Caliphate Journal of Science & Technology (CaJoST)

ISSN: 2705-313X (PRINT); 2705-3121 (ONLINE) Review Article

Open Access Journal available at: https://cajost.com.ng/index.php/files and https://www.ajol.info/index.php/cajost/index

DOI: https://dx.doi.org/10.4314/cajost.v7i1.9

Article Info

Received: 2nd October 2024

Revised: 20th January 2025

Accepted: 26th January 2025

Palm Kernel Shell-Derived Nanoporous Carbon Materials: A Review on Preparation, Modification and Application

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Cite this: *CaJoST,* 2025, 1, 73-99

Nanoporous carbon materials derived from the palm kernel shell is a type of carbon materials with improved properties attuned for the applications in plethora of sophisticated technology in the world today. They are generally prepared by methods involving carbonization and activation steps and can be tailored to possess targeted properties based on their intended use. Nanoporous carbon materials have been applied in the water treatment, adsorption of gases, solar cells, energy storage and medicine. This mini review gives a summary of preparations, characterizations and modifications of nanoporous carbon materials. The applications of nanoporous carbon materials in environmental remediation and water treatment, adsorption of gases, energy storage and batteries, and sensors were also elaborated. This review gives a basis for the importance of the materials in meeting global challenges in environment, clean water, medicine, and energy thus provides motivation for comprehensive studies into the synthesis of functional nanoporous carbon materials and its application.

Keywords: Nanoporous carbon; Palm kernel shell; Highly porous carbon; Ecofriendly adsorbent; Functional nanomaterial.

1. Introduction

Carbon is a captivating element in various field due to its ability to form bonds with numerous different elements to form stable covalent compound. Under ideal circumstances, carbon is weakly reactive in comparison to many other elements. It is resistant to oxidation and does not react at high temperature and pressure with sulfuric acid, hydrochloric acid, chlorine, or any alkali metal. With addition of heat from high temperature, carbon will react with oxygen to form carbon dioxides while reaction with metals will form metal carbides. Carbon has a large and flexible electronic structure, making it essential for improving carbon skeleton-based chemistry (Jirimali *et al.,* 2022). Carbon is the main element in several valuable materials such as diamond, graphite, fullerene, charcoal, and amorphous carbon that can be found in a wide variety and can exist in many forms such as nanoporous carbon, carbon aerogels, carbon nanotubes, carbon nanofiber, biochar and graphene (Hamad and Idrus, 2022). A recent research investigation looked at the scientific production of carbon based materials over the last 25 years, revealing numerous publications on the seven carbon base materials: activated carbon, graphite, graphene, carbon nanotubes, fullerenes, carbon fibers, and carbon black; highlighting clearly an increase in the contributions related to carbon nanotubes, graphene, carbon fibers and activated carbon (Gonzalez-Garcia, 2018). The adsorption efficiency of carbon base material determines the quality of its adsorbent, that is, surface area, pore structure, carbon particle size, surface acidity, and functionality of the adsorbent are considered to be the most critical factors that can affect absorbate adsorption (Zhang *et al.,* 2016).

Continuous search for alternative ecofriendly adsorbent source becomes imperative. Nanoporous carbon (NC) material is one of the adsorbent that can be found in our environment from agricultural waste (Baby and Hussein 2020; Rouzitalab *et al.* 2018), biomass (Fernandes *et al.,* 2020; Nda-Umar *et al.,* 2020), biowaste (Wong *et al.,* 2018; Mashhadi *et al.,* 2016), food waste, (Peng *et al.,* 2016), coal (Ambika et al., 2022; Bolan *et al.,* 2022), polymer (Memetova *et al.,* 2022b; Prasetyo *et al.,* 2017) and wood (Dehghani *et al.,* 2020; Kazemi *et al.,* 2016).

Nanoporous carbon is a carbon rich material with a solid amorphous structure which has been activated and as a result possessed a highly porous surface with numerous functional groups such as carboxylic acids, phenols, carbonyls, and lactones (Benedetti *et al.,* 2018). NC materials are strongly heterogeneous with larger surface area. The different pores character and chemical nature of their surface have made them an excellent adsorbent (Elinge *et al.,* 2011). Furthermore, the morphology of pores is important in determining the form and framework of a material along its width and volume. The IUPAC implies characterizing pores based on their size. Their pores' structure are micropores with widths smaller than 2 nm, mesopores with widths between 2 to 50 nm and macropores with widths greater than 50 nm (Choma and Jaroniec 2006; Mestre and Carvalho 2018). Nitrogen adsorption-desorption data were used to classify pores, with each pore size range corresponding to a different pore filling mechanism revealed by the isotherm profile (Memetova *et al.,* 2022b). The physisorption process is divided into three stages: monolayer adsorption in which all adsorbate molecules come into contact with the adsorbent's surface, successive adsorbate layers (multilayer adsorption), and capillary condensation (Thommes *et al.,* 2015). NC (active carbon, active carbon fibre and ordered mesoporous) are one of the best materials that can be turned or tailored in various application due to its large pore volume as adsorbent (Ania *et al.,* 2020) mounting to 99% of the world market application ("Activated Carbon — Market Report — Roskill" n.d.).

One of the uniqueness of nanoporous carbon materials are low cost of production and pore development (Rodriguez-Reinoso, 1989), specific porosity (Jaroniec and Choma, 2021), surface area and adsorption in the pores structure (Dubinin 1966). Such structures have increasingly been studied because of their improved performances in a wide range of applications. Some outstanding properties of these carbon materials include absorption properties, chemical and thermal stability, as well as strong electrical conductivity and catalytic activity. Owing to these characteristics, nanoporous carbon materials is very attractive for various applications including environmental remediation, biofiltration, water treatment, gas separation, optoelectronics, energy storage systems and catalysis (Young *et al.,* 2018). Henceforth, this review is thus aimed at examining the properties of PKS, some natural sources, methods of preparations, characterizations and potential applications of NC derived from PKS.

2. Palm kernel shell as Nanoporous carbon precursor

Oil palm originated in west Africa, where Nigeria was the leading producer from 1901 to 1977, when Malaysia took over the industry after years of intensive research and improvement of seedlings from the west African country. Malaysia (25%) and Indonesia (59%) currently dominate global total palm oil production, accounting for 85% of global palm oil plantation (Sundalian *et al.,* 2021; Obuka *et al.,* 2018).

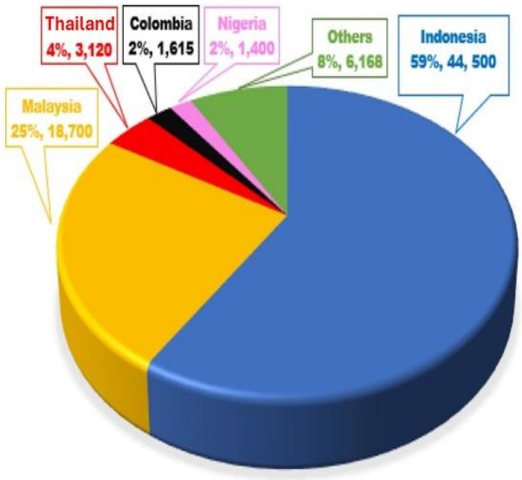

Figure 1: Worlds producers of palm oil in thousand metric tonnes in 2021/2022

Figure 1 illustrates the top palm oil producing countries in 2021/2022, with Malaysia alone producing 100 million tonnes of palm waste per year, with a 5% annual growth projection (Shahbandeh, 2022). Palm kernel shell is the hard covering of the palm kernel that is left over after extracting palm oil from the mesocarp and removing the kernel nut. High volumes of palm kernel shells (PKS) waste are generated as a result of the processing of palm oil from palm fruits, which require utilization for a variety of applications, particularly due to their perceived low carbon content (Uchegbulam *et al.,* 2022).

Palm kernel shell (PKS) is one of the agricultural wastes that was obtained from oil palm production, which recently being used as precursor (Table 1) to prepare NC for various applications. Researchers are very concerned about the efforts to investigate the potential for a comparable low-cost nanoporous carbon from a low-cost raw material. Palm Kernel Shells are among the agricultural residues that has received a lot of attention. PKS is abundant as a byproduct of palm oil mills in Indonesia, Singapore and Malaysia. This biomass by-product is characterised as a potential low-cost, high mechanical strength, porous surface, high chemical stability, different functional groups, and insolubility in water material that is also environmentally friendly (Asnawi *et al.*, 2019; Hambali and Rivai, 2017; Rashidi and Yusup, 2019).

Table 1: Some sources of nanoporous carbon materials derived from palm kernel shell with their BET surface area reported in literature

Nanoporous Carbon Materials Sources	BET Surface Area ($m^2 g^{-1}$)	References
Palm kernel shell	1099	Baby and Hussein, 2020
Palm kernel shell	700	Ooi *et al.,* 2019
Palm kernel shell	1324	Nasir *et al.,* 2018
Palm kernel shell	367	Rashidi *et al.,* 2021
Palm kernel shell	700	Baby *et al.,* 2021
Palm kernel shell	1865	Lin *et al.,* 2020
Palm kernel shell	1298	Yeboah *et al.* 2021
Palm kernel shell	1559	Pam *et al.,* 2018
Palm kernel shell	750	Liew *et al.,* 2018
Palm kernel shell	711	To *et al.,* 2017
Palm kernel shell	570	Yek *et al.,* 2019
Palm kernel shell	803	Prasetyo *et al.,* 2020
Palm kernel shell	923	Ukanwa *et al.,* 2020
Palm kernel shell	1223	Hidayu and Muda, 2016
Palm kernel shell	1086	Panneerselvam *et al.,* 2012
Palm kernel shell	1366	Guo and Lua, 2003
Palm kernel shell	1109	Lim *et al.,* 2010
Palm kernel shell	1014	Guo *et al.,* 2005
Palm kernel shell	2247	Hamad *et al.,* 2010
Palm kernel shell	1059, 1083, 1004, 1040	Isokise *et al.,* 2021
Palm kernel shell	1267	Pam *et al.,* 2021
Palm kernel shell	1413	Pam, 2019
Palm kernel shell	1800	Lin *et al.,* 2020
Palm kernel shell	700	Nicholas *et al.,* 2020
Palm kernel shell	934	Ipeaiyeda *et al.,* 2020
Palm kernel shell	903	Murillo *et al.,* 2020
Palm kernel shell	1257	Atunwa *et al.,* 2022
Palm kernel shell	870	Zaini *et al.,* 2023
Palm kernel shell	3368	Abdullah *et al.,* 2021

PKS is the shell fractions left over after the nut has been removed in the Palm Oil mill. Kernel shells are a fibrous material that can be handled in bulk from the manufacturing line to the end user. Proper management of such cheap and abundant raw materials to produce valuable materials is of great importance. While different kinds of precursors have been utilized for NC production, low-cost production of NC is still a challenging problem. Therefore, the utilization of PKS for the production of NC can provide a better option with low-cost synthetic routes. PKS is derived from the processing of oil palm nuts. Commonly, a major part of PKS is burnt directly in boilers of palm oil mills generating steam and electricity for the milling process. PKS is a renewable waste and lignocellulosic biomass, which consists of 22% cellulose, 22% hemicellulose and 42% lignin with small fractions of nonstructural components such as extractives and ash. The inorganic components are mainly constituted of silica (Babinszki *et al.,* 2021). Cellulose is known to produce a higher fraction of non-aromatic chars before conversion into condensed aromatic chars with a higher surface area than lignin-derived char. Lawal et al. (2021) compared the structural properties of NC derived from commercial cellulose (100% cellulose), oil palm frond (39.5% cellulose), and palm kernel shell (20.5% cellulose). Their findings showed that the higher cellulose content will produce higher external surface area, larger total pore volume, and wider average pore size. Besides that, some studies utilized PKS as a starting material due to its high mechanical strength, high chemical stability, various functional groups, and hydrophobic (Rashidi and Yusup 2019). Corroborating this claim, Deng et al. (2015) confirmed the presence of a lower percentage of micropores in cellulose-derived biochar – 80% for cellulose biochar and 87% for lignin biochar – suggesting that lignin predominantly produces microporous biochar.

3. Preparation of Nanoporous carbon derived from PKS

Various carbon precursors can be used to synthesize nanoporous carbon with various porous structures, functional groups, and morphologies. Furthermore, the nature, chemical composition, and structure of the precursors are important in controlling the structure and properties of the NC (Singh *et al.,* 2021). However, because these carbon-based precursors have a high surface area and numerous binding sites on the surface (Zhu *et al.,* 2017), converting PKS precursors into nanoporous carbons is an interesting approach in facilitating adsorption-based applications in the removal of contaminants (Zaini *et al.,* 2023). The general process for preparation of NC is shown in Figure 2, which involves, raw materials procurement, pre-treatment, carbonization and activation. The preparation of NC utilizing PKS as the precursor material with different methods of carbonization temperature, time and activating agent (H_3PO_4) as shown in Table 2.

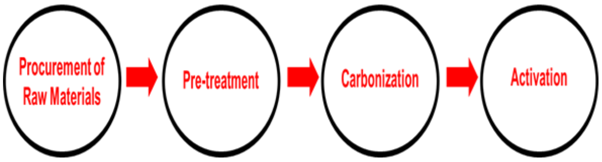

Figure 2: General flow diagram for the preparation of nanoporous carbon

3.1. Pre-treatment

Pre-treatment is majorly aimed at (i) removing dirt by washing (ii) drying to remove free moistures, which may affect the next steps (iii) milling/crushing and sieving to obtain powder or granules of specific dimensions and (iv) reduction of the inorganic content by acid washing and pre-oxidation to prevent fluidization of coking coal during carbonization. Pre-treatment might also be aimed at targeting a specific particle size or shape (Sadeek *et al.,* 2020; Mestre and Carvalho 2018).

3.2. Carbonization

Carbonization is a pre-activation step that involves heating raw lignocellulosic to increase carbon content of which moisture, low molecular weight volatiles, aromatics, and ultimately hydrogen gas are released (Gonzalez *et al.,* 2013). Nowadays, several techniques are introduced to produce a high-quality nanoporous carbon such as pyrolysis (occurs at high temperatures in an inert or limited oxygen environment) and hydrothermal carbonization (HTC) (a thermochemical process that converts biomass to carbonaceous materials) (Manasa *et al.,* 2022). The pyrolysis and gasification involve carbonization of materials to produce an activated carbon at elevated temperature of 300–650 ^{0}C and 600–1200 ^{0}C in an inert atmosphere (Cha *et al.,* 2016). However, the biochar produced by pyrolysis of biomass is porous, while activation increases pore volume and specific surface area (Zhai *et al.,* 2011). Choi et al. (2015) reported that palm kernel shells (PKS) were pyrolyzed in a fluidized bed reactor at temperatures ranging from 479 to 555 °C to produce nanoporous carbon. Similar alternative precursor has been used to produce nanoporous carbon using pyrolysis mixed with potassium hydroxide (Kaewtrakulchai *et al.,* 2020) On the contrary, the HTC process requires a lower temperature on the range of 200–350 ^{0}C. However, the HTC process involves sub- merging materials in water and is heated in a sealed system under auto-generous inner pressure where water-soluble components and 'hydro char,' a carbon-rich hydrophilic solid, are formed (You *et al.,* 2019). Jha and colleagues reported that hydrothermal carbonization is an alternative auspicious thermochemical process that can transform biomass into nanoporous carbon in an economically and environmentally friendly manner, with few requirements in terms of biomass preparation and treatment, and no pre-drying required for wet waste as in other thermal treatment processes, making it an economically appealing alternative (Jha *et al.,* 2021). Carbonization parameters have a significant impact on the process and the quality of the final products; therefore, careful parameter selection is critical (Dhyani and Bhaskar, 2018). The carbonization temperature is critical because it has the greatest impact on the process, followed by the heating rate of reactions, the amount of inert gas and its flow rate, and finally the carbonization residence or holding time. In general, as the temperature rises, more volatile species are released, as is the fixed carbon and ash content. This, however, reduces the biochar yield (González-García, 2018). The lower yield is thought to be caused by the primary decomposition (devolatilization) of biomass at high temperatures, as well as the secondary decomposition (cracking) of biochar residue. However, higher temperatures produce higher-quality biochar as a result (Reza *et al.,* 2020).

Many methods have been used to synthesize nanoporous carbon of various special, tunable, and pore sizes, with hydrothermal carbonization being one of the most convenient ways to transform material into carbonaceous nanostructures with good porosity, low cost, availability, more environmentally friendly, high thermal stability, and ease of functionalization (Mao *et al.,* 2018; Wang *et al.,* 2019). However, drug delivery, organic pollutant adsorption, energy storage can be achieved through well-developed nanoporous carbon. Furthermore, numerous papers on the synthesis of nanoporous carbon have been published through hydrothermal carbonization such as durian peel (Sitthisantikul *et al.,* 2020), Argy-wormwood (Dai *et al.,* 2018), waste resources (Joseph *et al.,* 2020), horse manure (Pasee *et al.,* 2019), olive milling by-product (Azzaz *et al.,* 2020), water hyacinth (Sukulbrahman *et al.,* 2022).

3.3. Activation

Carbon activation begins with the removal of tarry substances in order to remove deposited tars that cause pore blockage and to aid in the activating agent's later reaction with biochar (Yahya *et al.,* 2015). The aim of activation process is to increase and enhance the porous network, pore volume, pore diameter and surface area for adsorptive capacity of the carbonized materials which is classified into two such as physical and chemical activation (Senthil and Lee, 2021). The activation process is affected by particle size, retention time, impregnation ratio, procedure configuration, activation period, precursor properties, and chemical substances. However, activation of nanoporous carbon can be done either by chemical, physical or physicochemical methods. Steam, CO_2, N_2 or mixture of both are used in physical activation, while acid, base, metal oxide and alkaline metal are used in chemical activation. Among these two methods, chemical activation provides more advantages than physical activation because the operation can be done at lower temperature, rapid, and low cost (Pam *et al.,* 2021).

