated carbon; however, this bond was absent in the DES-functionalized activated carbon because the reaction of H from DES with C from cerebrin promoted a new band, which is a C-H bond from the alkane group at peaks 1477.89 cm⁻¹ to 1478.35 cm⁻¹.

The C-O stretch existed in the non-functionalized activated carbon at peaks 1055.02 cm⁻¹ to 1150.09 cm⁻¹. However, this bond was absent in the DES-functionalized activated carbon. The C-N stretch bond from the aliphatic amine group existed only in the DES-functionalized activated carbon because it is attributed to the choline chloride of DES.

The C-H bond from the alkane group was present at peaks 955.94 cm⁻¹ to 956.58 cm⁻¹ for the DES-functionalized activated carbon but was absent in the raw and non-functionalized activated carbon. The C-H bond was likely attributed to glycerol in DES. The C-Cl stretch from the alkyl halide group was present only in the DES-functionalized activated carbon because of the presence of Cl element in the choline chloride. As such, the functionalization process added several functional groups to the surface of the activated carbon. The presence of DES increases the number of active sites on the surface and enhances the CO₂ adsorption capacity [22].
| Bond                  | Functional group                                      | Raw     | AC-AAG | AC-CO$_2$ | AC-N$_2$ | AC-S  | AC-AAG-D | AC-CO$_2$-D | AC-N$_2$-D | AC-S-D   |
|----------------------|------------------------------------------------------|---------|--------|-----------|----------|-------|----------|-------------|-------------|----------|
| O–H stretch, H–bonded| alcohols, phenols                                     | 3411.10 | 3429.82| 3430.09   | 3415.09  | 3429.17| 3401.20  | 3399.77     | 3399.93     | 3400.00  |
| C–H stretch          | alkanes                                              | 2923.78 | 2043.6 | 2051.88   | 2053.3   | 2081.40| 2942.90  | 2941.62     | 2944.48     | 2937.06  |
| N–H bend             | primary amine                                        | -       | -      | -         | -        | -     | 1635.98  | 1638.00     | 1638.51     | 1636.21  |
| C–C               (in–ring) | aromatics                                              | 1622.97 | 1617.60| 1554.40   | 1542.23  | 1570.20| -        | -           | -          | -        |
| C–H bend             | alkanes                                              | 1452.05 |        | 1146.76   | 1146.78  | 1144.05| 1150.09  | 1478.35     | 1478.02     | 1477.98  | 1477.89  |
| C–O                 (stretch) | alcohols, carboxylic acids, esters, ethers          | 1055.02 | 1146.76| 1146.78   | 1144.05  | 1150.09| -        | -           | -          | -        |
| C–N                 (stretch) | aliphatic amines                                     | -       | -      | -         | -        | -     | -        | 1205.81     | 1206.90     | -        |
| C–H bend             | alkanes                                              | -       | -      | -         | -        | -     | 1083.92  | 1084.17     | 1084.19     | 1084.09  |
| C–Cl                 (stretch) | alkyl halides                                     | -       | -      | -         | -        | -     | 1048.33  | 1046.35     | 1048.45     | 1046.89  |
|                      |                                                      | -       | -      | -         | -        | -     | 955.95   | 956.19      | 956.58      | 955.94   |
|                      |                                                      | -       | -      | -         | -        | -     | -        | 864.41      | 885.70      | 864.92   |
|                      |                                                      | -       | -      | -         | -        | -     | -        | 561.70      | 570.22      | 553.18   | 565.59   |
Figure 2. Reaction of DES on the surface of the activated carbon.

Figure 3. Mechanism of CO$_2$ interaction with DES.
3.1.3. Surface Morphology. Surface morphology represents the physical structure of each sample as shown in figure 4(a)-(i).
Figure 4(a) shows the physical structure of a raw sample. Evidently, the pore volume was very limited and not well developed. After carbonization and impregnation with H$_3$PO$_4$ were conducted, a honeycomb-like pore structure with a high pore volume was clearly observed, as confirmed by the BET results [figures 4(b) to 4(e)]. The pore structures were developed during physiochemical activation with the help of H$_3$PO$_4$, which assists the development of pores [23]. The well-developed pores resulted in the large surface area and pore structure, which allowed a good surface for CO$_2$ adsorption. These images also confirmed that no chemical was attached to the surface of the activated carbon. Thus, CO$_2$ adsorption occurred between the activated carbon particle surface and CO$_2$ molecules, and this process is known as physisorption.

After impregnation with DES was completed, few pores were found clogged. Consequently, the pore volume decreased. CO$_2$ adsorption occurred primarily through chemisorption as the DES on the surface of activated carbon assisted CO$_2$ adsorption; thus, CO$_2$ adsorption in the activated carbon was enhanced [22].
3.1.4. Energy-dispersive X-Ray (EDX) analysis. EDX is an X-ray technique used to identify the elemental composition of materials. Elemental analysis revealed that the raw, non-functionalized, and DES-functionalized activated carbon contained C, O, P, N, and Cl (table 3). Approximately 58.00% to 88.00% carbon content was found in all samples related to the original content in sea mango (Cerbera odollam). After the raw material was activated, the composition of C increased significantly from 66.00% to 88.00%. This finding showed that the activation process helped increase C composition because heat supply during activation initiates thermal degradation; thus, volatile matter is removed and a stable carbon element is retained [24].

