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A Critical Review on Abatement of VOCs By Adsorption: Adsorbent Types and Their Characteristics

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Abstract Volatile organic compounds (VOCs) are considered one of the hazardous air pollutants that are discharged from various anthropogenic and natural sources, which have the potential to cause catastrophic damage to both the health of human beings and the environment. Over the years, many control methodologies have been developed to get rid of the menace of VOCs. Adsorption has emerged as one of the popular control techniques for the treatment of gas streams containing VOCs. The cost-effectiveness on account of low energy consumption and high efficiency are the two major factors that give adsorption an edge over other techniques like oxidation (thermal and catalytic), condensation, absorption, membrane separation, etc. The VOCs abatement by adsorption, in terms of adsorption capacity, relies on the properties of the adsorbent material such as surface area, pore structure, and presence of functional groups. This review paper encompasses a variety of adsorbent materials (carbon-based, oxygen-based, organic polymers, and composite materials) that are used by numerous investigators to treat different types of VOCs. MOF-based composite materials are future adsorbents as an alternative to zeolites and activated carbon, but further research to address the problem of costly treatment steps is the need of the hour. Magnetic composite materials are also emerging adsorbents for the VOCs removal, which have attracted the attention of many researchers. This comprehensive review of adsorbents enables budding researchers to cautiously scrutinize and select the appropriate adsorbent depending on the characteristics of the target VOCs.

Keywords Adsorption · VOCs · Adsorption capacity · Adsorbent material · Benzene · Toluene

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1 Introduction

Volatile organic compounds (VOCs) belong to the class of organic chemicals that are described by low boiling points. Several definitions of VOCs are proposed by various international agencies. As per the US Environmental Protection Agency (US EPA), "VOCs are carbon-bearing compounds excluding CO, CO_2, H_2CO_3, metal carbides or carbonates, and $(NH_4)_2CO_3$, which participates in atmospheric photochemical reactions". VOCs belong to the class of

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organic chemicals that are described by low boiling points. As per the World Health Organization (WHO), VOCs are organic compounds having vapor pressures over 133.32 Pa and boiling points between 50 to 260℃ at 1 atm pressure (Zavyalova et al., 2008) and based on their boiling points VOCs can be either (i) very- and semi-volatile organic compounds (VVOCs & SVOCs), or (ii) particulate organic matters (POMs). VOCs may have different molecular structures and based on the extent of the molecular polarity they are classified as polar and non-polar. The comprehensive categorization of VOCs is demonstrated in Fig. 1. In addition, pesticides, herbicides, and organophosphate esters also belong to the family of VOCs.

The VOCs are usually discharged from anthropogenic and natural sources. The spike in urbanization and industrialization in the last two or three decades are the two major reasons behind the incessant rise in VOCs emissions from anthropogenic sources. For instance, in China, VOCs emissions were predicted to increase at an average annual rate of over 5.9% (Zhu et al., 2020). Figure 2 shows the percentage contribution of VOCs emitted from various anthropogenic sources with industrial emissions being highest at 43%. The industries responsible for the generation of VOCs in greater amounts are related to petroleum refining, solvent manufacturing, and coal combustion (He et al., 2019). Coal combustion in power plants among the various industrial processes is reported to be the main source of VOCs emission i.e. 37% (Yan et al., 2017). Coal combustion results in the generation of the most hazardous air pollutants, popularly known as BTEX (benzene, toluene, ethylbenzene, and xylene). In addition to anthropogenic

Fig. 2 VOCS emission from different sources. Reprinted with Permission from Yang et al. (2019a). Copyright Elsevier 2019