Physical activation is a two-step process in which biomass is first pre-treated at a suitable temperature (400 – 450^0 C) in an inert atmosphere before being carbonized at high temperatures using either air (600 ^{0}C), steam, or CO_2 to enhanced the specific surface area of the carbonized materials (Durga *et al.,* 2022; Shaker *et al.,* 2021; Abioye *et al.,* 2015; Bergna *et al.,* 2018). Carbon dioxide has been widely used because it is clean, easy to handle, and the activation process can be easily controlled at temperatures around 800 ^{0}C due to its slow reaction rate and moreover, greater pore uniformity and superior quality of high porous surface area can also be achieved with CO_2 activation when compared to steam activation (Naji and Tye, 2022). The advantages associated with physical activation methods over chemicals activation include their simplicity, lower activation cost and the absence of chemical in the production of microporous structures (Muhammad *et al.,* 2022; Pallarez *et al.,* 2018). Physical activation, on the other hand, is time and energy consuming, and because of the high temperature required during the activation, the nanoporous carbon produced through this method is scarce in some characteristics, making it unsuitable as a catalyst or adsorbent (Tadda *et al.,* 2016; Yahya *et al.,* 2015).

Chemical activation is the most commonly method for the preparation of nanoporous carbon, because it is of superior quality with minimal energy and time conditions, high porosity, large surface area, and high material yield (Durga *et al.,* 2022; He *et al.,* 2021; Lozano-Castello *et al.,* 2007). This method is commonly used for cellulose-rich raw materials such as palm kernel shell where it's impregnated or mixed with chemical agents such as acids, bases, or salts for chemical activation. The impregnated mixture is then activated and carbonized in a single step at a low temperature (400 ^{0}C to 800 ^{0}C) to produce nanoporous carbon with appropriate porosity (Joseph *et al.,* 2020; Gan, 2021). The precursor under controlled activating agent ratio, temperature, time are considered during the impregnation processes with $ZnCl_2$, KCO_3, KOH, H_3PO_4, NaOH, HNO_3, H_2SO_4, K_2CO_3, Na_2CO_3, $Na_2S_2O_3$ as chemical agent (Demir and Doguscu, 2022; Togibasa *et al.,* 2021; Herou *et al.,* 2020; Sulyman *et al.,* 2017; Hesas *et al.,* 2013), as they are used in aiding the development of the nanoporous carbon material pores structure. H_3PO_4 and $ZnCl_2$ are the most commonly used chemical activating agents due to lower environmental and toxicological challenge as well as enhances the material structure of the prepared porous material (Isokise *et al.,* 2021). Phosphoric acid (H_3PO_4) impregnation treatment has several advantages leading to pore size distribution, high yield, low activating time, low temperature and one heating step (Memetova *et al.,* 2022a; Zhang and Shen, 2019; Ceyhan *et al.,* 2013). Detailed research has shown H_3PO_4 chemical activation for nanoporous carbon production derived from PKS and other precursor source in Table 2 and Table 3, respectively. With increasing temperature, the structure of the phosphorous compound changes in the PKS-H_3PO_4 treatment. At lower temperature between 100 – 400^0 C, H_3PO_4 act as a catalyst, making the release of CO_2 and absorbed water as a result of dehydration. Furthermore, from 400 – 700^0 C, the phosphor compound transformed to P_4O_{10}, which acted as an oxidant, reacted with carbon forming new pores and the released of CO_2 and H_2O (*Li et al.,* 2015; Arami-Niya *et al.,* 2011).

4. Factors affecting the Nanoporous carbon preparation

Irrespective of whether carbon materials are used, one of the most important aspects of their production is the development of porosity. The development of material porosity of the nanoporous carbon is determined by the activation process, which includes temperature, time, activating agent, and precursor sources. These variables influence the rate of activation and the formation of pore structures in nanoporous carbon.

4.1. Effect of activating temperature

The activation temperature influences both the process rate and the porous structure of the final nanoporous carbon material. The activation rate of most chemical reactions increases as the temperature increases. As a result of the low temperatures, the rate of chemical reaction between carbon and the oxidizing agent is slow, limiting the overall process, resulting in a homogeneous product with uniform pore distribution across the granule volume. At high temperatures, the rate of the chemical reaction increases, and the process is limited by oxidant diffusion into the granule (Memetova *et al.,* 2022a). To investigate the relationship between the carbon material properties and the activation temperature, Kwon et al. (2015), investigated the effect of increasing the activation temperature (600 - 900 °C) on the physical properties of the material. They arrived at the conclusion that increasing the activation temperature increases the surface area of the resulting nanoporous carbon material. The preferable activation temperature in the preparation of nanoporous carbon when using alkaline base activating agent is within the range of 450-850 °C, but at higher activation temperatures above 900 °C, the carbon material quality deteriorates significantly. Redondo et al. (2015) investigated KOH activation at temperatures ranging from 700 to 1000 °C. At 700-800 °C, they discovered nanoporous carbon with a narrow pore distribution. However, increasing the activation temperature to 1000 °C contribute the emergence of greater nanopores and mesopores as a result in the changes of the pore size distribution (Li *et al.,* 2017), while Han et al., reported an increase of specific surface area from 813 – 1381 m^2/g as the activating temperature increases from 500 – 800^0 C (Han *et al.,* 2019). On the contrary, the optimal temperature for the activation of nanoporous carbon using acidic activating agents (particularly H_3PO_4) is between 400 and 600 °C, with highly developed porosity represented by both micro and mesopores as shown in Table 2.2. Yakout and El-Deen, 2016 and Li et al., 2015, reported an increase in specific surface area and pore volume as a result of heating to 500^0 C (Yakout and El-Deen, 2016; Li *et al.,* 2015). Conversely, it was reported that, activating agent (H_3PO_4) can lead to the development of narrow micropore size nanoporous carbon materials in a two-step activation (Hu *et al.,* 2021). Moulefera and Co, described the textural effect of the surface of a nanoporous carbon synthesized in two steps with phosphoric acid. The result revealed the development of highly specific surface area nanoporous carbon with 1937 m^2/g and 0.89 cm^3/g micropore volume which indicates the availability of available micropores (Moulefera *et al.,* 2020).

Table 2 Prepared nanoporous carbon from palm kernel shell-based carbon materials reported in literature

Precursor	Activating agent	Temp (^0C)	Time (hr)	BET (m^2/g)	Reference
PKS	H_3PO_4	500	2	700	Nicholas *et al.,* 2020
PKS	H_3PO_4/DES	600	2	1413	Pam, 2019
PKS	H_3PO_4	900	3	1324	Nasir *et al.,* 2018
PKS	H_3PO_4	600	1	456	Lee *et al.,* 2018
PKS	H_3PO_4	500	2	1099	Baby *et al.,* 2021
PKS	H_3PO_4	500	1	934	Ipeaiyeda *et al.,* 2020
PKS	H_3PO_4	600	2	1366	Guo and Lua, 2003
PKS	H_3PO_4	500	1	1680	Ulfah *et al.,* 2016
PKS	H_3PO_4	450	2	903	Murillo *et al.,* 2020
PKS	H_3PO_4	500	2	1257	Atunwa *et al.,* 2022
PKS	H_3PO_4	600	1	1559	Pam *et al.,* 2018
PKS	H_3PO_4	450	2	1653	Arami-Niya *et al.,* 2011

DES = Choline chloride/urea

Table 3 Prepared nanoporous carbon from other source precursor reported in literature

Precursor	Activating agent	BET (m^2/g)	Reference
Rattan sawdust	H_3PO_4	1151	Adebisi *et al.,* 2017
Posidonia oceánica	H_3PO_4	946	Ncibi *et al.,* 2014
Peach stones	H_3PO_4	1225	Maia *et al.,* 2010
Olive stones	H_3PO_4	990	Garcia-Mateos *et al.,* 2015
Chinese fir	H_3PO_4	2518	Zuo *et al.,* 2010
Phoenix dactylifera L	H_3PO_4	1225	Danish *et al.,* 2014
Chinese fir	H_3PO_4	1910	Zuo *et al.,* 2009
Prosopis ruscifolia	H_3PO_4	1638	Nabarlatz *et al.,* 2012
Starch-rich banana	H_3PO_4	2068	Romero-Anaya *et al.,* 2011
Waste tea	H_3PO_4	1398	Gokce and Aktas, 2014
Apricot and Peach stones	H_3PO_4	1740	Deng *et al.,* 2014
Olive stones	H_3PO_4	1014	Doke and Khan, 2017
Orange	H_3PO_4	1056	Guerrero-Perez *et al.,* 2011
Stem of date palm	H_3PO_4	1100	Jibril *et al.,* 2008
Hemp	H_3PO_4	1200	Williams and Reed, 2004
Chestnut	H_3PO_4	783	Gomez-Serrano *et al.,* 2005
Apple pulp	H_3PO_4	1004	Suarez-Garcia *et al.,* 2002
Date stones	H_3PO_4	1100	Hazourli *et al.,* 2009
Pinus sylvestris	H_3PO_4	1093	Alvarez *et al.,* 2007
Coffee	H_3PO_4	696	Tehrani *et al.,* 2015
Peanut shells	H_3PO_4	751	Gueye *et al.,* 2014
Corncobs	H_3PO_4	960	Ahmed and Theydan, 2014
E. camaldulensis Dehn	H_3PO_4	1239	Patnukao *et al.,* 2008
S. alterniflora	H_3PO_4	687	Li and Wang, 2009
Nut shells	H_3PO_4	1557	Tajar *et al.,* 2009
Olive fruit stone	H_3PO_4	1565	Obregon-Valencia *et al.,* 2014
Sky fruit husk	H_3PO_4	1211	Njoku *et al.,* 2014

4.2. Effect of activating time

One of the factors influencing the preparation of nanoporous carbon is the activation time. The total pore volume and mesopore volume formed during the activation process increase with increasing activation time, with the effect being more pronounced at low activation temperatures. These regularities are attributed to the fact that as activation time increases, the pores expand due to the burnout of carbon from the pore walls up to the burning of the barriers between the pores, resulting in a shift in pore size distribution from micropore to mesopore or even macropores (Memetova *et al.,* 2020a). It is well known that as the activation time increases, the productivity of the nanoporous carbon material surface area decreases, which is associated with pore sintering. As a result, the activation time is critical because it has a negative impact on carbon material during longer activation (Bagheri and Abedi, 2009). Romero-Anaya and Co. conducted research on the effect of activation time.

The study concluded that a longer activation time improves the morphology of carbon pores. However, when using H_3PO_4 activation, they were able to produce nanoporous carbon with micropore volumes of up to 0.76 cm^3/g and surface areas of 2100 m^2/g (Romero-Anaya *et al.,* 2011). Saygili and Güzel (2016) produced nanoporous carbon by considering the influence of activating time on the properties of carbon materials. They observed an increase in the total pore volume and specific surface area of 0.5 cm^3/g and 1093 m^2/g, respectively, when increasing the activating time from 0.5–1 h. In contrast, with a long activation time, such as 4 h, the surface area decreases, which could be due to pore sintering. In general, it is observed that the activation temperature is more important than the activation time, and thus it should be understood that longer activation times at high temperatures result in a degradation of the target carbon-based materials' characteristics (Theydan and Ahmed, 2012; Alhamed, 2006) .

4.3. Effect of activating agent

In recent years, various activating agents have been used based on the activation mechanism. These activating agents are regarded as alkaline, acidic, or neutral. Different carbon precursors cause these agents to react differently, resulting in different activation mechanisms. One of the oldest and most widely used chemical activation methods are both acid and alkali activation (Narvekar *et al.,* 2021; Wang *et al.,* 2020; Islam *et al.,* 2017; Ozpinar *et al.,* 2022). Xi et al. (2018) investigated the mechanisms of activating agents' effects on the degree of graphitization pore structure and surface area using KOH, K_2CO_3, $K_2C_2O_4$, and K_3PO_4. At 500^0 C, the degree of graphitization and porous structure of the carbon precursor using K_3PO_4 and $K_2C_2O_4$ were poorly developed, resulting in a weak reaction. On the other hand, using KOH and K_2CO_3 activation temperatures above 800^0 C contributed to a high degree of graphitization and extensive pore development. The most commonly used activating agent to activate various precursors is phosphoric acid, which can promote the formation of nanoporous carbon at low temperatures by accelerating the pyrolytic decomposition of the starting material and the formation of a cross-linked structure (Shi *et al.,* 2019). Among all acidic activating agents, H_3PO_4 appears to be the most effective for obtaining materials with micropore - mesopore porosity. This is confirm by Cao and Co. They produced a well-developed porous structure with favorable micropore volume 0.53 cm^3/g, mesopore volume 0.66 cm^3/g, and specific surface area of 1547 m^2/g by synthesizing a nanoporous carbon material from pine sawdust using (600^0 C/ 2:1 H_3PO_4) activating parameters (Cao *et al.,* 2018). Using H_3PO_4 as an activating agent in the preparation of porous materials allows for significant specific surface area and porosity values. Villota et al. (2019), for example, investigated the H_3PO_4 activation of cocoa husk waste at 450^0 C and found a specific surface area of 1139 m^2/g and a total pore volume of 1.062 cm^3/g (Villota *et al.,* 2019).

4.4. Effect of washing

Washing is necessary for the chemical activation of nanoporous carbon. Since this activating agent's chemical compounds remain in the carbon after activation, and in order to improve the porous structure, the spaces occupied must be cleaned through washing (Sych *et al.,* 2012). Acid, alkali, or water depending on the activating agent were used to wash the nanoporous carbon. Acid-treated nanoporous carbon has since been found to be more hydrophilic and thermally active. Jacob et al. (2018) washed the nanoporous carbon with nitric and hydrofluoric acid, increasing the mesopore volume fraction to 56% and the specific surface area from 2458 to 2970 m^2 /g.

4.5. Effect of impregnating ratio

The weight ratio of the activating agent to the precursor is known as the impregnation ratio. It was classified as one of the most important factors, along with carbonization, in the activation procedure that produces pores (Yahya *et al.,* 2018). Uner and Bayrak, investigated the effect of impregnation ratio on the properties of Arundo donax nanoporous carbon carbon. The impregnated ratios range from 0.5 to 1.5, and the raw materials were carbonized for 60 minutes at 400^0 C C. The nanoporous carbon with the highest surface area of 1781 m^2/g was produced by using an impregnation ratio of 1.5 and a carbonization temperature of 400^0 C (Uner and Bayrak, 2018).

The effect of H_3PO_4 - Precursor impregnation ratio 3, 4, and 5 and activation temperature 300, 400, and 500^0 C on the yield of mangrove-based nanoporous carbon was reported by Zakaria and Co. The results showed a gradual decrease in nanoporous carbon yield from 45 to 41% as the impregnation ratio was increased from 3 to 5 (Zakaria *et al.,* 2021). It should be noted that, a decrease in activated carbon yield with increasing impregnation ratio could be due to the reaction between the H_3PO_4 and the char and volatile matter during the activation process. However, Zhang and Co-researchers, on the other hand, investigate the effect of impregnation ratio using H_3PO_4 on the activation of coconut shell and wood-plastic composite for a catalytic pyrolysis process. The study showed a high H_3PO_4 impregnation ratio increased the dehydration step, resulting in a larger surface area and pore volume. This increase in surface area could be attributed to molecule accumulation on the nanoporous carbon surface as the impregnation ratio increases (Zhang *et al.,* 2020).

5. Modification of Nanoporous carbon derived from palm kernel shell

When carbon-based materials are activated, they form a well-defined porous structure materials. Even though most nanoporous carbons have sufficient adsorption capacity for the treatment of wastewater contaminants, researchers have always been convinced that much more can be accomplished to enhance nanoporous carbon adsorption efficiency. To boost the porosity and surface area of the particles, several methods have been studied which includes incorporation or modification of nanoporous carbon with metal, metal oxides, specific chemical compounds, polymeric materials for specific adsorption (Muhammad *et al.,* 2022; Joseph *et al.,* 2020). This can be achieved by surface modification using physical and chemical modification technology. Acid surface modification techniques is used to change nanoporous carbon surface into highly acidic by inserting carbon–oxygen surface groups. The chemical oxidation treatment is well adopted to enrich oxygen atoms by employing oxidizing gases agent such as O_2, O_3, CO_2, steam, etc, or oxidizing solutions for example HNO_3, H_2SO_4, H_2O_2, etc (Bhatnagar *et al.,* 2013). The presence of nitrogen functional groups, which can bind with protons resonating -electrons of carbon aromatic rings that attracted protons, can explain the basicity of nanoporous carbon. There are two ways to introduce nitrogen- groups on the surface of the nanoporous carbon that includes surface modification with reagents like ammonia, nitric acid, and amines and activation of raw carbon material with a high nitrogen content (Drage *et al.,* 2007).

Many approaches for enhancing the qualities and functions of carbon materials have been developed. Carbon materials ranging from micropores to macropores, have been comprehensively explored, with an emphasis on controlling the precursor, became easier to control the shape/orientation, doping of heteroatom as well as hybridization with other functional materials (Khan *et al.,* 2019). Many nanocarbon compounds, such as nanoporous carbon and templated porous carbons, were synthesized through a different route of carbonization and activation processes through a well control pores structure (Haque *et al.,* 2018). Carbon materials were being synthesized using a variety of templated methods, including direct carbonization from carbon precursors and soft- and hard-templating techniques. Moreover, the electrochemical performance of nanoporous carbon as electrode materials can be improved through the doping of heteroatoms such as nitrogen, sulfur, and boron (Tan *et al.* 2019).