P was present in the non-functionalized activated carbon and DES-functionalized activated carbon, and this finding indicated a reaction with H₃PO₄ during the impregnation process. N and Cl were also detected in the DES-functionalized activated carbon possibly because of the presence of choline chloride of DES. This finding confirmed that N was successfully attached to the surface of the activated carbon; as a result, more active sites become available for CO₂ adsorption, and CO₂ capture is enhanced [22].

Table 3. Elemental analyses of the samples.

| Sample   | C (wt%) | O (wt%) | P (wt%) | N (wt%) | Cl (wt%) |
|----------|---------|---------|---------|---------|----------|
| RAW      | 58.5    | 36.67   | 0       | 0       | 0        |
| AC-AAG   | 86.93   | 5.51    | 1.83    | 0       | 0        |
| AC-S     | 87.99   | 5.92    | 0.99    | 0       | 0        |
| AC-CO₂   | 88.6    | 6.87    | 0.77    | 0       | 0        |
| AC-N₂    | 83.53   | 9.49    | 2.8     | 0       | 0        |
| AC-AAG-D | 68.05   | 14.98   | 0.94    | 5.66    | 8.53     |
| AC-S-D   | 66.07   | 16.75   | 0.53    | 5.16    | 9.01     |
| AC-CO₂-D | 66.13   | 17.05   | 1.15    | 5.97    | 8.93     |
| AC-N₂-D  | 70.14   | 16.87   | 0.06    | 3.79    | 7.75     |

3.2. Breakthrough time of CO₂ adsorption
The CO₂ adsorption test was conducted to determine the breakthrough time of each sample. Figure 5 illustrates the breakthrough time curve for the non-functionalized sample by using different types of flowing gas treatment.

Table 4. Breakthrough time and CO₂ adsorption capacity of the samples.

| Sample   | Breakthrough time (seconds) | CO₂ adsorption capacity (mgCO₂/gsol) |
|----------|-----------------------------|------------------------------------|
| AC-AAG   | 1152                        | 9.585                              |
| AC-S     | 1140                        | 9.485                              |
| AC-CO₂   | 1008                        | 8.412                              |
| AC-N₂    | 1116                        | 9.286                              |
| AC-AAG-D | 1164                        | 9.685                              |
| AC-S-D   | 1158                        | 9.636                              |
| AC-CO₂-D | 1184                        | 9.851                              |
| AC-N₂-D  | 1146                        | 9.536                              |

In figure 5(a) and table 4, the highest CO₂ adsorption capacity and the longest breakthrough time of the non-functionalized activated carbon were observed in the AC-AAG sample at 9.585 mgCO₂/gsol, followed by AC-S at 9.485 mgCO₂/gsol, AC-N₂ at 9.286 mgCO₂/gsol, and AC-CO₂ at 8.412 mgCO₂/gsol. The highest adsorption capacity was detected in AC-AAG because it exhibited the highest surface area, which allows more CO₂ molecules to bind to the active sites of the activated carbon [5].
For the DES-functionalized activated carbon [figure 5(b) and table 4], the highest CO$_2$ adsorption capacity was found in AC-CO$_2$-D at 9.851 mg$_{CO_2}$/g$_{sol}$, followed by AC-AAG-D at 9.685 mg$_{CO_2}$/g$_{sol}$, AC-S-D at 9.636 mg$_{CO_2}$/g$_{sol}$, and AC-N$_2$-D at 9.536 mg$_{CO_2}$/g$_{sol}$. The highest CO$_2$ adsorption capacity was observed in AC-CO$_2$-D because of its surface area and available elemental N on the surface, which significantly accelerated CO$_2$ adsorption [21]. Hence, the DES-functionalized activated carbon demonstrated a more efficient performance than the non-functionalized activated carbon did.
4. Conclusion
The DES-functionalized activated carbon yielded a higher CO₂ adsorption capacity than the non-functionalized activated carbon did because the elemental N on the surface of the activated carbon increased the number of active sites for CO₂ capture. Although the surface area of the DES-functionalized activated carbon was reduced to almost half of the non-functionalized activated carbon, the adsorption capacity of the DES-functionalized activated carbon was improved. Therefore, the DES-functionalized activated carbon underwent chemisorption in its active site. Elemental N from DES played a vital role in CO₂ adsorption.