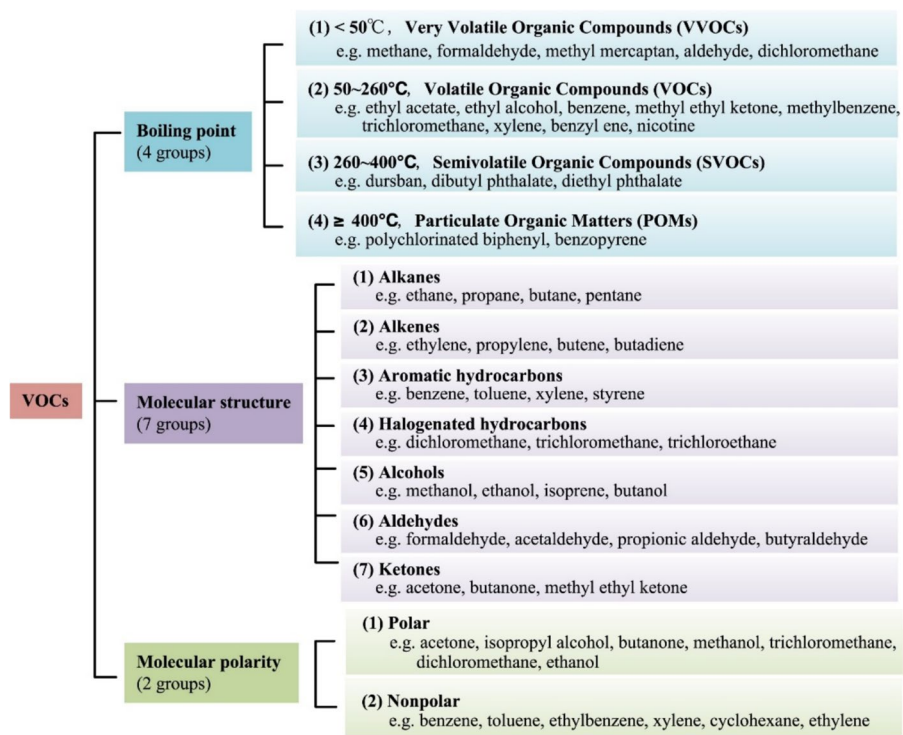

Fig. 1 The classification of different VOCs. Reprinted with Permission from Zhu et al. (2020). Copyright Elsevier 2020

sources of emission, there are biogenic emission sources which mainly come from natural sources. There are two sources of biogenic VOCs emissions, namely, terrestrial and oceans. Natural sources can emit up to 1150×10^{12} g carbon/year as compared to 142×10^{12} g carbon/year through human activities (Li et al., 2002). Isoprenes and monoterpenes are the two commonly known biogenic VOCs with the contribution of isoprenes from terrestrial sources around 500×10^{12} g carbon/year (Muller et al., 1992). Oceans are also regarded as a great VOCs emission source as it was reported that microlayers of seawater were supersaturated with acetone and acetaldehyde (Singh et al., 2003). There have been a lot of studies that established the involvement of ocean biology in the generation of VOCs. Marine sources were found to emit dimethyl sulfide and methyl iodide in good amounts. Further, it was also discovered that ocean water also acted as a sink for VOCs.

The harmful effects of VOCs on the ecological environment and the health of human beings have also been extensively reported in the literature. VOCs are responsible for the formation of ozone due to their reaction with NO_x, one of the primary ingredients of smog which causes serious health concerns to human beings. PM2.5 formation also occurs when oxygenated VOCs undergo condensation and nucleation. The emission of VOCs also contributes to the greenhouse effect. The harmful effects of VOCs are listed in Table 1.

There are various control techniques available for the abatement of VOCs which are further classified into destruction and recovery methods. The destruction techniques comprise of thermal oxidation, catalytic oxidation, and biofiltration. Whereas, adsorption, absorption, condensation, and membrane separation are a few of the recovery techniques. The pros and cons of all the available control techniques are presented in Table 2.

Amongst the available VOCs treatment technologies, adsorption is regarded as one of the preferred techniques on account of the advantages it offers such as less energy consumption hence low operational cost, flexibility of operation, and high efficiency. There are a large number of porous materials that are available for this application, the characteristics of these materials such as adsorption capacity, hydrophobicity, pore size, stability, etc., were investigated in detail in this review paper.

Most of the earlier review papers in this field dealt only with carbonaceous materials as it is the most popular and widely employed adsorbent. This paper reviewed carbon-based materials, oxygen-containing materials, organic polymers, and composite materials. The interaction between VOCs and adsorbents along with the methods to enhance adsorption performance were also discussed. A literature review was performed by considering the research papers published from 2000 to 2025. A literature search was executed by using the keywords such as"adsorption"and"volatile organic compounds"in Scopus and Science Direct. Further, the search was done for various adsorbents employed for the VOCs adsorption. In this study, an attempt was made to cover a variety of adsorbents