Pam et al., (2018) reported the doped EDTA on palm kernel shell for the removal of Pb(II). The study shows the modification of palm kernel shell as precursor with ethylenediaminetetraacetic acid (EDTA) with higher BET surface area of 1100.7m^2/g for the removal of Pb (II) in aqueous solution using batch and column studies. However, Pam (2019) reported a novel method of synthesis of nanoporous carbon material from palm kernel shell using choline – urea deep eutectic solvent. The studies demonstrated good BET surface area of 1413m^2/g for the removal of Pb (II) in aqueous solution. Rabia Baby and Co. in two different studies used nanoporous carbon for the treatment of heavy metal in water. Thus, they works on modifying nanoporous carbon from palm kernel shell. The studies shows the modification of nanoporous carbon with nitric acid (HNO_3) and a sulfo (SO_4^{-2}) group purposely for the removal of heavy metals from contaminated water respectively (Baby *et al.,* 2021; Baby *et al.,* 2023). Conversely, similar report was reported for chemically modified palm kernel shell for the removal of heavy metals from waste water (Imran – Shaukat *et al.,* 2021; Baby and Hussein, 2020). The adsorption of phenol from palm kernel shell as precursor was reported. The results show the modification of nanoporous carbon with silver nanoparticle with an optimum phenol uptake of 91.70% (Aremu *et al.,* 2020). Similarly, Kyi et al., (2020) reported the removal of crystal violet using palm kernel shell derived biochar from textile waste water. The study shows a good percentage removal and adsorption capacity with increased in pH of the solution which enhances the electrostatic attraction between crystal violet molecules and biochar derived palm kernel shell. Ismaiel et al. (2013) works on the modification of nanoporous carbon material from palm kernel shell. The study shows the modification of the precursor palm kernel shell with task – specific ions – liquids as novel adsorbent for the removal of mercury from contaminated water using batch adsorption technique.

Additionally, it was reported by Ipeaiyeda *et al.,* 2020 that a nanoporous carbon from palm kernel shell was modified with ammonium and ammonium acetate with a good surface area in the range of 934 – 1646 m^2/g and it was confirmed by FTIR and SEM analysis. However, Oladele *et al.,* 2020 reported a modified palm kernel shell with cassava peel for straitening of epoxycomposites. The study shows a treatment of palm kernel shell and cassava peel as hybrid reinforcement on selected mechanical properties. The results show a good means of enhancing the mechanical properties with less porosity content. Baffour-Awuah *et al.,* 2021 reported a precursor features of palm kernel shell toward polymer mono-composites. The results revealed depending on geographical location of palm kernel shell (lignin, cellulose, and hemicellulose) shows palm kernel shell as a good filler material in polymer composites. Several researchers shows modification of palm kernel shell (nanoporous carbon) with different polymer composites; PKS/ 3-aminopropyl trimethoxysilane for tensile strength (Daud *et al.,* 2016), PKS/unsaturated polyester (Sahari and Maleque, 2016), PKS/polyvinyl alcohol (Alias *et al.,* 2018), PKS/polylactic acid (Dato'Hasnan *et al.,* 2016).

Nanoporous carbons have also been used as additives to semiconductors e.g., TiO_2/nanoporous carbon, Bi_2WO_6/nanoporous carbon, WO_3/nanoporous carbon and these materials have been greatly applied as photocatalysts (Gomis-Berenguer *et al.,* 2017). Some other modifications of nanoporous carbon materials earlier reported are citric acid modification (Chen *et al.,* 2003), NH_3 modification (Liu *et al.,* 2008), and liquid-phase oxidation (Song *et al.,* 2010). Novel materials have been reported by utilizing several modification methods together. For example, Gao *et al.,* (2018) prepared porous carbon nanofibers via co-doped with nitrogen and sulfur (N, S-doped). Some reported modified nanoporous carbon materials from different precursor and their applications are given in Table 4.

Table 4 Some modified nanoporous carbon materials reported in different precursor

Modified Nanoporous Carbon Materials	Applications	References
NPC@Nafion	Simultaneous determination of dopamine and uric acid	Baikeli *et al.,* 2019a
NPC@H_2O_2 & H_2SO_4	Supercapacitor	Song *et al.,* 2020
NPC@H_2O_2	Oxidation removal of metronidazole	Ariyanto *et al.,* 2019
NPC@Iron & Nitrogen	Determination of chloramphenicol and metronidazole	Baikeli *et al.,* 2020
NPC@polyelectrolyte	Removal of aromatic organic acid	Anbia and Salehi 2012
NPC@ doped N and S	Sodium storage	Liu *et al.,* 2018
NPC@N-doped	Advanced sodium storage	Zhao *et al.,* 2017
NPC@Nitrogen doped	Voltammetry detection of Pb(II)	Baikeli *et al.,* 2019b
NPC@Fe_3O_4	Simultaneous determination of diethylstilbestrol and 17β – estradiol	Chen *et al.,* 2018
NPC@MIP	Sensor for detection of calycosin	Sun *et al.,* 2019
NPC@amine	Adsorption of CO_2 & CH_4	Salehi and Hosseinifard 2021
NPC@polyethylenimine	Adsorption of mercury	Saleh *et al.,* 2017
NPC@disulfide polymer	Heavy metals removal	Ko *et al.,* 2018
NPC@polysulfide	Chromium removal	Mortazavian *et al.,* 2019
NPC@bakers yeast	Magnetic solid phase extraction of Hg	Mahmoud *et al.,* 2015
NPC@nano-sized α-Fe_2O_3	Enhanced removal of Cr(II)	Li *et al.,* 2019
NPC@iron oxide catalyst	Degradation of SO_2	Stanisavljevic *et al.,* 2019
NPC@$ZnFe_2O_4$	Microwave absorber	Di *et al.,* 2021

6. Applications of nanoporous carbon

Nanoporous carbon (eco-friendly, cost-effective, non-toxic) has a high specific surface area, a large pore volume, and a hierarchical porous structure that is suitable for adsorption of organic and inorganic contaminants from aqueous environments (Ouyang *et al.,* 2020; Han *et al.,* 2018b). They had been actively used in the remediation of toxic and harmful pollutants such as heavy metals, dyes, and pesticides (Khan *et al.,* 2021).

6.1. Water purification

Water is the most valuable renewable resource and a serious threat from pollution caused by anthropogenic activities, such as industrialization and rapid urbanization. Based on their chemical composition, water pollutants were classified as inorganic (metal ions) and organic (dye) category (Memetova *et al.,* 2022a). Nanoporous carbon material is widely used in the purification of industrial wastewater and contaminated groundwater due to their remarkable high specific surface area, high pore volume, and adjustable surface physical and chemical properties (Guo *et al.,* 2019). One of the 2030 sustainable development goals is clean hygienic water, nanoporous carbons are being used in water purification to remove contaminants and pollutants (Wong *et al.,* 2018). Several studies have reported the elimination of different pollutants from water using carbon-base materials. include the removal of heavy metals (Gottipati 2012; Momčilović *et al.,* 2011; Xu *et al.,* 2015; Zhang *et al.,* 2011), caffeine (Lin and Chen 2016), fluorides (Wendimu *et al.,* 2017), herbicides (Sarker *et al.,* 2017), biowastes (Wong *et al.,* 2018). Torad *et al.,* (2014) also demonstrated the use of nanoporous carbon materials in removing a range of pollutants from contaminated water. Fahmi et al. (2019) reported a high absorption capacity for the bio-absorbent in removing methylene blue dye from its solution after obtaining nanoporous carbon from low temperature pyrolysis of palm kernel shell. Similar research has reported the use of palm kernel shell-based nanoporous carbon carbon to remove crystal violet from wastewater, with absorption efficiencies of 86.4% crystal violet (Kyi *et al.,* 2020). Moreover, Hayawin et al., (2020) and Hairuddin et al., (2019) synthesized a bioabsorbent of nanoporous carbon from palm kernel shell for lowering pollutant levels in palm oil mill effluent and removing up to 93.39% of phenol from wastewater respectively. Table 5 summarised some of the reported NC from PKS that was used in water treatment.

6.2. Heavy metals removal

Nanoporous carbon is one of the most universal adsorbents for the remediation of noxious metal impurities, because of its high surface area, porous texture, and surface chemistry explain the common applications in adsorption of heavy metal ions: mercury Hg (II), chromium Cr (III) and Cr (IV), cadmium Cd (II), nickel (Ni), zinc (Zn), copper (Cu), manganese (Mn), arsenic As (V), and lead Pb (II) (Ahmad and Azam, 2019; Chuah *et al.,* 2005; Khosravi *et al.,* 2018). Metal ions from corrosion of pipes, soldered joints, and plumbing materials pollute aquatic habitats are regularly found in contaminated streams, where these metal ions are known to cause health issues (Zhou *et al.,* 2020), prompting researchers to investigate techniques to manage their concentration in water, even in tiny amounts (Guo *et al.,* 2019).

Table 5: Examples of nanoporous carbon materials derived from palm kernel shell used in water treatment reported in literature

Reference	Pollutant	% Removal/Adsorption (mg/g)
Katibi *et al.,* 2021	Bisphenol	94.2%
Yi *et al.,* 2014	Uranium	51.81 mg/g
Zaini *et al.,* 2017	Methyl violet dye	42 mg/g
Adlim *et al.,* 2021	Ammonia vapor odour	1 – 4 mg/g
Hamad *et al.,* 2010	4-chloroguaiacol removal	454.4 mg/g
Tan *et al.,* 2009	2,4,6-trichlorophenol	9.04
Panneerselvam *et al.,* 2012	Rhodamine B Dye	625 mg/g
Anisuzzaman *et al.,* 2021	Methylene Blue	97.63%
Hasana *et al.,* 2021	Methylene Blue	98.5%
Jawing *et al.,* 2021	Methylene Blue	99%
Yeboah, 2021	Methylene Blue	417 mg/g
Muhammad Razi *et al.,* 2018	Greywater	56.44% COD
Garcia *et al.,* 2018	Dye removal	225.3 mg/g

Below in Table 6 summarized a few examples of nanoporous carbon derived from palm kernel shell used in the removal of heavy metals.

6.3. Adsorption of gases

Nanoporous carbon has found effective usage in the adsorption of greenhouse gases and other polluted gases in the environment that are produced from burning of fossil fuels (Hossain *et al.,* 2019). Table 7 has summarized some of the application of NC for gas adsorption purpose. According to Ogungbenro *et al.,* (2017), nanoporous carbon is a promising solid adsorbent that can be used to adsorb CH_4, CO_2, H_2S, H_2 and NO_2 gases due to its numerous advantages such as low cost, high surface area, easy regeneration, insensitivity to moisture, high gas adsorption capacity at normal atmosphere, sufficient pore size distribution, high mechanical stability, and very low energy requirement. The reported mode of adsorption of these pollutant gases is via H-H interactions, dipole-dipole bonds, and covalent bonds between the gas and functional groups on the surface of the nanoporous carbon, resulting in increased efficiency (Reza *et al.,* 2020). The adsorption of these harmful gases by nanoporous carbon is determined by the surface area, micropore structure, and adsorption capability (Sharma *et al.,* 2011; Nasri *et al.,* 2014).

Recently, solid based adsorbents for capturing and storage of CO_2 have attracted recognition. Among the different forms of material used, such as zeolites, metal organic frameworks and amine-doped porous for solid based adsorbents, nanoporous carbons have been chosen as the precursor of choice due to their low cost and easy availability. This is mainly due to their inherent high surface area with the presence of developed microspores and mesopores, their chemical and thermal stability, and their easily tunable chemistry and structure (Volperts *et al.,* 2017)**.**

Table 6: Examples of nanoporous carbon materials derived from palm kernel shell with their heavy metals removal/adsorptions reported in literature

Authors	Heavy metals	pH Range	(%) Removal/Adsorption (mg/g)
Baby et al., 2023	Cr^{+6}, Cd^{2+}, Zn^{2+},	4 – 6	83 – 99%
Baby *et al.,* 2021	Pb^{2+}		
Baby and Hussein, 2020			
Baby *et al.,* 2019			
Pam, 2019	Pb^{2+}	4 – 5	43 – 104 mg/g
Pam *et al.,* 2018			
Yerima *et al.,* 2021	Pb^{2+}	5 – 7	96%
Lin *et al.,* 2020	Cr^{6+}		39.67 mg/g
Naihi *et al.,* 2021	Cd^{2+}	6	227 mg/g
Jawing *et al.,* 2021	Pb^{2+}	4.5 - 7	95 – 98 %
Isokise *et al.,* 2021	Pb^{2+}	4	222 mg/g
Muhammad *et al.,* 2011	Cd^{2+} - Zn^{2+}	5 – 7	53.13 mg/g – 36.83 respectively
Wang *et al.,* 2009	Hg^{2+}	5.5	800 mg/g
Imran – Shaukat *et al.,* 2021	Cr^{6+}, Ni^{2+}, Cu^{2+}	7	42.97%, 96.77% and 99.29% respectively
Asnawi *et al.,* 2019	Cu^{2+}	3 – 6	12 mg/g
Razavi *et al.,* 2019	Cr^{6+}	2	125 mg/g
Rilyanti and Sari *et al.,* 2021	Cd^{2+}	6	80%
Abdullah *et al.,* 2018	Hg^{2+}	Constant pH	97.7%/22.98 mg/g
Isa *et al.,* 2022	Hg^{2+}	6	70 – 90%
Faisal *et al.,* 2021	Pb^{2+}		93%
Mansa *et al.,* 2021	Pb^{2+}		200mg/g
Prabu *et al.,* 2020	Cd^{2+}	6	425 mg/g

Rashidi and Yusup (2021) reported that nanoporous carbon produced from palm kernel shells by 1 – step activation and a pyrolysis process displayed a remarkable CO_2 adsorption capacity of 2.14 mmol g^{-1} at 1 MPa and 25 °C**.** Conversely, Nasri et al., (2014) reported a 2 – step activation with CO_2 adsorption capacity of 1.66 mmol/g. Prasetyo and co – workers reported a CO_2/CH_4 separation/adsorption by nanoporous carbon derived from palm kernel shell via molecular sieves. The finding showed, at 1 atm and 30^0C an adsorption capacity of 2 mmol/g and 1.1 mmol/g for CO_2 and CH_4 respectively. However, in their conclusion of research showed that CO_2 can be separated from the mixture of CO_2/CH_4 to a high purity of 95% CH_4 (Prasetyo *et al.,* 2020). Interestingly, similar result was reported by Ariyanto *et al.,* 2020. In the year 2019, and 2023, Rashidi and Yusop using nanoporous carbon derived from palm kernel shell reported an adsorption capacity of CO_2 to the range of 2.13 – 4.32 mmol/g, similar result was presented by Rashidi et al (2021). An impregnated nanoporous carbon from palm kernel shell loaded with metal oxides was reported for CO_2 capture. The authors elucidated that loaded nanoporous carbon help to promote remarkable CO_2 adsorption due to its reaction with the metal oxides (Hidayu and Muda, 2016). Hydrogen is a promising energy carrier that has the potential to ease the transition from fossil fuels to sustainable energy sources while producing no harmful byproducts. Physical adsorption in porous materials opens up the possibility of flexible hydrogen storage. Hydrogen molecules that have been physically adsorbed are weakly bound to a surface and thus easily released.

6.4. Energy storage and supercapacitor

Because of their long cycle life and high-power density, supercapacitors are used in energy storage devices. Carbon-based materials are used as electrode active resources in commercially available supercapacitors due to their remarkable cycle stability, high power density, ease of fabrication, and non-toxicity (Volperts *et al.,* 2015). Recent research has shown that fabricating nanoporous carbon with or without functionalization with various additions improves electrochemical performance compared to non-modified nanoporous carbon (Shao *et al.,* 2020). Nanoporous carbon is now the most extensively used electrode material due to its unique functional groups and high specific surface area. Depared nanoporous carbon materials have demonstrated considerable potential for energy storage applications, despite their chaotic architecture. Thus, these materials should be rapidly researched and scaled up to fulfil their potential usage in electrochemical energy storage devices (Bai *et al.,* 2017; Wang *et al.,* 2017). There are several reviews of carbon-based materials for super capacitors in the literature. However, a study of nanoporous carbon-based functional materials produced from waste resources is urgently required

In 2017, Xu *et al.* reported a nanoporous activated carbon material from palm kernel shell with an average pore size of 2.3 nm and 2760 m^2 g^{-1} surface areas. The material was proposed as a potential candidate as electrode material for supercapacitor because it's doped with nitrogen, sulfur and phosphorus that exhibited an excellent electrochemical performance and cycling stability of 380 F g^{-1}**.** Nasir *et al.,* (2018) reported that good performance was obtained when nanoporous carbon produced from palm kernel shell acts as electrode materials in super capacitor. The material demonstrated high specific capacitance (up to 434 F g^{-1} at 0.1 A g^{-1}). Several researchers successfully used nanoporous carbon derived from palm kernel shell for electrochemical storage capacitance (Kaarik *et al.,* 2020; Misnon *et al.,* 2019), and heteroatom – doped nanoporous carbon for lithium – sulfur batteries for energy storage (Han *et al.,* 2020). Zhang and co – workers reported a nanoporous carbon of 2218 m^2 g^{-1} surface area with high conductivity and disordered surface morphology. Their finding elucidated an advantageous working super capacitor in an aqueous electrolyte that showcase a specific capacitance of 312 F g^{-1} at 1 A g^{-1} (Zhang *et al.,* 2016). In a recent review, Li *et al.,* (2020b) reviewed progress on the synthesis and applications of porous carbon materials and showed their increasing applications in several areas including electrochemistry and hydrogen storage. Sdanghi *et al.,* (2020) successfully applied nanoporous carbon materials for hydrogen storage and compression. The system was proposed to become a valid alternative to mechanical compressors from an industrial point of view.