References
[1] Santos S C G, Garrido Pedrosa A M, Souza M J B, Cecilia J A and Rodriguez-Castellón E 2015 Carbon dioxide adsorption on micro-mesoporous composite materials of ZSM-12/MCM-48 type: The role of the contents of zeolite and functionalized amine Materials Research Bulletin 70 663–672
[2] Oliveres-Marin M, Sanz-Perez E S, Wong M S and Maroto- Valer M M 2011 Development of regenerative sorbents from abundant wastes for capture of CO₂ Energy Procedia 4 1118-1124
[3] Brunetti A, Scura F, Barbieri G and Drioli E 2010 Membrane Technology for CO₂ separation J. of Membrane Sci. 359 115-125
[4] Tuinier M J, Van Sint Annaland M, Kramer G J and Kuipers J A M 2010 Cryogenic capture using dynamically operated packed beds Chemical Eng. Sci. 65 114-119
[5] Lee C S, Ong Y L, Aroua M K and Daud W M A W 2013 Impregnation of palm shell-based activated carbon with sterically hindered amines for CO₂ adsorption Chemical Eng. J. 219 558–564
[6] Mohammad Saleh S, Wan Mohd Ashri W D, Amirhossein H and Ahmad Shamiri 2010 A review on surface modification of activated carbon for carbon dioxide adsorption J. of Analytical and Applied Pyrolysis 89 143–151
[7] Tony S S and Pant K K 2004 Equilibrium, kinetics and thermodynamic studies for adsorption of As(III) on activated alumina Separation and Purification Tech. 36 139–147
[8] Chung K L, Shin S L, Lain C J, Cheng C W, Kuen S L and Meng D L 2007 Application of MCM-41 for dyes removal from wastewater J. of Hazardous Materials 147 997–1005
[9] Jones D A, Lelyveld T P, Mavrofidis S D, Kingman S W and Miles N J 2002 Microwave heating applications in environmental engineering—a review Res., Conservation and Recycling 34 75–90
[10] Duan X, Srinivasakannan C and Liang J S 2014 Process optimization of thermal regeneration of spent coal based activated carbon using steam and application to methylene blue dye adsorption J. of the Taiwan Inst. of Chemical Engineers 45 1618–1627
[11] El-Shafey E I, Syeda N F A, Saleh A, Haider A J and Al-Lawati 2016 Preparation and characterization of surface functionalized activated carbons from date palm leaflets and application for methylene blue removal J. of Environ. Chemical Eng. 4 2713–2724
[12] Siti Nuraishah M R, Saidatul Shima J, Noor Asma F A S and Nur Aminatulmimi I 2016 Investigation of Impregnated Commercial Rice Husks, Activated Carbon with Alkanolamines as Carbon Dioxide (CO₂) Adsorbent ARPN J. of Eng. and Applied Sci. 11 4
[13] Saad H K, Aroua M K and Daud W M A W 2012 Study on the improvement of the capacity of amine- impregnated commercial activated carbon beds for CO₂ adsorbing Chemical Eng. J. 183 15-20
Karousos D S, Vangeli O C, Athanasekou C P, Sapalidis A A, Kouvelos E P, Romanos G E and Kanellopoulos N K 2016 Physically bound and chemically grafted activated carbon supported 1-hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl) imide and 1-ethyl-3-methylimidazolium acetate ionic liquid absorbents for SO$_2$/CO$_2$ gas separation Chemical Eng. J. 306 146–154

García G, Santiago A, Ruh U and Mert A 2015 Deep Eutectic Solvents: Physicochemical Properties and Gas Separation Applications Energy Fuel 29 2616-2644

Abbot A P, Barron J C, Ryder K S and Wilson D 2007 Eutectic-based ionic liquids with metal-containing anions and cations Chemical Review 13 6945-6501

Emma L S, Andrew P A and Karl S R 2014 Deep Eutectic Solvents (DESs) and Their Application Chemical Review 114 11060-11082

Ling G, Huang W, Shaokun T, Songjiang T and Xiangwen Z 2015 A novel deep eutectic solvent for biodiesel preparation using a homogeneous base catalyst Chemical Eng. J. 259 647–652

ASTM D2866-11 2011 Standard Test Method for Total Ash Content of Activated Carbon ASTM International West Conshohocken PA

Gray M L, Champagne K J, Fauth D, Baltrus J P and Henry P 2008 Performance of immobilized tertiary amine solid sorbents for the capture of carbon dioxide Inter. J. of Green House Gas Control 2 3–8

Yew Liang O 2014 Impregnation of palm shell-based activated carbon with sterically hindered amines for carbon dioxide adsorption in packed column Unpublished Master’s Thesis University of Malaya, Kuala Lumpur, Malaysia

Khalid M A, Abdul hakim M A, Hayyana M, Shatirah A and Mohd Ali H 2016 Functionalization of CNTs surface with phosphonium based deep eutectic solvents for arsenic removal from water Applied Surface Sci. 389 216–226

Budinova T, Ekinci E, Yardim F, Grimm A, Björnbom E, Minkova V and Goranova M 2006 Characterization and application of activated carbon produced by H$_3$PO$_4$ and water vapor activation Fuel Processing Tech. 87 899–905

Olugbenga S B, Mohd Azmier A and Tan T S 2011 Utilization of Cocoa Pod Husk for the Removal of Remazol Black B. Reactive Dye from Aqueous Solutions: Kinetic, Equilibrium and Thermodynamic Studies Trends in Applied Sci. Res. 6(8) 794-812