Table 1 Effect of VOCs on health and environment

S.NO	Type of VOCS	Impact on health/environment
1	Acetone	May cause coughing, dizziness, dullness and headache
2	Benzene	May cause nausea, vomiting, etc
3	Carbon Tetrachloride	Possible carcinogen, Harmful to aquatic organisms
4	Formaldehyde	Eye, nose, throat irritation
5	Toluene	Effects kidney, nervous system, liver
6	Methyl Ethyl Ketone	Person with pre-existing eye, skin or respiratory conditions may be more susceptible
7	Chlorophenols	Precursors to PCDD/F formation which are highly toxic
8	Xylene	May cause drowsiness and dizziness, irritating to skin and eyes, toxic to aquatic organisms
9	Vinyl Chloride	Possible carcinogen
10	Chlorobenzene	Precursors to PCDD/F formation which are highly toxic

Table 2 Comparison of different VOCS control techniques (Khan & Ghoshal, 2000)

Technique	Removal efficiency (in %)	Secondary waste	Advantages	Limitations	Annual operating cost $/cfm	Energy consumption
Thermal oxidation	95–99	Combustion products	Energy recovery up to 85%	Separate control equipment downstream for halogenated compounds. Requirement of supplementary fuel	15–90 (recuperative), 20–150 (regenerative)	Moderate
Catalytic oxidation	90–98	Combustion products	Energy recovery up to 70%	Catalyst poisoning. Requirement of separate control equipment downstream. Auxiliary fuel is necessary	15–90	Moderate
Bio-filtration	60–95	Biomass	Low investment, non-harmful secondary waste	Slow, microbes consisting of mixed culture are required for decomposing specific organics	15–75	Low
Absorption	90–98	Wastewater	VOCS recovery compensates for operating expenses	Thorough maintenance, non-availability of equilibrium data for most of the systems	25–120	Moderate
Condensation	70–85	Condensate	VOCS recovery offsets operating expenses	Thorough maintenance limits its application for VOCs having boiling points greater than 33℃	20–120	High
Adsorption	80–96	Saturated carbon	VOCS recovery offsets operating expenses	Moisture-prone, VOCs like ketones and esters may block the pores of the adsorbent	10–35	Moderate
Membrane separation	90–99	Exhausted membranes	No additional separation, solvent recovery offsets operating expenses	High cost of membranes	15–30	High

that can be used for the capture of VOCs to enable researchers to judiciously select an adsorbent.

2 Materials

2.1 Carbon-Based Materials

Carbon-based materials are the most versatile and popular adsorbents for the adsorption of VOCs. The large surface area, adjustable porosity, and, most importantly, its moderate cost is some of its attributes.