6.5. Medicine and healthcare

Nanoporous carbon materials have been greatly applied in medicines as drug delivery agents. Desai *et al.,* (2007) extensively discussed nanoporous materials used as implants for controlled drug delivery. Also, nanoporous carbon materials with metalorganic frameworks (MOFs) which exhibited very high biocompatibility were prepared and suggested as intracellular drug delivery carriers (Torad *et al.,* 2014b). Heong and Co works on nanoporous carbon derived palm kernel shell for urea removal during dialysis treatment. They reported a poor uremic toxin clearance causes toxic waste to build up in the bodies of patients, leading to cardiovascular disease and death. To improve urea removal efficiency and regenerate the dialysate, nanoporous materials with superior pore properties and adsorption capacity could be introduced to the hemodialysis system (Ooi *et al.,* 2019). The ability of nanoporous carbon derived palm kernel shell (PKS) to remove pharmaceutically active compounds Atenolol (ATE), Acebutolol (ACE), and Carbamazepine (CBM) was reported with the maximal adsorption capabilities of ATE, ACE, and CBM were 0.69, 0.67, and 0.72 mmol/g, respectively (To *et al.,* 2017). Conversely, Yi et al. reported the removal of uranium (threat to human health resulting in serious lung, kidney, and liver damages, cancer, leukemia, genetic aberrations, and even death) using nanopororous carbon derived pks with adsorption capacity of 51.81 mg/g (Yi *et al.,* 2014). Recently, Yallappa *et al.,* (2018) reported nanoporous carbon from oil palm leaves as a good candidate for cellular imaging and targeted drug delivery in cancer treatment.

Table 7: Examples of nanoporous carbon materials derived from other precursors for gas adsorption reported in literature

Source	Gas	Adsorption capacity	Reference
Olive stones	CH_4	4.69 mmol/g	Djeridi *et al.,* 2015
Coconut shell	CO_2	1.8 mmol/g	Rashidi *et al.,* 2014
Almond shell	CO_2	2.7 mmol/g	Gonzalez *et al.,* 2013
Rice husk	CO_2	1.3 mmol/g	Boonpoke *et al.,* 2011
Peanut shell	CO_2	4.0 mmol/g	Deng *et al.,* 2015
Bamboo	CO_2	4.5 mmol/g	Wei *et al.,* 2012
Palm stone	CO_2	2.7 mmol/g	Vargas *et al.,* 2013

Syamsurizal et al., (2019) contrasted the absorption capacity of commercial charcoal to nanoporous carbon from PKS to solve plaque and tooth discoloration. However, Lestari et al., (2019) created a powdered deodorant preparation from nanoporous carbon base pks for sweat absorption. The results of this synthesis revealed that the powder had superior storage stability and sweat absorption from the skin when compared to an ordinary deodorant roll-on.

6.6. Catalyst support

The high cost and susceptibility of traditional catalysts such as Pt and Pd have triggered intense research into the field of non-noble metals catalysts supported on nanoporous carbon. These include compounds of transition metals (Fe, Co, Ni, Mn) such as iron carbide and iron nitride supported on porous carbons that have been used for oxygen reduction reactions (ORR) (Ren *et al.,* 2016b; Yang *et al.,* 2015). Also, metal-free catalysts (doped with B, N, P, S, Cl, I, *etc*.) supported on nanoporous carbon have been applied for such ORR reactions (Sun *et al.,* 2013). Abdullah et al. created a highly effective bifunctional catalyst from palm kernel shell by hydrothermal – assisted carbonazation for biodiesel production. These nanoporous carbon were tested for its suitability for simultaneous esterification and transesterification processes that produces 95.36 ± 1.4% of biodiesel and undergoes five subsequent reaction cycles (Abdullah *et al.,* 2021). Liew et al. synthesize nanoporous carbon catalyst support from palm kernel shell via microwave vacuum pyrolysis. This study extended the nickel on the nanoporous carbon material and tested for their performance in the methane dry reforming reaction. The catalysts had a high methane conversion rate (up to 43%) and produced about 22 percent gaseous products CO + H_2 (Liew *et al.,* 2018). These findings indicate that nanoporous carbon derived from palm kernel shell microwave pyrolysis is a viable catalytic support material. Sulfonated carbon catalysts were generated from palm kernel shell biomass via direct, chemical, and template carbonization processes at 400 and 800 ^{0}C in a CO_2 environment respectively for glycerol acetylation evaluation. Their finding showed a higher selectivity to triacetin (58.9%) with over 97% glycerol conversion template method with s 5.8 and 32.2% monoacetin and diacetin selectivity respectively (Nda - Umar *et al.,* 2020). The catalyst's catalytic activity was attributable to the synergistic effect of good physicochemical qualities, such as textural properties and a high acidic content. Furthermore, Abdullah et al., (2020) used nanoporous carbon from PKS as transesterification-esterification nanocatalysts for the conversion of waste cooking oil to biodiesel. Accordingly, Quah et al., (2020) used the same material biochar infused with Fe_3O_4 to create a magnetic and sulfonated catalyst for biodiesel transesterification from used cooking oil. Another study used fluidized bed catalytic pyrolysis of PKS, implying massive oil potential for biodiesel and petrochemical refinery (Kim *et al.,* 2014).

7. Conclusion and future direction

The field of preparing functional nanoporous carbon materials is fast and widely evolving. Literature has revealed that today, nanoporous carbon materials can be prepared cheaply from a range of carbon-rich biowaste materials, such as shells, roots, husks, sawdust, stall, etc. These materials can be modified to give materials with properties for targeted applications in environmental remediation and water treatment, adsorption of gases, solar cells, energy storage and in medicine. Nowadays, great challenges of water, environment, health and energy avails and this review should provide a basis for exploring more sources, derivatization of nanoporous carbons for meeting these challenges.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgement

The authors would like to thank to the Tertiary Education Fund (TETFUND) for supporting this project. The authors confirmed that there is no conflict of interests to disclose.

References

"Activated Carbon — Market Report — Roskill." (n.d.). <https://roskill.com/market-report/activated-carbon/> (Jul. 23, 2021)

Abdullah, R. F., Rashid, U., Taufiq-Yap, Y. H., Ibrahim, M. L., Ngamcharussrivichai, C., & Azam, M. (2020). Synthesis of bifunctional nanocatalyst from waste palm kernel shell and its application for biodiesel production. *RSC advances*, *10*(45), 27183-27193. https://doi.org/10.1039/D0RA04306K

Abdullah, N. S., Sharifuddin, S. S., & Hussin, M. (2018). Study on adsorption of mercury from aqueous solution on activated carbons prepared from palm kernel shell. In *Key Engineering Materials* (Vol. 783, pp. 109-114). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/KEM.783.109

Abioye, A. M., & Ani, F. N. (2015). Recent development in the production of activated carbon electrodes from agricultural waste biomass for supercapacitors: A review. *Renewable and sustainable energy reviews*, *52*, 1282-1293. https://doi.org/10.1016/j.rser.2015.07.129

Adebisi, G. A., Chowdhury, Z. Z., Abd Hamid, S. B., & Ali, E. (2017). Equilibrium isotherm, kinetic, and thermodynamic studies of divalent cation adsorption onto Calamus gracilis sawdust-based activated carbon. *BioResources*, *12*(2), 2872-2898. Htttps://doi:10.15376/biores.12.2.2872-2898

Adlim, M., Rahmayani, R. F. I., Zarlaida, F., Hanum, L., Rizki, M., Manatillah, N. U., & Muktaridha, O. (2021). Simple Preparations and Characterizations of Activated-Carbon-Clothes from Palm-Kernel-Shell for Ammonia Vapor Adsorption and Skim-Latex-Odor Removal. *Indonesian Journal of Chemistry*, *21*(4), 920-931. https://doi.org/10.22146/ijc.63570

Aguayo-Villarreal, I. A., Bonilla-Petriciolet, A., & Muñiz-Valencia, R. (2017). Preparation of activated carbons from pecan nutshell and their application in the antagonistic adsorption of heavy metal ions. *Journal of Molecular Liquids*, *230*, 686-695. https://doi.org/10.1016/j.molliq.2017.01.039

Ahmad, A., & Azam, T. (2019). Water purification technologies. In *Bottled and Packaged Water* (pp. 83-120). Woodhead Publishing. https://doi.org/10.1016/B978-0-12-815272-0.00004-0

Ahmed, M. J., & Theydan, S. K. (2014). Fluoroquinolones antibiotics adsorption onto microporous activated carbon from lignocellulosic biomass by microwave pyrolysis. *Journal of the Taiwan Institute of Chemical Engineers*, *45*(1), 219-226. https://doi.org/10.1016/j.jtice.2013.05.014

Alias, N. F., Ismail, H., Wahab, M. K., Ragunathan, S., Ardhyananta, H., & Ting, S. S. (2018). Development of new material based on polyvinyl alcohol/palm kernel shell powder biocomposites. *Advances in Environmental Studies*, *2*(2), 98-107. https://doi.org/10.1016/j.fuel.2023.127523

Alhamed, Y. A. (2006). Activated carbon from dates' stone by $ZnCl_2$ activation. *JKAU Eng Sci*, *17*(2), 5-100.

Alvarez, P., Blanco, C., & Granda, M. (2007). The adsorption of chromium (VI) from industrial wastewater by acid and base-activated lignocellulosic residues. *Journal of Hazardous Materials*, *144*(1-2), 400-405. https://doi.org/10.1016/j.jhazmat.2006.10.052

Ambika, S., Kumar, M., Pisharody, L., Malhotra, M., Kumar, G., Sreedharan, V., & Bhatnagar, A. (2022). Modified biochar as a green adsorbent for removal of hexavalent chromium from various environmental matrices: Mechanisms, methods, and prospects. *Chemical Engineering Journal*, 135716. https://doi.org/10.1016/j.cej.2022.135716

Anbia, M., & Salehi, S. (2012). Synthesis of polyelectrolyte-modified ordered nanoporous carbon for removal of aromatic organic acids from purified terephthalic acid wastewater. *Chemical Engineering Research and Design*, *90*(7), 975-983. https://doi.org/10.1016/j.cherd.2011.10.010

Ania, C. O., Armstrong, P. A., Bandosz, T. J., Beguin, F., Carvalho, A. P., Celzard, A., & Pereira, M. F. R. (2020). Engaging nanoporous carbons in "beyond adsorption" applications: Characterization, challenges and performance. *Carbon*, *164*, 69-84. https://doi.org/10.1016/j.carbon.2020.03.056

Arami-Niya, A., Daud, W. M. A. W., & Mjalli, F. S. (2011). Comparative study of the textural characteristics of oil palm shell activated carbon produced by chemical and physical activation for methane adsorption. *Chemical Engineering Research and Design*, *89*(6), 657-664. https://doi.org/10.1016/j.cherd.2010.10.003

Aremu, M. O., Arinkoola, A. O., Olowonyo, I. A., & Salam, K. K. (2020). Improved phenol sequestration from aqueous solution using silver nanoparticle modified palm kernel shell activated carbon. *Heliyon*, *6*(7), e04492.

Ariyanto, T., Sarwendah, R. A. G., Amimmal, Y. M. N., Laksmana, W. T., & Prasetyo, I. (2019). Modifying nanoporous carbon through hydrogen peroxide oxidation for removal of metronidazole antibiotics from simulated wastewater. *Processes*, *7*(11), 835. https://doi.org/10.3390/pr7110835

Asnawi, T. M., Husin, H., Adisalamun, A., Rinaldi, W., Zaki, M., & Hasfita, F. (2019). Activated carbons from palm kernels shells prepared by physical and chemical activation for copper removal from aqueous solution. In *IOP Conference Series: Materials Science and Engineering* (Vol. 543, No. 1, p. 012096). IOP Publishing. DOI 10.1088/1757-899X/543/1/012096

Atunwa, B. T., Dada, A. O., Inyinbor, A. A., & Pal, U. (2022). Synthesis, physiochemical and spectroscopic characterization of palm kernel shell activated carbon doped AgNPs (PKSAC@ AgNPs) for adsorption of chloroquine pharmaceutical waste. *Materials Today: Proceedings*, *65*, 3538-3546. https://doi.org/10.1016/j.matpr.2022.06.099

Ayinla, R. T., Dennis, J. O., Zaid, H. B. M., Usman, Fahad., & Yar, Asfand. (2020). Effect of particle size on the physical properties of activated palm kernel shell for supercapacitor application. In *Key Engineering Materials* (Vol. 833, pp. 129-133). Trans Tech Publications Ltd. https://doi.org/10.4028/www.scientific.net/KEM.833.129

Azzaz, A. A., Jeguirim, M., Jellali, S., & Ghimbeu, C. (2020). Hydrothermal carbonization and slow pyrolysis as two thermal techniques for the production of carbon rich, added-value materials using olive milling byproduct: Quid optimus?. In *2020 11th International Renewable Energy Congress (IREC)* (pp. 1-4). IEEE. https://doi.org/10.1109/IREC48820.2020.9310403

Babinszki, B., Jakab, E., Terjék, V., Sebestyén, Z., Várhegyi, G., May, Z. & Czégény, Z. (2021). Thermal decomposition of biomass wastes derived from palm oil production. *Journal of Analytical and Applied Pyrolysis*, *155*, 105069. https://doi.org/10.1016/j.jaap.2021.105069

Baby, R., Hussein, M. Z., Zainal, Z., & Abdullah, A. H. (2023). Preparation of functionalized palm kernel shell bio-adsorbent for the treatment of heavy metal-contaminated water. *Journal of Hazardous Materials Advances*, 100253. https://doi.org/10.1016/j.hazadv.2023.100253

Baffour-Awuah, E., Akinlabi, S. A., Jen, T. C., Hassan, S., Okokpujie, I. P., & Ishola, F. (2021). Characteristics of palm kernel shell and palm kernel shell-polymer composites: a review. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1107, No. 1, p. 012090). IOP Publishing. **DOI** 10.1088/1757-899X/1107/1/012090

Bagheri, N., & Abedi, J. (2009). Preparation of high surface area activated carbon from corn by chemical activation using potassium hydroxide. *Chemical engineering research and design*, *87*(8), 1059-1064. https://doi.org/10.1016/j.cherd.2009.02.001

Bai, Q., Xiong, Q., Li, C., Shen, Y., & Uyama, H. (2017). Hierarchical porous carbons from poly (methyl methacrylate)/bacterial cellulose composite monolith for high-performance supercapacitor electrodes. *ACS Sustainable Chemistry & Engineering*, *5*(10), 9390-9401. https://doi.org/10.1021/acssuschemeng.7b02488

Benedetti, V., Patuzzi, F., & Baratieri, M. (2018). Characterization of char from biomass gasification and its similarities with activated carbon in adsorption applications. *Applied Energy*, *227*, 92-99. https://doi.org/10.1016/j.apenergy.2017.08.076

Bergna, D., Varila, T., Romar, H., & Lassi, U. (2018). Comparison of the properties of activated carbons produced in one-stage and two-stage processes. *Carbon*, *4*(3), 41. https://doi.org/10.3390/c4030041

Bhatnagar, A., Hogland, W., Marques, M., & Sillanpää, M. (2013). An overview of the modification methods of activated carbon for its water treatment applications. *Chemical Engineering Journal*, *219*, 499-511. https://doi.org/10.1016/j.cej.2012.12.038

Bohli, T., Ouederni, A., Fiol, N., & Villaescusa, I. (2015). Evaluation of an activated carbon from olive stones used as an adsorbent for heavy metal removal from aqueous phases. *Comptes rendus chimie*, *18*(1), 88-99. https://doi.org/10.1016/j.cej.2012.12.038

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A. & Van Zwieten, L. (2022). Multifunctional applications of biochar beyond carbon storage. *International Materials Reviews*, *67*(2), 150-200. https://doi.org/10.1080/09506608.2021.1922047

Boonpoke, A., Chiarakorn, S., Laosiripojana, N., Towprayoon, S., & Chidthaisong, A. (2011). Synthesis of activated carbon and MCM-41 from bagasse and rice husk and their carbon dioxide adsorption capacity. *Journal of Sustainable Energy & Environment*, *2*(2), 77-81.

Cao, L., Iris, K. M., Tsang, D. C., Zhang, S., Ok, Y. S., Kwon, E. E. & Poon, C. S. (2018). Phosphoric acid-activated wood biochar for catalytic conversion of starch-rich food waste into glucose and 5-hydroxymethylfurfural. *Bioresource technology*, *267*, 242-248. https://doi.org/10.1016/j.biortech.2018.07.048

Ceyhan, A. A., Şahin, Ö., Saka, C., & Yalçın, A. (2013). A novel thermal process for activated carbon production from the vetch biomass with air at low temperature by two-stage procedure. *Journal of analytical and applied pyrolysis*, *104*, 170-175. https://doi.org/10.1016/j.jaap.2013.08.007

Cha, J. S., Park, S. H., Jung, S. C., Ryu, C., Jeon, J. K., Shin, M. C., & Park, Y. K. (2016). Production and utilization of biochar: A review. *Journal of Industrial and Engineering Chemistry*, *40*, 1-15. https://doi.org/10.1016/j.jiec.2016.06.002

Chen, X., Shi, Z., Hu, Y., Xiao, X., & Li, G. (2018). A novel electrochemical sensor based on Fe_3O_4-doped nanoporous carbon for simultaneous determination of diethylstilbestrol and 17β-estradiol in toner. *Talanta*, *188*, 81-90. https://doi.org/10.1016/j.talanta.2018.05.063

Chen, J. P., Wu, S., & Chong, K. H. (2003). Surface modification of a granular activated carbon by citric acid for enhancement of copper adsorption. *Carbon*, *41*(10), 1979-1986. https://doi.org/10.1016/S00086223(03)00197-0

Choi, G. G., Oh, S. J., Lee, S. J., & Kim, J. S. (2015). Production of bio-based phenolic resin and activated carbon from bio-oil and biochar derived from fast pyrolysis of palm kernel shells. *Bioresource technology*, *178*, 99-107. https://doi.org/10.1016/j.biortech.2014.08.053

Choma, J., & Jaroniec, M. (2006). Characterization of nanoporous carbons by using gas adsorption isotherms. In *Interface Science and Technology* (Vol. 7, pp. 107-158). Elsevier. https://doi.org/10.1016/S1573-4285(06)80012-8

Chuah, T. G., Jumasiah, A., Azni, I., Katayon, S., & Choong, S. T. (2005). Rice husk as a potentially low-cost biosorbent for heavy metal and dye removal: an overview. *Desalination*, *175*(3), 305-316. https://doi.org/10.1016/j.desal.2004.10.014

Dai, C., Wan, J., Yang, J., Qu, S., Jin, T., Ma, F., & Shao, J. (2018). H_3PO_4 solution hydrothermal carbonization combined with KOH activation to prepare argy wormwood-based porous carbon for high-performance supercapacitors. *Applied Surface Science*, *444*, 105-117. https://doi.org/10.1016/j.apsusc.2018.02.261

Danish, M., Hashim, R., Ibrahim, M. M., & Sulaiman, O. (2014). Optimized preparation for large surface area activated carbon from date (Phoenix dactylifera L.) stone biomass. *Biomass and bioenergy*, *61*, 167-178. https://doi.org/10.1016/j.biombioe.2013.12.008

Dato'Hasnan, M. A., Husseinsyah, S., Lim, B. Y., & Rahman, M. F. A. (2016). *Chemical Modification of Palm Kernel Shell Filled Polylactic Acid Biocomposite Flims* (Doctoral dissertation, School of Materials Engineering).

Daud, S. H. Ismail, and A. A. Bakar, (2016) "Procedia Chemistry," vol. 19, pp. 327-334, 2016

Dehghani, M. H., Karri, R. R., Yeganeh, Z. T., Mahvi, A. H., Nourmoradi, H., Salari, M., & Sillanpää, M. (2020). Statistical modelling of endocrine disrupting compounds adsorption onto activated carbon prepared from wood using CCD-RSM and DE hybrid evolutionary optimization framework: Comparison of linear vs non-linear isotherm and kinetic parameters. *Journal of Molecular Liquids*, *302*, 112526. https://doi.org/10.1016/j.molliq.2020.112526

Demir, M., & Doguscu, M. (2022). Preparation of porous carbons using NaOH, K_2CO_3, Na_2CO_3 and $Na_2S_2O_3$ activating agents and their supercapacitor application: a comparative study. *ChemistrySelect*, *7*(4), e202104295. https://doi.org/10.1002/slct.202104295

Deng, S., Hu, B., Chen, T., Wang, B., Huang, J., Wang, Y., & Yu, G. (2015). Activated carbons prepared from peanut shell and sunflower seed shell for high CO_2 adsorption. *Adsorption*, *21*, 125-133. https://doi.org/10.1007/s10450-015-9655-y

Deng, S., Wei, H., Chen, T., Wang, B., Huang, J., & Yu, G. (2014). Superior CO_2 adsorption on pine nut shell-derived activated carbons and the effective micropores at different temperatures. *Chemical Engineering Journal*, *253*, 46-54. https://doi.org/10.1016/j.cej.2014.04.115

Desai, T. A., Sharma, S., Walczak, R. J., Boiarski, A., Cohen, M., Shapiro, J. & Ferrari, M. (2007). Nanoporous implants for controlled drug delivery. *BioMEMS and Biomedical Nanotechnology: Volume III Therapeutic Micro/Nanotechnology*, 263-286. https://doi.org/10.1007/978-0-387-25844-7_15

Dhyani, V., & Bhaskar, T. (2018). A comprehensive review on the pyrolysis of lignocellulosic biomass. *Renewable energy*, *129*, 695-716. https://doi.org/10.1016/j.renene.2017.04.035

Djeridi, W., Mansour, N. B., Ouederni, A., Llewellyn, P. L., & El Mir, L. (2015). Influence of the raw material and nickel oxide on the CH_4 capture capacity behaviors of microporous carbon. *International Journal of Hydrogen Energy*, *40*(39), 13690-13701. https://doi.org/10.1016/j.ijhydene.2015.05.010

Di, X., Wang, Y., Fu, Y., Wu, X., & Wang, P. (2021). Wheat flour-derived nanoporous carbon@ $ZnFe_2O_4$ hierarchical composite as an outstanding microwave absorber. *Carbon*, *173*, 174-184. https://doi.org/10.1016/j.carbon.2020.11.006

Di Natale, F., Erto, A., Lancia, A., & Musmarra, D. (2015). Equilibrium and dynamic study on hexavalent chromium adsorption onto activated carbon. *Journal of hazardous materials*, *281*, 47-55. https://doi.org/10.1016/j.jhazmat.2014.07.072

Doke, K. M., & Khan, E. M. (2017). Equilibrium, kinetic and diffusion mechanism of Cr (VI) adsorption onto activated carbon derived from wood apple shell. *Arabian journal of chemistry*, *10*, S252-S260. https://doi.org/10.1016/j.arabjc.2012.07.031

Drage, T. C., Arenillas, A., Smith, K. M., Pevida, C., Piippo, S., & Snape, C. E. (2007). Preparation of carbon dioxide adsorbents from the chemical activation of urea–formaldehyde and melamine–formaldehyde resins. *Fuel*, *86*(1-2), 22-31. https://doi.org/10.1016/j.fuel.2006.07.003

Dubinin, M. M. (1966). Porous structure and adsorption properties of active carbons. *Chemistry and physics of carbon*, *9*, 51-119.

Durga, M. L., Gangil, S., & Bhargav, V. K. (2022). Conversion of agricultural waste to valuable carbonaceous material: brief review. *Materials Today: Proceedings*, *56*, 1290-1297. https://doi.org/10.1016/j.matpr.2021.11.259

Elinge, C. M., Itodo, A. U., Peni, I. J., Birnin-Yauri, U. A., & Mbongo, A. N. (2011). Assessment of heavy metals concentrations in bore-hole waters in Aliero community of Kebbi State. *Advances in applied science Research*, *2*(4), 279-282.

Fahmi, A. G., Abidin, Z., Kusmana, C., Kharisma, D., Prajaputra, V., & Rahmawati, W. R. (2019). Preparation and characterization of activated carbon from palm kernel shell at low temperature as an adsorbent for methylene blue. In *IOP conference series: earth and environmental science* (Vol. 399, No. 1, p. 012015). IOP Publishing. **DOI** 10.1088/1755-1315/399/1/012015

Faisal, M., Gani, A., & Fuadi, Z. (2021). Utilization of ctivated carbon from palm kernel shells as the bioadsorbent of lead waste. *GEOMATE Journal*, *20*(78), 81-86.

Fernandes, D. M., Mestre, A. S., Martins, A., Nunes, N., Carvalho, A. P., & Freire, C. (2020). Biomass-derived nanoporous carbons as electrocatalysts for oxygen reduction reaction. *Catalysis Today*, *357*, 269-278. https://doi.org/10.1016/j.cattod.2019.02.048

Gan, Y. X. (2021). Activated carbon from biomass sustainable sources. *C*, *7*(2), 39. https://doi.org/10.3390/c7020039

Gao, S., Liu, J., Luo, J., Mamat, X., Sambasivam, S., Li, Y. & Hu, G. (2018). Selective voltammetric determination of Cd (II) by using N, S-codoped porous carbon nanofibers. *Microchimica Acta*, *185*(6), 282. https://doi.org/10.1007/s00604-018-2818-2

García, J. R., Sedran, U., Zaini, M. A. A., & Zakaria, Z. A. (2018). Preparation, characterization, and dye removal study of activated carbon prepared from palm kernel shell. *Environmental Science and Pollution Research*, *25*, 5076-5085. https://doi.org/10.1007/s11356-017-8975-8

García-Mateos, F. J., Ruiz-Rosas, R., Marqués, M. D., Cotoruelo, L. M., Rodríguez-Mirasol, J., & Cordero, T. (2015). Removal of paracetamol on biomass-derived activated carbon: Modeling the fixed bed breakthrough curves using batch adsorption experiments. *Chemical* *engineering journal*, *279*, 18-30. https://doi.org/10.1016/j.cej.2015.04.144

Gomis-Berenguer, A., Velasco, L. F., Velo-Gala, I., & Ania, C. O. (2017). Photochemistry of nanoporous carbons: Perspectives in energy conversion and environmental remediation. *Journal of colloid and interface science*, *490*, 879-901. http://doi.org/10.1016/j.jcis.2016.11.046

González, A. S., Plaza, M. G., Rubiera, F., & Pevida, C. (2013). Sustainable biomass-based carbon adsorbents for post-combustion CO_2 capture. *Chemical engineering journal*, *230*, 456-465. https://doi.org/10.1016/j.cej.2013.06.118

Guerrero-Pérez, M. O., Rosas, J. M., López-Medina, R., Bañares, M. A., Rodríguez-Mirasol, J., & Cordero, T. (2011). Lignocellulosic-derived catalysts for the selective oxidation of propane. *Catalysis Communications*, *12*(11), 989-992. https://doi.org/10.1016/j.catcom.2011.03.010

Gueye, M., Richardson, Y., Kafack, F. T., & Blin, J. (2014). High efficiency activated carbons from African biomass residues for the removal of chromium (VI) from wastewater. *Journal of Environmental Chemical Engineering*, *2*(1), 273-281. https://doi.org/10.1016/j.jece.2013.12.014

Guo, J., Song, Y., Ji, X., Ji, L., Cai, L., Wang, Y. & Song, W. (2019). Preparation and characterization of nanoporous activated carbon derived from prawn shell and its application for removal of heavy metal ions. *Materials*, *12*(2), 241. https://doi.org/10.3390/ma12020241

Guo, J., Xu, W. S., Chen, Y. L., & Lua, A. C. (2005). Adsorption of NH_3 onto activated carbon prepared from palm shells impregnated with H_2SO_4. *Journal of colloid and interface science*, *281*(2), 285-290. https://doi.org/10.1016/j.jcis.2004.08.101

Guo, J., & Lua, A. C. (2003). Adsorption of sulphur dioxide onto activated carbon prepared from oil-palm shells with and without pre-impregnation. *Separation and purification technology*, *30*(3), 265-273. https://doi.org/10.1016/S13835866(02)00166-1

Gupta, V. K., Pathania, D., & Sharma, S. (2017). Adsorptive remediation of Cu (II) and Ni (II) by microwave assisted H_3PO_4 activated carbon. *Arabian Journal of Chemistry*, *10*, S2836-S2844. https://doi.org/10.1016/j.arabjc.2013.11.006

Hairuddin, M. N., Mubarak, N. M., Khalid, M., Abdullah, E. C., Walvekar, R., & Karri, R. R. (2019). Magnetic palm kernel biochar potential route for phenol removal from wastewater. *Environmental Science and Pollution Research*, *26*, 35183-35197. https://doi.org/10.1007/s11356-019-06524-w

Hamad, H. N., & Idrus, S. (2022). Recent developments in the application of bio-waste-derived adsorbents for the removal of methylene blue from wastewater: a review. *Polymers*, *14*(4), 783. https://doi.org/10.3390/polym14040783

Hamad, B. K., Noor, A. M., Afida, A. R., & Asri, M. M. (2010). High removal of 4-chloroguaiacol by high surface area of oil palm shell-activated carbon activated with NaOH from aqueous solution. *Desalination*, *257*(1-3), 1-7. https://doi.org/10.1016/j.desal.2010.03.007

Hambali, E., & Rivai, M. (2017, May). The potential of palm oil waste biomass in Indonesia in 2020 and 2030. In *IOP Conference Series: Earth and Environmental Science* (Vol. 65, No. 1, p. 012050). IOP Publishing. **DOI** 10.1088/1755-1315/65/1/012050

Han, J., Zhang, L., Zhao, B., Qin, L., Wang, Y., & Xing, F. (2019). The N-doped activated carbon derived from sugarcane bagasse for CO_2 adsorption. *Industrial Crops and Products*, *128*, 290-297. https://doi.org/10.1016/j.indcrop.2018.11.028

Han, X., Wang, H., & Zhang, L. (2018). Efficient removal of methyl blue using nanoporous carbon from the waste biomass. *Water, Air, & Soil Pollution*, *229*, 1-10. https://doi.org/10.1007/s11270-017-3682-0

Haque, E., Yamauchi, Y., Malgras, V., Reddy, K. R., Yi, J. W., Hossain, M. S. A., & Kim, J. (2018). Nanoarchitectured Graphene-Organic Frameworks (GOFs): Synthetic Strategies, Properties, and Applications. *Chemistry–An Asian Journal*, *13*(23), 3561-3574. https://doi.org/10.1002/asia.201800984

Hasana, N. H., Wahi, R., & Yusof, Y. (2021). Ethanol, Methanol, and Magnesium-Treated Palm Kernel Shell Biochar for Methylene Blue Removal: Adsorption Isotherms. *Int J Cur Res Rev| Vol*, *13*(04), 2. http://dx.doi.org/10.31782/IJCRR.2021.SP130

Hayawin, Z. N., Ibrahim, M. F., Faizah, J. N., Ropandi, M., Astimar, A. A., Noorshamsiana, A. W., & Abd-Aziz, S. (2020). Palm oil mill final discharge treatment by a continuous adsorption system using oil palm kernel shell activated carbon produced from two-in-one carbonization activation reactor system. *Journal of Water Process Engineering*, *36*, 101262. https://doi.org/10.1016/j.jwpe.2020.101262

Hazourli, S., Ziati, M., & Hazourli, A. (2009). Characterization of activated carbon prepared from lignocellulosic natural residue:-Example of date stones. *Physics Procedia*, *2*(3), 1039-1043. https://doi.org/10.1016/j.phpro.2009.11.060

He, H., Zhang, Y., Wang, P., & Hu, D. (2021). Preparation of sponge-cake-like N-doped porous carbon materials derived from silk fibroin by chemical activation. *Microporous and Mesoporous Materials*, *317*, 110998. https://doi.org/10.1016/j.micromeso.2021.110998

Hérou, S., Crespo, M., & Titirici, M. (2020). Investigating the effects of activating agent morphology on the porosity and related capacitance of nanoporous carbons. *CrystEngComm*, *22*(9), 1560-1567. https://doi.org/10.1039/C9CE01702J

Hesas, R. H., Arami-Niya, A., Daud, W. M. A. W., & Sahu, J. N. (2013). Comparison of oil palm shell-based activated carbons produced by microwave and conventional heating methods using zinc chloride activation. *Journal of Analytical and Applied Pyrolysis*, *104*, 176-184. https://doi.org/10.1016/j.jaap.2013.08.006

Hossain, M. A., Shams, S., Amin, M., Reza, M. S., & Chowdhury, T. U. (2019). Perception and barriers to implementation of intensive and extensive green roofs in Dhaka, Bangladesh. *Buildings*, *9*(4), 79. https://doi.org/10.3390/buildings9040079

Hu, S. C., Cheng, J., Wang, W. P., Sun, G. T., Hu, L. L., Zhu, M. Q., & Huang, X. H. (2021). Structural changes and electrochemical properties of lacquer wood activated carbon prepared by phosphoric acid-chemical activation for supercapacitor applications. *Renewable Energy*, *177*, 82-94. https://doi.org/10.1016/j.renene.2021.05.113

Hussein, M. Z., & Baby, R. (2019). Application of palm kernel shell as bio adsorbent for the treatment of heavy metal contaminated water. *Journal of Advanced Research in Applied Mechanics*, *60*(1), 10-16. https://www.akademiabaru.com/submit/index.php/aram/article/view/1846

Imran-Shaukat, M., Wahi, R., Rosli, N. R., Aziz, S. M. A., & Ngaini, Z. (2021). Chemically modified palm kernel shell biochar for the removal of heavy metals from aqueous solution. In *IOP Conference Series: Earth and Environmental Science* (Vol. 765, No. 1, p. 012019). IOP Publishing. **DOI** 10.1088/1755-1315/765/1/012019

Islam, M. A., Ahmed, M. J., Khanday, W. A., Asif, M., & Hameed, B. H. (2017). Mesoporous activated carbon prepared from NaOH activation of rattan (Lacosperma secundiflorum) hydrochar for methylene blue removal. *Ecotoxicology and environmental safety*, *138*, 279-285. https://doi.org/10.1016/j.ecoenv.2017.01.010

Ismaiel, A. A., Aroua, M. K., & Yusoff, R. (2013). Palm shell activated carbon impregnated with task-specific ionic-liquids as a novel adsorbent for the removal of mercury from contaminated water. *Chemical Engineering Journal*, *225*, 306-314. https://doi.org/10.1016/j.cej.2013.03.082

Isokise, E. M., Abdullah, A. H., & Ping, T. Y. (2021). Sequestration of Pb (II) from Aqueous Environment by Palm Kernel Shell Activated Carbon: Isotherm and Kinetic Analyses. *Pertanika Journal of Science & Technology*, *29*(3).