2.1.1 Activated Carbon

Activated carbon (AC) is considered one of the well-accepted and recognized adsorbents among the research community working in the field of adsorption of VOCs. Its highly porous structure, large surface area, and excellent chemical stability are some of its characteristics that enhance the adsorption ability of activated carbon. Moreover, it is cost-effective also. Activated carbon can be manufactured by utilizing a variety of raw materials containing large amounts of carbon content (carbonaceous materials). The precursors generally employed for the preparation of activated carbon are pepper stalks (Dolas et al., 2023), corn cob (Bagheri & Abedi, 2009; Jawad et al., 2020), green coffee (Bozaci & Acarali, 2023), coffee grounds (Ching et al., 2011), nut-peanut shells (Yang & Lua, 2003), banana trunk (Danish et al., 2022), moso bamboo (Yuan et al., 2021), cassava stem (Sulaiman et al., 2018), rice straw (Sangon et al., 2018), palm kernel shell (Karri & Sahu, 2018), tannery solid waste (Yuvaraj et al., 2018), barley husk, corn cob, and Agave salmiana leaves (Canales-Flores & Prieto-Garcia, 2020), coconut shells (Zhang et al., 2020), dirty plastic waste (Cansado et al., 2022), agro-industrial residues such as cork powder and peach stones (Cabrita et al., 2010), municipal solid waste (Karimi et al., 2020), carob waste (Viegas et al., 2020), pomelo peel (Sun et al., 2021). The AC is generally available in granular, pellet, or powder form. A lot of literature is available in the field of preparation of AC along with its modification and suitability as an adsorbent for the removal of VOCs. AC is considered as one of the promising adsorbents in the field of dyes removal (Akbar Ali et al., 2020; Azzouni et al., 2023; Grigoras et al., 2020), heavy metals adsorption (Liu et al., 2023; Gorzin & Abadi, 2017; Worku et al., 2023; El-Nemr et al., 2023), CO_2 capture (Cruz Jr. et al., 2023; Lim et al., 2023; Wang et al., 2023; Xing et al., 2023), SO_2 adsorption (Jacobs et al., 2023), NH_3 adsorption (Cardenas et al., 2023; Wu et al., 2023), phenol removal (Cao et al., 2020; Dehmani et al., 2023; Zhang et al., 2023), adsorption of pharmaceuticals (El Mouchtari et al., 2020; Jaria et al., 2020), dissolved organic matter from landfill leachate (Zeng et al., 2020), indoor air purification (Zheng et al., 2023), flavonoids removal (Lu et al., 2023), and adsorption of VOCs (Gupta & Kumar, 2020; Lashaki et al., 2023). To date, a lot of studies have been conducted for the adsorption of VOCs on AC to access its adsorption capacity under varying operating conditions. Oh et al. (2010) studied the adsorption behavior of methanol, ethanol, methyl ethyl ketone, benzene, n-propanol, toluene, and o-xylene on granular activated carbon (GAC) at 101.3 kPa and in 298–323 K temperature range. The adsorbent's surface area and pore volume were 804.6 $m^2.g^{-1}$ and 0.4734 $cm^3.g^{-1}$, respectively, and the adsorption capacities of these various VOCs lay from 10.4 to 89.4 mg. g^{-1}. Liu et al. (2011) employed AC entrapped with stainless steel fibers having a specific surface area of 769 $m^2.g^{-1}$ for the adsorption of toluene. The breakthrough time was found to increase by 15 min in comparison to adsorption over GAC. Kalluri et al. (2008) used microfibrous entrapped carbon adsorbent for hexane adsorption and found substantial improvement in the breakthrough time compared to adsorption on the same size of AC. Li et al. (2011) performed adsorption of o-xylene over chemically treated GAC. For this, separate solutions of 10 M nitric acid (NA), 9 M sulfuric acid (SA), 7.3 M phosphoric acid (PA), and 10 M sodium hydroxide (SH) were prepared. GAC particles were then dipped in each of these solutions to obtain modified GACs named GAC/NA, GAC/SA, GAC/PA, and GAC/SH. GAC/SH possessed the highest BET surface area of 868 $m^2.g^{-1}$ with a maximum adsorption capacity of 295.403 $mg.g^{-1}$. Kim et al. (2006) adsorbed benzene and toluene on AC treated with 1 wt% H_3PO_4 whose specific surface area was found to be 1109 $m^2.g^{-1}$. The adsorption capacity for benzene and toluene was obtained to be 499.9 $mg.g^{-1}$ and 372.6 mg. g^{-1}, respectively. The incomplete desorption of AC results in the formation of a heel, which adversely affects the longevity and regeneration cost (Jahandar

Lashaki et al., 2016). It was attributed to irreversible adsorption, including chemisorption. The adsorption of various VOCS vapors on activated carbon are summarized in Table 3.

It is apparent from Table 3 that a fairly good adsorption capacity of up to around 900 mg VOCs adsorbed/g AC can be achieved under various conditions. The capacity of the adsorbent is also strongly dependent upon its physicochemical properties such as pore volume, surface area of the adsorbent, pore structure, pore size, etc. along with the properties of VOCs molecules and adsorption conditions. However, the flammable nature of AC poses a risk of fire in case of exothermic adsorption processes. Further, the high resistance, pore blocking, and hygroscopic nature of activated carbon limit its implementation in the control of VOCs.

2.1.2 Biochar

Biochar is a solid material consisting of high carbon content which is obtained by heating the carbonaceous material especially biomass in the absence of oxygen (Fig. 3). Notably, the raw materials employed for the

Table 3 Summary of applications of AC on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Methanol	10.6	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
Ethanol	15.9	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
Benzene	27.5	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
o-Xylene	90.4	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
Methyl Ethyl Ketone	24.3	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
n-Propanol	30.3	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
Toluene	59.2	25 °C, 120 $mL.min^{-1}$, 6000 ppmv	Oh et al. (2010)
o-Xylene	305.7	22–27 °C, 45 $mL.min^{-1}$, 2176–2239 $mg.m^{-3}$	Li et al. (2011)
Toluene	401.79	25 °C, 30 $mL.min^{-1}$, 5 $mg.L^{-1}$	Mohan et al. (2009)
Cyclohexane	229.4	27 °C, 0.55 $mL.min^{-1}$, 72.76 $mg.L^{-1}$	Gironi and Piemonte (2011)
Benzene	340	30 °C, 250 $mL.min^{-1}$, 1000 ppmv	Cal et al. (1996)
Toluene	240.6	28 ± 1 °C, 0.076 $m.s^{-1}$, 70 ppmv	Shiue et al. (2010)
Benzene	220	30 °C, 2000 $mL.min^{-1}$ $0.015P_0$,	Chiang et al. (2002)
Hexane	403.2	25 °C, $0.8P_0$	Ramos et al. (2010)
Benzene	561.6	25 °C, $0.8P_0$	Ramos et al. (2010)
Toluene	552	25 °C, $0.8P_0$	Ramos et al. (2010)
Hexane	369.6	25 °C, $0.8P_0$	Cardoso et al. (2008)
Toluene	22.5	24℃, $0.9P_0$	Bajwa et al. (2016)
Benzene	31.1	24℃, $0.9P_0$	Bajwa et al., (2016)
Xylene	27.5	24℃, $0.9P_0$	Bajwa et al. (2016)
Hexane	25	24℃, $0.9P_0$	Bajwa et al. (2016)
Toluene	350	21℃, 250 $mL.min^{-1}$, 100 ppmv	Anfruns et al. (2011)
Methyl Ethyl Ketone	220	21℃, 250 $mL.min^{-1}$, 100 ppmv	Anfruns et al. (2011)
Limonene	640	21℃, 250 $mL.min^{-1}$, 50 ppmv	Anfruns et al. (2011)
Ethyl Benzene	339	25℃, $0.99P_0$	Bedane et al. (2019)
Toluene	368	25℃, $0.99P_0$	Bedane et al. (2019)
p-Xylene	318	25℃, $0.99P_0$	Bedane et al. (2019)
n-Hexane	244	25℃, 95 $mL.min^{-1}$, 0.0013 $g.cm^{-3}$	Dobre et al. (2014)
2-Propanol	357	25℃, 95 $mL.min^{-1}$, 0.000248 $g.cm^{-3}$	Dobre et al. (2014)
Benzene	892	20℃, $0.986P_0$	Xu et al. (2017)
Toluene	692	20℃, $0.986P_0$	Xu et al. (2017)

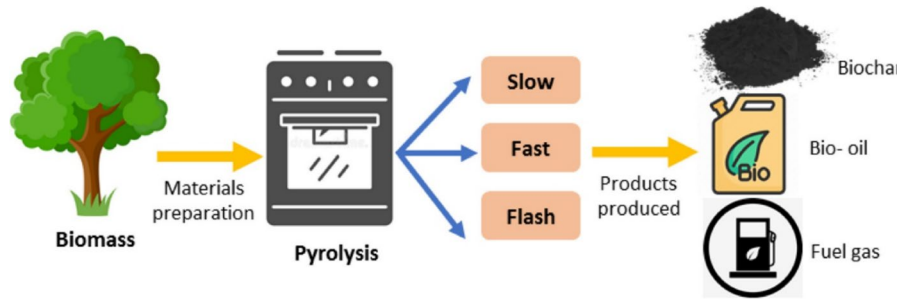

Fig. 3 General concept of pyrolysis process (Amalina et al., 2022). Open access under the CC BY license