Ipeaiyeda, A. R., Choudhary, M. I., & Ahmed, S. (2020). Ammonia and ammonium acetate modifications and characterisation of activated carbons from palm kernel shell and coconut shell. *Waste and Biomass Valorization*, *11*, 983-993. https://doi.org/10.1007/s12649-018-0414-7

Isa, S. A., Hafeez, M. A., Singh, B. K., Kwon, S. Y., Choung, S., & Um, W. (2022). Efficient mercury sequestration from wastewaters using palm kernel and coconut shell derived biochars. *Environmental Advances*, *8*, 100196. https://doi.org/10.1016/j.envadv.2022.100196

Jacob, J. M., Karthik, C., Saratale, R. G., Kumar, S. S., Prabakar, D., Kadirvelu, K., & Pugazhendhi, A. (2018). Biological approaches to tackle heavy metal pollution: a survey of literature. *Journal of environmental management*, *217*, 56-70. https://doi.org/10.1016/j.jenvman.2018.03.077

Jaroniec, M., & Choma, J. (2021). Theory of gas adsorption on structurally heterogeneous solids and its application for characterizing activated carbons. In *Chemistry and physics of carbon* (pp. 197-243). CRC Press.

Jawing, D., Syahril, S., Bahrun, M. H. V., & Mansa, R. F. (2021). Palm kernel shell activated carbon for lead and methylene blue removal. *Transactions on Science and Technology*, *8*(3-2), 290-304.

Jha, M. K., Joshi, S., Sharma, R. K., Kim, A. A., Pant, B., Park, M., & Pant, H. R. (2021). Surface modified activated carbons: Sustainable bio-based materials for environmentalremediation. *Nanomaterials*, *11*(11), 3140. https://doi.org/10.3390/nano11113140

Jibril, B., Houache, O., Al-Maamari, R., & Al-Rashidi, B. (2008). Effects of H_3PO_4 and KOH in carbonization of lignocellulosic material. *Journal of Analytical and applied pyrolysis*, *83*(2), 151-156. https://doi.org/10.1016/j.jaap.2008.07.003

Jirimali, H., Singh, J., Boddula, R., Lee, J. K., & Singh, V. (2022). Nano-Structured Carbon: Its synthesis from renewable agricultural sources and important applications. *Materials*, *15*(11), 3969. https://doi.org/10.3390/ma15113969

Kaewtrakulchai, N., Faungnawakij, K., & Eiad-Ua, A. (2020). Parametric study on microwave-assisted pyrolysis combined KOH activation of oil palm male flowers derived nanoporous carbons. *Materials*, *13*(12), 2876. https://doi.org/10.3390/ma13122876

Katibi, K. K., Yunos, K. F., Man, H. C., Aris, A. Z., Mohd Nor, M. Z., & Azis, R. S. (2021). An insight into a sustainable removal of bisphenol a from aqueous solution by novel palm kernel shell magnetically induced biochar: synthesis, characterization, kinetic, and thermodynamic studies. *Polymers*, *13*(21), 3781. https://doi.org/10.3390/polym13213781

Kazemi, F., Younesi, H., Ghoreyshi, A. A., Bahramifar, N., & Heidari, A. (2016). Thiol-incorporated activated carbon derived from fir wood sawdust as an efficient adsorbent for the removal of mercury ion: Batch and fixed-bed column studies. *Process Safety and Environmental Protection*, *100*, 22-35. https://doi.org/10.1016/j.psep.2015.12.006

Khan, F. S. A., Mubarak, N. M., Tan, Y. H., Khalid, M., Karri, R. R., Walvekar, R. & Mazari, S. A. (2021). A comprehensive review on magnetic carbon nanotubes and carbon nanotube-based buckypaper for removal of heavy metals and dyes. *Journal of Hazardous Materials*, *413*, 125375. https://doi.org/10.1016/j.jhazmat.2021.125375

Khan, J. H., Marpaung, F., Young, C., Lin, J., Islam, M. T., Alsheri, S. M. & Kim, J. (2019). Jute-derived microporous/mesoporous carbon with ultra-high surface area using a chemical activation process. *Microporous and Mesoporous Materials*, *274*, 251-256. https://doi.org/10.1016/j.micromeso.2018.07.050

Khan, J. H., Lin, J., Young, C., Matsagar, B. M., Wu, K. C., Dhepe, P. L. & Hossain, M. S. A. (2018). High surface area nanoporous carbon derived from high quality jute from Bangladesh. *Materials Chemistry and Physics*, *216*, 491-495. https://doi.org/10.1016/j.matchemphys.2018.05.082

Khosravi, R., Moussavi, G., Ghaneian, M. T., Ehrampoush, M. H., Barikbin, B., Ebrahimi, A. A., & Sharifzadeh, G. (2018). Chromium adsorption from aqueous solution using novel green nanocomposite: adsorbent characterization, isotherm, kinetic and thermodynamic investigation. *Journal of Molecular Liquids*, *256*, 163-174. https://doi.org/10.1016/j.molliq.2018.02.033

Kim, S. W., Koo, B. S., & Lee, D. H. (2014). Catalytic pyrolysis of palm kernel shell waste in a fluidized bed. *Bioresource technology*, *167*, 425-432. https://doi.org/10.1016/j.biortech.2014.06.050

Ko, D., Mines, P. D., Jakobsen, M. H., Yavuz, C. T., Hansen, H. C. B., & Andersen, H. R. (2018). Disulfide polymer grafted porous carbon composites for heavy metal removal from stormwater runoff. *Chemical Engineering Journal*, *348*, 685-692. https://doi.org/10.1016/j.cej.2018.04.192

Kyi, P. P., Quansah, J. O., Lee, C. G., Moon, J. K., & Park, S. J. (2020). The removal of crystal violet from textile wastewater using palm kernel shell-derived biochar. *Applied Sciences*, *10*(7), 2251. https://doi.org/10.3390/app10072251

Kwon, S. H., Lee, E., Kim, B. S., Kim, S. G., Lee, B. J., Kim, M. S., & Jung, J. C. (2015). Preparation of activated carbon aerogel and its application to electrode material for electric double layer capacitor in organic electrolyte: Effect of activation temperature. *Korean Journal of Chemical Engineering*, *32*, 248-254. https://doi.org/10.1007/s11814-014-0215-z

Lawal, A. A., Hassan, M. A., Zakaria, M. R., Yusoff, M. Z. M., Norrrahim, M. N. F., Mokhtar, M. N., & Shirai, Y. (2021). Effect of oil palm biomass cellulosic content on nanopore structure and adsorption capacity of biochar. *Bioresource Technology*, *332*, 125070. https://doi.org/10.1016/j.biortech.2021.125070

Lee, C. L., H'ng, P. S., Paridah, M. T., Chin, K. L., Rashid, U., Maminski, M., ... & Khoo, P. S. (2018). Production of bioadsorbent from phosphoric acid pretreated palm kernel shell and coconut shell by two-stage continuous physical activation via N_2 and air. *Royal Society open science*, *5*(12), 180775 https://doi.org/10.1098/rsos.180775

Lestari, U., Farid, F. A. I. Z. A. R., & Fudholi, A. H. M. A. D. (2019). Formulation and effectivity test of deodorant from activated charcoal of palm shell as excessive sweat adsorbent on body. *Asian Journal of Pharmaceutical and Clinical Research*, *12*(10), 193-196. http://dx.doi.org/10.22159/ajpcr.2019.v12i10.33490

Li, K., Xie, L., Hao, Z., & Xiao, M. (2020a). Effective removal of Hg (II) ion from aqueous solutions by thiol functionalized cobalt ferrite magnetic mesoporous silica composite. *Journal of Dispersion Science and Technology*, *41*(4), 503-509. https://doi.org/10.1080/01932691.2019.1591974

Li, B., Yin, W., Xu, M., Tan, X., Li, P., Gu, J. & Wu, J. (2019). Facile modification of activated carbon with highly dispersed nano-sized α-Fe_2O_3 for enhanced removal of hexavalent chromium from aqueous solutions. *Chemosphere*, *224*, 220-227.

https://doi.org/10.1016/j.chemosphere.2019.02.121

Li, S., Han, K., Li, J., Li, M., & Lu, C. (2017). Preparation and characterization of super activated carbon produced from gulfweed by KOH activation. *Microporous and Mesoporous Materials*, *243*, 291-300. https://doi.org/10.1016/j.micromeso.2017.02.052

Li, Y., Zhang, X., Yang, R., Li, G., & Hu, C. (2015). The role of H_3PO_4 in the preparation of activated carbon from NaOH-treated rice husk residue. *RSC advances*, *5*(41), 32626-32636. https://doi.org/10.1039/C5RA04634C

Li, K., & Wang, X. (2009). Adsorptive removal of Pb (II) by activated carbon prepared from Spartina alterniflora: equilibrium, kinetics and thermodynamics. *Bioresource Technology*, *100*(11), 2810-2815. https://doi.org/10.1016/j.biortech.2008.12.032

Liew, R. K., Chong, M. Y., Osazuwa, O. U., Nam, W. L., Phang, X. Y., Su, M. H. & Lam, S. S. (2018). Production of activated carbon as catalyst support by microwave pyrolysis of palm kernel shell: a comparative study of chemical versus physical activation. *Research on Chemical Intermediates*, *44*, 3849-3865. https://doi.org/10.1007/s11164-018-3388-y

Lim, W. C., Srinivasakannan, C., & Balasubramanian, N. (2010). Activation of palm shells by phosphoric acid impregnation for high yielding activated carbon. *Journal of analytical and applied pyrolysis*, *88*(2), 181-186. https://doi.org/10.1016/j.jaap.2010.04.004

Lin, K. Y. A., & Chen, B. C. (2016). Efficient elimination of caffeine from water using Oxone activated by a magnetic and recyclable cobalt/carbon nanocomposite derived from ZIF-67. *Dalton Transactions*, *45*(8), 3541-3551. https://doi.org/10.1039/C5DT04277A

Liu, Y., Qiao, Y., Wei, G., Li, S., Lu, Z., Wang, X., & Lou, X. (2018). Sodium storage mechanism of N, S co-doped nanoporous carbon: Experimental design and theoretical evaluation. *Energy Storage Materials*, *11*, 274-281. https://doi.org/10.1016/j.ensm.2017.09.003

Liu, C., Liang, X., Liu, X., Wang, Q., Zhan, L., Zhang, R. & Ling, L. (2008). Surface modification of pitch-based spherical activated carbon by CVD of NH_3 to improve its adsorption to uric acid. *Applied surface science*, *254*(21), 6701-6705. https://doi.org/10.1016/j.apsusc.2008.04.064

Lozano-Castelló, D., Calo, J. M., Cazorla-Amorós, D., & Linares-Solano, A. (2007). Carbon activation with KOH as explored by temperature programmed techniques, and the effects of hydrogen. *Carbon*, *45*(13), 2529-2536. https://doi.org/10.1016/j.carbon.2007.08.021

Maia, D. A. S., Sapag, K., Toso, J. P., López, R. H., Azevedo, D. C., Cavalcante Jr, C. L., & Zgrablich, G. (2010). Characterization of activated carbons from peach stones through the mixed geometry model. *Microporous and mesoporous materials*, *134*(1-3), 181-188. https://doi.org/10.1016/j.micromeso.2010.05.024

Mahmoud, M. E., Ahmed, S. B., Osman, M. M., & Abdel-Fattah, T. M. (2015). A novel composite of nanomagnetite-immobilized-baker's yeast on the surface of activated carbon for magnetic solid phase extraction of Hg (II). *Fuel*, *139*, 614-621. https://doi.org/10.1016/j.fuel.2014.09.002

Manasa, P., Sambasivam, S., & Ran, F. (2022). Recent progress on biomass waste derived activated carbon electrode materials for supercapacitors applications—A review. *Journal of Energy Storage*, *54*, 105290. https://doi.org/10.1016/j.est.2022.105290

Mansa, R. F., Ting, M. L., Patrick, A. O., & Kumaresan, S. (2021). *Simulation of Lead Removal Using Palm Kernel Shell Activated Carbon in a Packed Bed Column* (No. 6781). EasyChair.

Mao, H., Chen, X., Huang, R., Chen, M., Yang, R., Lan, P. & Zhou, X. (2018). Fast preparation of carbon spheres from enzymatic hydrolysis lignin: Effects of hydrothermal carbonization conditions. *Scientific reports*, *8*(1), 9501. https://doi.org/10.1038/s41598-018-27777-4

Mashhadi, S., Sohrabi, R., Javadian, H., Ghasemi, M., Tyagi, I., Agarwal, S., & Gupta, V. K. (2016). Rapid removal of Hg (II) from aqueous solution by rice straw activated carbon prepared by microwave-assisted H_2SO_4 activation: Kinetic, isotherm and thermodynamic studies. *Journal of Molecular Liquids*, *215*, 144-153. https://doi.org/10.1016/j.molliq.2015.12.040

Mazaheri, H., Ghaedi, M., Azqhandi, M. A., & Asfaram, A. J. P. C. C. P. (2017). Application of machine/statistical learning, artificial intelligence and statistical experimental design for the modeling and optimization of methylene blue and Cd (II) removal from a binary aqueous solution by natural walnut carbon. *Physical Chemistry Chemical Physics*, *19*(18), 11299-11317. https://doi.org/10.1039/C6CP08437K

Memetova, A., Tyagi, I., Karri, R. R., Memetov, N., Zelenin, A., Stolyarov, R. & Galunin, E. (2022b). High-Density Nanoporous carbon materials as storage material for Methane: A value-added solution. *Chemical Engineering Journal*, *433*, 134608. https://doi.org/10.1016/j.cej.2022.134608

Memetova, A., Tyagi, I., Singh, L., Karri, R. R., Tyagi, K., Kumar, V. & Agarwal, S. (2022a). Nanoporous carbon materials as a sustainable alternative for the remediation of toxic impurities and environmental contaminants: A review. *Science of the Total Environment*, 155943. https://doi.org/10.1016/j.scitotenv.2022.155943

Mestre, A. S., & Carvalho, A. P. (2018). Nanoporous carbon synthesis: An old story with exciting new chapters. *Porosity; Ghrib, T., Ed.; IntechOpen: London, UK*, 37-68.

Misnon, I. I., Zain, N. K. M., & Jose, R. (2019). Conversion of oil palm kernel shell biomass to activated carbon for supercapacitor electrode application. *Waste and Biomass Valorization*, *10*, 1731-1740. https://doi.org/10.1007/s12649-018-0196-y

Momčilović, M., Purenović, M., Bojić, A., Zarubica, A., & Ranđelović, M. (2011). Removal of lead (II) ions from aqueous solutions by adsorption onto pine cone activated carbon. *Desalination*, *276*(1-3), 53-59. https://doi.org/10.1016/j.desal.2011.03.013

Mortazavian, S., Saber, A., Hong, J., Bae, J. H., Chun, D., Wong, N. & Moon, J. (2019). Synthesis, characterization, and kinetic study of activated carbon modified by polysulfide rubber coating for aqueous hexavalent chromium removal. *Journal of industrial and engineering chemistry*, *69*, 196-210. https://doi.org/10.1016/j.jiec.2018.09.028

Moulefera, I., García-Mateos, F. J., Benyoucef, A., Rosas, J. M., Rodríguez-Mirasol, J., & Cordero, T. (2020). Effect of co-solution of carbon precursor and activating agent on the textural properties of highly porous activated carbon obtained by chemical activation of lignin with H_3PO_4. *Frontiers in materials*, *7*, 153. https://doi.org/10.3389/fmats.2020.00153

Muhammad, S., Abdul Khalil, H. P. S., Abd Hamid, S., Albadn, Y. M., Suriani, A. B., Kamaruzzaman, S. & Yahya, E. B. (2022). Insights into Agricultural-Waste-Based Nano-Activated Carbon Fabrication and Modifications for Wastewater Treatment Application. *Agriculture*, *12*(10), 1737. https://doi.org/10.3390/agriculture12101737

Mohammad Razi, M. A., Al-Gheethi, A., Al-Qaini, M., & Yousef, A. (2018). Efficiency of activated carbon from palm kernel shell for treatment of greywater. *Arab Journal of Basic and Applied Sciences*, *25*(3), 103-110. https://doi.org/10.1080/25765299.2018.1514142

Muhammad, Chuah, T. G., Robiah, Y., Suraya, A. R., & Choong, T. S. Y. (2011). Single and binary adsorptions isotherms of Cd (II) and Zn (II) on palm kernel shell based activated carbon. *Desalination and Water Treatment*, *29*(1-3), 140-148. https://doi.org/10.5004/dwt.2011.2210

Murillo-Acevedo, Y., Giraldo, L., & Moreno-Piraján, J. C. (2020). Nanoparticles size distribution and phenol photodegradation with TiO_2/C support obtained by phosphoric acid activation of palm kernel shell. *Microporous and Mesoporous Materials*, *304*, 109325. https://doi.org/10.1016/j.micromeso.2019.02.012

Nabarlatz, D., de Celis, J., Bonelli, P., & Cukierman, A. L. (2012). Batch and dynamic sorption of Ni (II) ions by activated carbon based on a native lignocellulosic precursor. *Journal of Environmental Management*, *97*, 109-115. https://doi.org/10.1016/j.jenvman.2011.11.008

Naihi, H., Baini, R., & Yakub, I. (2021). Oil palm biomass-based activated carbons for the removal of cadmium—a review. *AIMS Materials Science*, *8*(3), 453-468. DOI: 10.3934/matersci.2021028

Naji, S. Z., & Tye, C. T. (2022). A review of the synthesis of activated carbon for biodiesel production: Precursor, preparation, and modification. *Energy Conversion and Management: X*, *13*, 100152. https://doi.org/10.1016/j.ecmx.2021.100152

Narvekar, A. A., Fernandes, J. B., Naik, S. P., & Tilve, S. G. (2021). Development of glycerol based carbon having enhanced surface area and capacitance obtained by KOH induced thermochemical activation. *Materials Chemistry and Physics*, *261*, 124238. https://doi.org/10.1016/j.matchemphys.2021.124238

Nasri, N. S., Hamza, U. D., Ismail, S. N., Ahmed, M. M., & Mohsin, R. (2014). Assessment of porous carbons derived from sustainable palm solid waste for carbon dioxide capture. *Journal of Cleaner Production*, *71*, 148-157. https://doi.org/10.1016/j.jclepro.2013.11.053

Ncibi, M. C., Ranguin, R., Pintor, M. J., Jeanne-Rose, V., Sillanpää, M., & Gaspard, S. (2014). Preparation and characterization of chemically activated carbons derived from Mediterranean Posidonia oceanica (L.) fibres. *Journal of Analytical and Applied Pyrolysis*, *109*, 205-214. https://doi.org/10.1016/j.jaap.2014.06.010

Nda-Umar, U. I., Ramli, I., Muhamad, E. N., Taufiq-Yap, Y. H., & Azri, N. (2020). Synthesis and characterization of sulfonated carbon catalysts derived from biomass waste and its evaluation in glycerol acetylation. *Biomass Conversion and Biorefinery*, 1-16. https://doi.org/10.1007/s13399-020-00784-0

Njoku, V. O., Islam, M. A., Asif, M., & Hameed, B. H. (2014). Utilization of sky fruit husk agricultural waste to produce high quality activated carbon for the herbicide bentazon adsorption. *Chemical engineering journal*, *251*, 183-191. https://doi.org/10.1016/j.cej.2014.04.015

Nicholas, A. F., Hussein, M. Z., Zainal, Z., & Khadiran, T. (2020). The effect of surface area on the properties of shape-stabilized phase change material prepared using palm kernel shell activated carbon. *Scientific Reports*, *10*(1), 15047. https://doi.org/10.1038/s41598-020-72019-1

Obregón-Valencia, D., & del Rosario Sun-Kou, M. (2014). Comparative cadmium adsorption study on activated carbon prepared from aguaje (Mauritia flexuosa) and olive fruit stones (Olea europaea L.). *Journal of Environmental Chemical Engineering*, *2*(4), 2280-2288. https://doi.org/10.1016/j.jece.2014.10.004

Obuka, N., Onyechi, P. C., & Okoli, N. C. (2018). Palm oil biomass waste a renewable energy resource for power generation. *Saudi J Eng Technol*, 680-91.