synthesis of activated carbon and biochar along with the manufacturing techniques are the same. The temperature needed for carrying out pyrolysis operation in the case of biochar production is relatively lower (around 700℃). Biochar offers advantages such as the availability of abundant feedstocks accompanied by low manufacturing costs. Hence, it is seen as an effective and potential replacement for activated carbon. The cost incurred during the production of biochar is reported to be only one-sixth of the commercial activated carbon. The major field in which biochar has been extensively employed is related to soil fertility in agriculture. The type of feedstock employed for the production of biochar influences its physicochemical properties which subsequently affects its performance as an adsorbent. Table 4 shows a variety of raw materials when subjected to different pyrolysis temperatures leading to the production of biochar with different specific surface areas and adsorption capacities. Pyrolysis temperature between 500—550℃ yielded surface area as high as 110 m^2. g^{-1} for sludge-based biochar compared to biochar derived from other raw materials (Table 4). The two influencing parameters that determine the adsorption characteristics of biochar are its aromaticity and polarity. The molar ratios, H/C and O/C, in biochar, are utilized to estimate aromaticity and polarity. Low H/C indicates higher aromaticity which is attributed to the greater pyrolysis temperature that subsequently results in the production of biochar with a greater extent of carbonization. High pyrolysis temperature expedites the removal of surface functional groups containing oxygen thus enhancing its aromaticity and at the same its affinity towards hydrophobic VOCs (non-polar aromatic hydrocarbons). The adsorption capacity of biochar produced at 700℃ was found to be more compared to biochar produced at 300℃ in adsorbing trichloroethylene, a non-polar compound (Ahmad et al., 2013). Chen et al., (2008) also reported similar results wherein nitrobenzene and naphthalene were adsorbed onto biochar prepared in the temperature range of 100–700℃. Moreover, greater pyrolytic temperatures cause specific surface areas to increase and the pore size of the resulting biochar to decrease. It is also evident from Table 4, that the highest specific areas of 467.8 and 517.28, respectively, were obtained when biochar from pistachio shells and bamboo, respectively, were produced at higher pyrolysis temperatures of 900 and 1000℃, respectively. The high polarity (i.e., high O/C ratio) biochar is found to be more suitable for the adsorption of hydrophilic VOCs (aldehydes and ketones) and it also suggests the presence of more acidic functional groups. Ball milling is one such operation that augments the hydrophilicity and polarity of biochar by bringing in oxygen-holding functional groups on the surface (Zhang et al., 2021).

The dominant mechanisms responsible for the uptake of organic compounds on biochar are reported to be π-π interactions, hydrogen bonds, hydrophobic interactions, and electrostatic effects (Wang et al., 2013). While the following mechanisms are suggested for the adsorption of VOCs: electrostatic interactions, polar VOCs—hydrophilic site interactions, non-polar VOCs – hydrophobic site interactions, and partition in non-carbonized content (Fig. 4). In general, the controlling adsorption mechanism is influenced by the pyrolysis temperature. At lower pyrolysis temperatures (100—300℃), the non-carbonized portion in char is quite more owing to which partition mechanism plays a dominant role in VOCs removal. Higher non-carbonized organic matter is also a consequence of the occurrence of the high amount of volatile matter in biochar yielded at lower temperatures (Kumar et al., 2019). Biochars produced at higher temperatures (400 −700℃) utilize the adsorption of VOCs onto the surface as the key mechanism (Ahmad

Table 4 Summary of physiochemical properties and environmental applications of biochar

Biochar type	Pyrolysis Temperature, ℃	Specific surface area, $m^2.g^{-1}$	Adsorbate	Temperature, ℃	Maximum Adsorption capacity, q_m $mg.g^{-1}$	Reference
Dyes Removal						
Korean cabbage biochar	500	11.44	Crystal violet	30	1304	Sewu et al. (2017)
Vermicompost derived biochar	700	76.296	Methylene blue	30	27.35	Yang et al. (2016)
Pulp and paper sludge biochar	750	174	Methyl orange	25	20.53	Chaukura et al. (2017)
Hydrolyzed rice straw biochar	450	232.31	Brilliant green	30	111.11	Saifurrehman et al. (2016)
Bamboo biochar	1000	517.28	Acid black 172	20	384.62	Yang et al. (2014)
Eucalyptus wood particles biochar	450		Malachite green	30	156.25	Singh et al. (2016)
Pistachio shells biochar	900	467.8	Congo red	30	614.7	Saghir et al. (2022)
Raw industrial sludge biochar	750	157	Methylene blue	20	48.5	Jellali et al. (2022)
Sludge and lirioden-dron leaves biochar	550	39.485	Methyl orange	25	85.1	Cheng et al. (2021)
Heavy metals removal						
Palm kernel cake residue biochar	350	89.385	Pb^{2+}	30	49.64	Maneechakr and Mongkollertlop (2020)
Peanut shell biochar	400	6.45	Cd^{2+}	25	188.6	Shan et al. (2020)
Seaweed biochar	550	50.24	Zn^{2+}	25	22.25	Shin (2017)
Manganese-rich pokeweed plants biochar	500	20.233	Cu^{2+}	25	248.309	Yang et al. (2021)
Polycyclic aromatic hydrocarbons (PAHs) removal						
Sewage sludge-based biochar	700		Phenanthrene	25	87.33	Guo et al. (2017)
Antibiotics removal						
Sludge derived biochar	550	110	Fluoroquinolone	25	19.80	Yao et al. (2013)
Walnut shell biochar	500		Sulfonamide	25	46	Geng et al. (2021)
Pesticides removal						
Eucalyptus wood chips biochar	450	10	Imidacloprid, Acetamiprid and Methomyl	25	32.42, 14.75, and 4.87	Srikhaow et al. (2022)
Sugar cane filter cake biochar	380	19.8	Thiamethoxam	25	10.17	Fernandes et al. (2021)