Ogungbenro, A. E., Quang, D. V., Al-Ali, K., & Abu-Zahra, M. R. (2017). Activated carbon from date seeds for CO_2 capture applications. *Energy Procedia*, *114*, 2313-2321. https://doi.org/10.1016/j.egypro.2017.03.1370

Ooi, C. H., Cheah, W. K., & Yeoh, F. Y. (2019). Comparative study on the urea removal by different nanoporous materials. *Adsorption*, *25*, 1169-1175. https://doi.org/10.1007/s10450-019-00130-5

Oladele, I. O., Ibrahim, I. O., Adediran, A. A., Akinwekomi, A. D., Adetula, Y. V., & Olayanju, T. M. A. (2020). Modified palm kernel shell fiber/particulate cassava peel hybrid reinforced epoxy composites. *Results in Materials*, *5*, 100053. https://doi.org/10.1016/j.rinma.2019.100053

Ouyang, J., Zhou, L., Liu, Z., Heng, J. Y., & Chen, W. (2020). Biomass-derived activated carbons for the removal of pharmaceutical mircopollutants from wastewater: A review. *Separation and Purification Technology*, *253*, 117536. https://doi.org/10.1016/j.seppur.2020.117536

Ozpinar, P., Dogan, C., Demiral, H., Morali, U., Erol, S., Samdan, C. & Demiral, I. (2022). Activated carbons prepared from hazelnut shell waste by phosphoric acid activation for supercapacitor electrode applications and comprehensive electrochemical analysis. *Renewable Energy*, *189*, 535-548. https://doi.org/10.1016/j.renene.2022.02.126

Pallarés, J., González-Cencerrado, A., & Arauzo, I. (2018). Production and characterization of activated carbon from barley straw by physical activation with carbon dioxide and steam. *Biomass and Bioenergy*, *115*, 64-73. https://doi.org/10.1016/j.biombioe.2018.04.015

Pam, A. A., Abdullah, A. H., Tan, Y. P., & Zainal, Z. (2021). Optimizing the route for medium temperature-activated carbon derived from agro-based waste material. *Biomass Conversion and Biorefinery*, *13*(1), 119-130. https://doi.org/10.1007/s13399-021-01597-5

Panneerselvam, P., Morad, N., Tan, K. A., & Mathiyarasi, R. (2012). Removal of rhodamine B dye using activated carbon prepared from palm kernel shell and coated with iron oxide nanoparticles. *Separation Science and Technology*, *47*(5), 742-752. https://doi.org/10.1080/01496395.2011.625069

Pasee, W., Puta, A., Sangnoi, S., Wettayavong, S., Kaewtrakulchai, N., Panomsuwan, G., & Eiad-ua, A. (2019). Synthesis of carbon nanofiber from horse manure via hydrothermal carbonization for dye adsorption. *Materials Today: Proceedings*, *17*, 1326-1331. https://doi.org/10.1016/j.matpr.2019.06.150

Patnukao, P., Kongsuwan, A., & Pavasant, P. (2008). Batch studies of adsorption of copper and lead on activated carbon from Eucalyptus camaldulensis Dehn. bark. *Journal of environmental sciences*, *20*(9), 1028-1034. https://doi.org/10.1016/S10010742(08)62145-2

Peng, Z., Guo, Z., Chu, W., & Wei, M. (2016). Facile synthesis of high-surface-area activated carbon from coal for supercapacitors and high CO_2 sorption. *RSC advances*, *6*(48), 42019-42028. https://doi.org/10.1039/C5RA26044B

Prasetyo, I., Rochmadi, R., Wahyono, E., & Ariyanto, T. (2017). Controlling synthesis of polymer-derived carbon molecular sieve and its performance for CO_2/CH_4 separation. *Engineering Journal*, *21*(4), 83-94. https://doi.org/10.4186/ej.2017.21.4.83

Prabu, D., Kumar, P. S., Varsha, M., Sathish, S., Vijai Anand, K., Mercy, J., & Tiwari, A. (2020). Potential of nanoscale size zero valent iron nanoparticles impregnated activated carbon prepared from palm kernel shell for cadmium removal to avoid water pollution. *International Journal of Environmental Analytical Chemistry*, *102*(18), 7224-7240. https://doi.org/10.1080/03067319.2020.1828387

Quah, R. V., Tan, Y. H., Mubarak, N. M., Kansedo, J., Khalid, M., Abdullah, E. C., & Abdullah, M. O. (2020). Magnetic biochar derived from waste palm kernel shell for biodiesel production via sulfonation. *Waste Management*, *118*, 626-636. https://doi.org/10.1016/j.wasman.2020.09.016

Rasheed, T., Shafi, S., Bilal, M., Hussain, T., Sher, F., & Rizwan, K. (2020). Surfactants-based remediation as an effective approach for removal of environmental pollutants—A review. *Journal of Molecular Liquids*, *318*, 113960. https://doi.org/10.1016/j.molliq.2020.113960

Rashidi, N. A., & Yusup, S. (2023). The insights of pet cokes/palm kernel shell activated carbon as CO_2 adsorbent: equilibrium, kinetics, thermodynamics, and regeneration performance. *Journal of Chemical Technology & Biotechnology*, *98*(3), 575-582. https://doi.org/10.1002/jctb.7064

Rashidi, N. A., Bokhari, A., & Yusup, S. (2021). Evaluation of kinetics and mechanism properties of CO_2 adsorption onto the palm kernel shell activated carbon. *Environmental Science and Pollution Research*, *28*, 33967-33979. https://doi.org/10.1007/s11356-020-08823-z

Rashidi, N. A., Yusup, S., Borhan, A., & Loong, L. H. (2014). Experimental and modelling studies of carbon dioxide adsorption by porous biomass derived activated carbon. *Clean Technologies and Environmental Policy*, *16*, 1353-1361. https://doi.org/10.1007/s10098-014-0788-6

Razavi Mehr, M., Fekri, M. H., Omidali, F., Eftekhari, N., & Akbari-adergani, B. (2019). Removal of chromium (VI) from wastewater by palm kernel shell-based on a green method. *Journal of Chemical Health Risks*, *9*(1), 75-86.

Redondo, E., Carretero-González, J., Goikolea, E., Ségalini, J., & Mysyk, R. (2015). Effect of pore texture on performance of activated carbon supercapacitor electrodes derived from olive pits. *Electrochimica Acta*, *160*, 178-184. https://doi.org/10.1016/j.electacta.2015.02.006

Ren, G., Lu, X., Li, Y., Zhu, Y., Dai, L., & Jiang, L. (2016b). Porous core–shell Fe_3C embedded N-doped carbon nanofibers as an effective electrocatalysts for oxygen reduction reaction. *ACS applied materials & interfaces*, *8*(6), 4118-4125. https://pubs.acs.org/doi/abs/10.1021/acsami.5b11786

Ren, C., Ding, X., Fu, H., Meng, C., Li, W., & Yang, H. (2016). Preparation of amino-functionalized $CoFe_2O_4$@ SiO_2 magnetic nanocomposites for potential application in absorbing heavy metal ions. *RSC Advances*, *6*(76), 72479-72486. https://doi.org/10.1039/C6RA13304E

Reza, M. S., Yun, C. S., Afroze, S., Radenahmad, N., Bakar, M. S. A., Saidur, R. & Azad, A. K. (2020). Preparation of activated carbon from biomass and its' applications in water and gas purification, a review. *Arab Journal of Basic and Applied Sciences*, *27*(1), 208-238. https://doi.org/10.1080/25765299.2020.1766799

Rilyanti, M., & Sari, M. (2021). Removal of Cd (II) ions in solution by activated carbon from palm oil shells modified with magnetite. *Desalination and Water Treatment*, *218*(1), 352-362. https://doi.org/10.5004/dwt.2021.26978

Rodriguez-Reinoso, F. (1989). Microporous structure of activated carbons as revealed adsorption methods. *Chemistry and physics of carbon*, *21*, 1.

Romero-Anaya, A. J., Molina, A., Garcia, P., Ruiz-Colorado, A. A., Linares-Solano, A., & de Lecea, C. S. M. (2011). Phosphoric acid activation of recalcitrant biomass originated in ethanol production from banana plants. *biomass and bioenergy*, *35*(3), 1196-1204. https://doi.org/10.1016/j.biombioe.2010.12.007

Rouzitalab, Z., Maklavany, D. M., Rashidi, A., & Jafarinejad, S. (2018). Synthesis of N-doped nanoporous carbon from walnut shell for enhancing CO_2 adsorption capacity and separation. *Journal of environmental chemical engineering*, *6*(5), 6653-6663. https://doi.org/10.1016/j.jece.2018.10.035

Sadeek, S. A., Mohammed, E. A., Shaban, M., Abou Kana, M. T., & Negm, N. A. (2020). Synthesis, characterization and catalytic performances of activated carbon-doped transition metals during biofuel production from waste cooking oils. *Journal of Molecular Liquids*, *306*, 112749. https://doi.org/10.1016/j.molliq.2020.112749

Sahari, J., & Maleque, M. A. (2016). Mechanical properties of oil palm shell composites. *International Journal of Polymer Science*, *2016*. https://doi.org/10.1155/2016/7457506

Saleh, T. A., Sarı, A., & Tuzen, M. (2017). Optimization of parameters with experimental design for the adsorption of mercury using polyethylenimine modified-activated carbon. *Journal of Environmental Chemical Engineering*, *5*(1), 1079-1088. https://doi.org/10.1016/j.jece.2017.01.032

Salehi, S., & Hosseinifard, M. (2021). Evaluation of CO_2 and CH_4 adsorption using a novel amine modified MIL-101-derived nanoporous carbon/polysaccharides nanocomposites: Isotherms and thermodynamics. *Chemical Engineering Journal*, *410*, 128315. https://doi.org/10.1016/j.cej.2020.128315

Sarker, M., Ahmed, I., & Jhung, S. H. (2017). Adsorptive removal of herbicides from water over nitrogen-doped carbon obtained from ionic liquid@ ZIF-8. *Chemical Engineering Journal*, *323*, 203-211. https://doi.org/10.1016/j.cej.2017.04.103

Sayğılı, H., & Güzel, F. (2016). High surface area mesoporous activated carbon from tomato processing solid waste by zinc chloride activation: process optimization, characterization and dyes adsorption. *Journal of Cleaner Production*, *113*, 995-1004. https://doi.org/10.1016/j.jclepro.2015.12.055

Sdanghi, G., Canevesi, R. L., Celzard, A., Thommes, M., & Fierro, V. (2020). Characterization of carbon materials for hydrogen storage and compression. *Carbon*, *6*(3), 46. https://doi.org/10.3390/c6030046

Senthil, C., & Lee, C. W. (2021). Biomass-derived biochar materials as sustainable energy sources for electrochemical energy storage devices. *Renewable and Sustainable Energy Reviews*, *137*, 110464. https://doi.org/10.1016/j.rser.2020.110464

Shahbandeh, M., 2022. "Leading producers of palm oil worldwide from 2021/2022". On line: .Accessed: 25/03/2022

Shahkarami, S., Azargohar, R., Dalai, A. K., & Soltan, J. (2015). Breakthrough CO_2 adsorption in bio-based activated carbons. *Journal of environmental sciences*, *34*, 68-76. https://doi.org/10.1016/j.jes.2015.03.008

Shaker, M., Ghazvini, A. A. S., Cao, W., Riahifar, R., & Ge, Q. (2021). Biomass-derived porous carbons as supercapacitor electrodes–a review. *New Carbon Materials*, *36*(3), 546-572. https://doi.org/10.1016/S1872-5805(21)60038-0

Sharma, P., Kaur, H., Sharma, M., & Sahore, V. (2011). A review on applicability of naturally available adsorbents for the removal of hazardous dyes from aqueous waste. *Environmental monitoring and assessment*, *183*, 151-195. https://doi.org/10.1007/s10661-011-1914-0

Shi, Y., Liu, G., Wang, L., & Zhang, H. (2019). Heteroatom-doped porous carbons from sucrose and phytic acid for adsorptive desulfurization and sulfamethoxazole removal: a comparison between aqueous and non-aqueous adsorption. *Journal of colloid and interface science*, *557*, 336-348. https://doi.org/10.1016/j.jcis.2019.09.032

Singh, G., Lee, J. M., Kothandam, G., Palanisami, T., Al-Muhtaseb, A. A. H., Karakoti, A. & Vinu, A. (2021). A review on the synthesis and applications of nanoporous carbons for the removal of complex chemical contaminants. *Bulletin of the Chemical Society of Japan*, *94*(4), 1232-1257. https://doi.org/10.1246/bcsj.20200379

Sitthisantikul, T., Poolsili, P., Devakula, J., Jaruwanawat, A., & Eiad-Ua, A. (2020). Nanoporous Carbon from Durian Peel via Hydrothermal-Carbonization and their Application in Ripening Delay of Durian. In *IOP Conference Series: Materials Science and Engineering* (Vol. 894, No. 1, p. 012006). IOP Publishing. **DOI** 10.1088/1757-899X/894/1/012006

Song, W., Zhang, Z., Wan, P., Wang, M., Chen, X., & Mao, C. (2020). Low temperature and highly efficient oxygen/sulfur dual-modification of nanoporous carbon under hydrothermal conditions for supercapacitor application. *Journal of Solid State Electrochemistry*, *24*, 761-770. https://doi.org/10.1007/s10008-019-04492-2

Song, X., Liu, H., Cheng, L., & Qu, Y. (2010). Surface modification of coconut-based activated carbon by liquid-phase oxidation and its effects on lead ion adsorption. *Desalination*, *255*(1-3), 78-83. https://doi.org/10.1016/j.desal.2010.01.011

Stanisavljević, M., Janković, S., Milisavić, D., Čađo, M., Kukrić, Z., Stević, D. & Atlagić, S. G. (2019). Novel Nanoporous Carbon/Iron Oxide Catalyst for SO_2 Degradation. *Materials Today: Proceedings*, *7*, 920-929. https://doi.org/10.1016/j.matpr.2018.12.095

Suarez-Garcia, F., Martinez-Alonso, A., & Tascon, J. M. D. (2002). Pyrolysis of apple pulp: effect of operation conditions and chemical additives. *Journal of Analytical and Applied Pyrolysis*, *62*(1), 93-109. https://doi.org/10.1016/S01652370(00)00216-3

Sukulbrahman, M., Siraorarnroj, S., Suksai, N., Kaewtrakulchai, N., Chutipaijit, S., Chanpee, S. & Jaruvanawat, A. (2022). Nanoporous Carbon from Water Hyacinth via Hydrothermal Carbonization assisted Chemical Activation for Dye adsorption. *CURRENT APPLIED SCIENCE AND TECHNOLOGY*, 10-55003. https://doi.org/10.55003/cast.2022.04.22.014

Sulyman, M., Namiesnik, J., & Gierak, A. (2017). Low-cost Adsorbents Derived from Agricultural By-products/Wastes for Enhancing Contaminant Uptakes from Wastewater: A Review. *Polish Journal of Environmental Studies*, *26*(3). https://doi.org/10.15244/pjoes/66769

Sun, B., Wang, C., Cai, J., Li, D., Li, W., Gou, X. & Hu, F. (2019). Molecularly imprinted polymer-nanoporous carbon composite-based electrochemical sensor for selective detection of calycosin. *Journal of the Electrochemical Society*, *166*(6), H187. **DOI** 10.1149/2.0971906jes

Sun, X., Zhang, Y., Song, P., Pan, J., Zhuang, L., Xu, W., & Xing, W. (2013). Fluorine-doped carbon blacks: highly efficient metal-free electrocatalysts for oxygen reduction reaction. *ACS catalysis*, *3*(8), 1726-1729. https://doi.org/10.1021/cs400374k

Sundalian, M., Larissa, D., & Suprijana, O. O. (2021). Contents and utilization of palm oil fruit waste. *Biointerface Research in Applied Chemistry*, *11*(3), 10148-10160.

Syamsurizal, Uce, L., Nurhasanah, (2019). Formulation of toothpaste activated charcoal from palm shell (Elaeis guineensis Jacg) as teeth whitening for nicotine addicts. Int. J. Pharm. Sci. Rev. Res. 58(1), 9-12.

Sych, N. V., Trofymenko, S. I., Poddubnaya, O. I., Tsyba, M. M., Sapsay, V. I., Klymchuk, D. O., & Puziy, A. M. (2012). Porous structure and surface chemistry of phosphoric acid activated carbon from corncob. *Applied surface science*, *261*, 75-82. https://doi.org/10.1016/j.apsusc.2012.07.084

Tadda, M. A., Ahsan, A., Shitu, A., ElSergany, M., Arunkumar, T., Jose, B. & Daud, N. N. (2016). A review on activated carbon: process, application and prospects. *Journal of Advanced Civil Engineering Practice and Research*, *2*(1), 7-13. http://ababilpub.com/download/jacepr2-1-3/

Tajar, A. F., Kaghazchi, T., & Soleimani, M. (2009). Adsorption of cadmium from aqueous solutions on sulfurized activated carbon prepared from nut shells. *Journal of Hazardous Materials*, *165*(1-3), 1159-1164. https://doi.org/10.1016/j.jhazmat.2008.10.131

Tan, H., Tang, J., Kim, J., Kaneti, Y. V., Kang, Y. M., Sugahara, Y., & Yamauchi, Y. (2019). Rational design and construction of nanoporous iron-and nitrogen-doped carbon electrocatalysts for oxygen reduction reaction. *Journal of Materials Chemistry A*, *7*(4), 1380-1393. https://doi.org/10.1039/C8TA08870E

Tan, F., Sun, D., Gao, J., Zhao, Q., Wang, X., Teng, F. & Chen, J. (2013). Preparation of molecularly imprinted polymer nanoparticles for selective removal of fluoroquinolone antibiotics in aqueous solution. *Journal of Hazardous Materials*, *244*, 750-757. https://doi.org/10.1016/j.jhazmat.2012.11.003

Tan, I. A. W., Ahmad, A. L., & Hameed, B. H. (2009). Fixed-bed adsorption performance of oil palm shell-based activated carbon for removal of 2, 4, 6-trichlorophenol. *Bioresource technology*, *100*(3), 1494-1496. https://doi.org/10.1016/j.biortech.2008.08.017

Tehrani, N. F., Aznar, J. S., & Kiros, Y. (2015). Coffee extract residue for production of ethanol and activated carbons. *Journal of Cleaner Production*, *91*, 64-70. https://doi.org/10.1016/j.jclepro.2014.12.031

Theydan, S. K., & Ahmed, M. J. (2012). Optimization of preparation conditions for activated carbons from date stones using response surface methodology. *Powder Technology*, *224*, 101-108. https://doi.org/10.1016/j.powtec.2012.02.037

Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and applied chemistry*, *87*(9-10), 1051-1069. https://doi.org/10.1515/pac-2014-1117

To, M. H., Hadi, P., Hui, C. W., Lin, C. S. K., & McKay, G. (2017). Mechanistic study of atenolol, acebutolol and carbamazepine adsorption on waste biomass derived activated carbon. *Journal of Molecular Liquids*, *241*, 386-398. https://doi.org/10.1016/j.molliq.2017.05.037

Togibasa, O., Mumfaijah, M., Allo, Y. K., Dahlan, K., & Ansanay, Y. O. (2021). The effect of chemical activating agent on the properties of activated carbon from sago waste. *Applied Sciences*, *11*(24), 11640. https://doi.org/10.3390/app112411640

Torad, N. L., Hu, M., Ishihara, S., Sukegawa, H., Belik, A. A., Imura, M. & Yamauchi, Y. (2014). Direct synthesis of MOF-derived nanoporous carbon with magnetic Co nanoparticles toward efficient water treatment. *small*, *10*(10), 2096-2107. https://doi.org/10.1002/smll.201302910

Torad, N. L., Li, Y., Ishihara, S., Ariga, K., Kamachi, Y., Lian, H. Y. & Yamauchi, Y. (2014b). MOF-derived nanoporous carbon as intracellular drug delivery carriers. *Chemistry Letters*, *43*(5), 717-719. https://doi.org/10.1246/cl.131174

Tran, V. T., Nguyen, D. T., Ho, V. T. T., Hoang, P. Q. H., Bui, P. Q., & Bach, L. G. (2017). Efficient removal of Ni 2 ions from aqueous solution using activated carbons fabricated from rice straw and tea waste. *J. Mater. Environ. Sci*, *8*(2), 426-437.

Uchegbulam, I., Momoh, E. O., & Agan, S. A. (2022). Potentials of Palm Kernel Shell Derivatives: A Critical Review on Waste Recovery for Environmental Sustainability. *Cleaner Materials*, 100154. https://doi.org/10.1016/j.clema.2022.100154

Ukanwa, K. S., Patchigolla, K., Sakrabani, R., & Anthony, E. (2020). Preparation and characterisation of activated carbon from palm mixed waste treated with trona ore. *Molecules*, *25*(21), 5028. https://doi.org/10.3390/molecules25215028

Ulfah, M., Raharjo, S., Hastuti, P., & Darmadji, P. (2016). The potential of palm kernel shell activated carbon as an adsorbent for β-carotene recovery from crude palm oil. In *AIP Conference Proceedings* (Vol. 1755, No. 1, p. 130016). AIP Publishing LLC. https://doi.org/10.1063/1.4958560

Üner, O., & Bayrak, Y. (2018). The effect of carbonization temperature, carbonization time and impregnation ratio on the properties of activated carbon produced from Arundo donax. *Microporous and mesoporous Materials*, *268*, 225-234.

https://doi.org/10.1016/j.micromeso.2018.04.037

Van Thuan, T., Quynh, B. T. P., Nguyen, T. D., & Bach, L. G. (2017). Response surface methodology approach for optimization of Cu^{2+}, Ni^{2+} and Pb^{2+} adsorption using KOH-activated carbon from banana peel. *Surfaces and interfaces*, *6*, 209-217. https://doi.org/10.1016/j.surfin.2016.10.007

Vargas, D. P., Giraldo, L., Erto, A., & Moreno-Piraján, J. C. (2013). Chemical modification of activated carbon monoliths for CO_2 adsorption. *Journal of thermal analysis and calorimetry*, *114*, 1039-1047. https://doi.org/10.1007/s10973-013-3086-3

Villota, S. M., Lei, H., Villota, E., Qian, M., Lavarias, J., Taylan, V. & Denson, M. (2019). Microwave-assisted activation of waste cocoa pod husk by H3PO4 and KOH—comparative insight into textural properties and pore development. *ACS Omega*, *4*(4), 7088-7095. https://doi.org/10.1021/acsomega.8b03514

Volperts, A., Dobele, G., Zhurinsh, A., Vervikishko, D., Shkolnikov, E., & Ozolinsh, J. (2017). Wood-based activated carbons for supercapacitor electrodes with a sulfuric acid electrolyte. *New carbon materials*, *32*(4), 319-326. https://doi.org/10.1016/S1872-5805(17)60125-2

Volperts, A., Dobele, G., Ozolins, J., & Mironova-Ulmane, N. (2015). Synthesis and application of nanoporous activated carbon in supercapacitors. *Materials Science and Applied Chemistry*, *31*, 16-20. https://doi.org/10.7250/msac.2015.003

Wei, H., Deng, S., Hu, B., Chen, Z., Wang, B., Huang, J., & Yu, G. (2012). Granular bamboo-derived activated carbon for high CO_2 adsorption: the dominant role of narrow micropores. *ChemSusChem*, *5*(12), 2354-2360. https://doi.org/10.1002/cssc.201200570

Wang, L., Sun, F., Hao, F., Qu, Z., Gao, J., Liu, M. & Qin, Y. (2020). A green trace K_2CO_3 induced catalytic activation strategy for developing coal-converted activated carbon as advanced candidate for CO_2 adsorption and supercapacitors. *Chemical Engineering Journal*, *383*, 123205. https://doi.org/10.1016/j.cej.2019.123205

Wang, G., Qin, J., Zhao, Y., & Wei, J. (2019). Nanoporous carbon spheres derived from metal-phenolic coordination polymers for supercapacitor and biosensor. *Journal of colloid and interface science*, *544*, 241-248. https://doi.org/10.1016/j.jcis.2019.03.001

Wang, F., Wu, X., Yuan, X., Liu, Z., Zhang, Y., Fu, L. & Huang, W. (2017). Latest advances in supercapacitors: from new electrode materials to novel device designs. *Chemical Society Reviews*, *46*(22), 6816-6854. https://doi.org/10.1039/C7CS00205J

Wang, J., Deng, B., Wang, X., & Zheng, J. (2009). Adsorption of aqueous Hg (II) by sulfur-impregnated activated carbon. *Environmental Engineering Science*, *26*(12), 1693-1699. https://doi.org/10.1089/ees.2008.0418

Williams, P. T., & Reed, A. R. (2004). High grade activated carbon matting derived from the chemical activation and pyrolysis of natural fibre textile waste. *Journal of analytical and applied pyrolysis*, *71*(2), 971-986. https://doi.org/10.1016/j.jaap.2003.12.007

Wendimu, G., Zewge, F., & Mulugeta, E. (2017). Aluminium-iron-amended activated bamboo charcoal (AIAABC) for fluoride removal from aqueous solutions. *Journal of water process engineering*, *16*, 123-131. https://doi.org/10.1016/j.jwpe.2016.12.012

Wong, S., Ngadi, N., Inuwa, I. M., & Hassan, O. (2018). Recent advances in applications of activated carbon from biowaste for wastewater treatment: a short review. *Journal of Cleaner Production*, *175*, 361-375. https://doi.org/10.1016/j.jclepro.2017.12.059

Xi, Y., Yang, D., Qiu, X., Wang, H., Huang, J., & Li, Q. (2018). Renewable lignin-based carbon with a remarkable electrochemical performance from potassium compound activation. *Industrial Crops and Products*, *124*, 747-754. https://doi.org/10.1016/j.indcrop.2018.08.018

Xu, H., Gao, B., Cao, H., Chen, X., Yu, L., Wu, K. & Fu, J. (2015). Nanoporous activated carbon derived from rice husk for high performance supercapacitor. *Journal of Nanomaterials*, *2014*, 229-229. https://doi.org/10.1155/2014/714010

Yahya, M. A., Mansor, M. H., Zolkarnaini, W. A. A. W., Rusli, N. S., Aminuddin, A., Mohamad, K., ... & Ozair, L. N. (2018). A brief review on activated carbon derived from agriculture by-product. In *AIP conference proceedings* (Vol. 1972, No. 1, p. 030023). AIP Publishing LLC. https://doi.org/10.1063/1.5041244

Yahya, M. A., Al-Qodah, Z., & Ngah, C. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. *Renewable and sustainable energy reviews*, *46*, 218-235. https://doi.org/10.1016/j.rser.2015.02.051

Yakout, S. M., & El-Deen, G. S. (2016). Characterization of activated carbon prepared by phosphoric acid activation of olive stones. *Arabian journal of chemistry*, *9*, S1155-S1162. https://doi.org/10.1016/j.arabjc.2011.12.002

Yallappa, S., Manaf, S. A. A., & Hegde, G. (2018). Synthesis of a biocompatible nanoporous carbon and its conjugation with florescent dye for cellular imaging and targeted drug delivery to cancer cells. *New Carbon Materials*, *33*(2), 162-172. https://doi.org/10.1016/S1872-5805(18)60332-4

Yang, W., Liu, X., Yue, X., Jia, J., & Guo, S. (2015). Bamboo-like carbon nanotube/Fe_3C nanoparticle hybrids and their highly efficient catalysis for oxygen reduction. *Journal of the American Chemical Society*, *137*(4), 1436-1439. https://doi.org/10.1021/ja5129132

Yi, Z. J., Yao, J., Xu, J. S., Chen, M. S., Li, W., Chen, H. L., & Wang, F. (2014). Removal of uranium from aqueous solution by using activated palm kernel shell carbon: adsorption equilibrium and kinetics. *Journal of Radioanalytical and Nuclear Chemistry*, *301*, 695-701. https://doi.org/10.1007/s10967-014-3242-7

You, F. T., Yu, G. W., Xing, Z. J., Li, J., Xie, S. Y., Li, C. X., & Wang, Y. (2019). Enhancement of NO catalytic oxidation on activated carbon at room temperature by nitric acid hydrothermal treatment. *Applied Surface Science*, *471*, 633-644. https://doi.org/10.1016/j.apsusc.2018.12.066

Young, C., Lin, J., Wang, J., Ding, B., Zhang, X., Alshehri, S. M. & Yamauchi, Y. (2018). Significant effect of pore sizes on energy storage in nanoporous carbon supercapacitors. *Chemistry–A European Journal*, *24*(23), 6127-6132. https://doi.org/10.1002/chem.201705465

Zaini, M. S. M., Arshad, M., & Syed-Hassan, S. S. A. (2023). Adsorption isotherm and kinetic study of methane on palm kernel shell-derived activated carbon. *Journal of Bioresources and Bioproducts*, *8*(1), 66-77. https://doi.org/10.1016/j.jobab.2022.11.002

Zaini, M. A. A., Salleh, L. M., Azizi, M., Yunus, C., & Naushad, M. (2017). Potassium hydroxide-treated palm kernel shell sorbents for the efficient removal of methyl violet dye. *Desalin. Water Treat*, *84*, 262-270. https://doi.org/10.5004/dwt.2017.21206

Zakaria, R., Jamalluddin, N. A., & Bakar, M. Z. A. (2021). Effect of impregnation ratio and activation temperature on the yield and adsorption performance of mangrove based activated carbon for methylene blue removal. *Results in Materials*, *10*, 100183. https://doi.org/10.1016/j.rinma.2021.100183

Zhai, Y., Dou, Y., Zhao, D., Fulvio, P. F., Mayes, R. T., & Dai, S. (2011). Carbon materials for chemical capacitive energy storage. *Advanced materials*, *23*(42), 4828-4850. https://doi.org/10.1002/adma.201100984

Zhang, L., Zhang, J., Li, X., Wang, C., Yu, A., Zhang, S. & Cui, Y. (2021). Adsorption behavior and mechanism of Hg (II) on a porous core-shell copper hydroxy sulfate@ MOF composite. *Applied Surface Science*, *538*, 148054. https://doi.org/10.1016/j.apsusc.2020.148054

Zhang, N., & Shen, Y. (2019). One-step pyrolysis of lignin and polyvinyl chloride for synthesis of porous carbon and its application for toluene sorption. *Bioresource technology*, *284*, 325-332. https://doi.org/10.1016/j.biortech.2019.03.149

Zhang, W., Zhang, L. Y., Zhao, X. J., & Zhou, Z. (2016). Citrus pectin derived porous carbons as a superior adsorbent toward removal of methylene blue. *Journal of Solid State Chemistry*, *243*, 101-105. https://doi.org/10.1016/j.jssc.2016.08.014

Zhang, J., Fu, H., Lv, X., Tang, J., & Xu, X. (2011). Removal of Cu (II) from aqueous solution using the rice husk carbons prepared by the physical activation process. *Biomass and Bioenergy*, *35*(1), 464-472. https://doi.org/10.1016/j.biombioe.2010.09.002

Zhao, G., Zou, G., Qiu, X., Li, S., Guo, T., Hou, H., & Ji, X. (2017). Rose-like N-doped porous carbon for advanced sodium storage. *Electrochimica Acta*, *240*, 24-30. https://doi.org/10.1016/j.electacta.2017.04.057

Zhou, Q., Yang, N., Li, Y., Ren, B., Ding, X., Bian, H., & Yao, X. (2020). Total concentrations and sources of heavy metal pollution in global river and lake water bodies from 1972 to 2017. *Global Ecology and Conservation*, *22*, e00925. https://doi.org/10.1016/j.gecco.2020.e00925

Zhu, J., Liu, Q., Li, Z., Liu, J., Zhang, H., Li, R. & Emelchenko, G. A. (2017). Recovery of uranium (VI) from aqueous solutions using a modified honeycomb-like porous carbon material. *Dalton Transactions*, *46*(2), 420-429. https://doi.org/10.1039/C6DT03227C

Zuo, S., Yang, J., & Liu, J. (2010). Effects of the heating history of impregnated lignocellulosic material on pore development during phosphoric acid activation. *Carbon*, *48*(11), 3293-3295. https://doi.org/10.1016/j.carbon.2010.04.042

Zuo, S., Yang, J., Liu, J., & Cai, X. (2009). Significance of the carbonization of volatile pyrolytic products on the properties of activated carbons from phosphoric acid activation of lignocellulosic material. *Fuel Processing Technology*, *90*(7-8), 994-1001. https://doi.org/10.1016/j.fuproc.2009.04.003