et al., 2014). Zhang et al. (2021) found a reduction in the adsorption capacity of biochar after five adsorption–desorption cycles, establishing it as an effective and reusable adsorbent for VOCs. Notably, the production of biochar is also accompanied by the release of VOCs, a deleterious effect on the environment (Zhu et al., 2020). Notwithstanding, the application of biochar as an adsorbent for VOCs abatement still needs to be explored by the research community. The superior properties (good adsorption capacity and low cost) of biochar are a testament to its suitability for VOCs adsorption. The complex adsorption

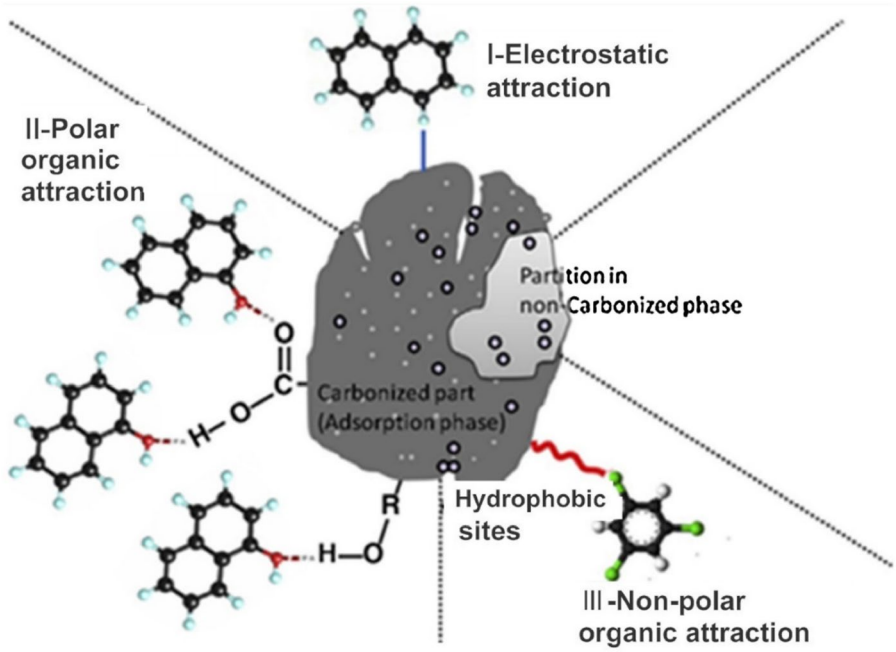

Fig. 4 Postulated mechanisms of the interactions of biochar with organic contaminants. Circles on biochar particle show partition or adsorption. I – electrostatic interaction between biochar and organic contaminant, II – electrostatic attraction between biochar and polar organic contaminant, and III – electrostatic attraction between biochar and non-polar organic contaminant. Reprinted with Permission from Zhang et al. (2017). Copyright Elsevier 2017

mechanism involved needs to be understood thoroughly to enable the efficient utilization of biochar for VOCs removal. Table 5 presents the application of biochar as an adsorbent for capturing various VOCs.

2.1.3 Activated Carbon Fiber

As the name indicates, activated carbon fibers (ACFs) are fibrous, and comprised of carbon-rich materials. It can be converted into various shapes such as yarn, thread, felt, fabric, paper cloth, etc. for its use in various engineering applications (Yue et al., 2017). It is known as third generation form of activated carbon followed by granular activated carbon and powdered activated carbon (Huang et al., 2021). The raw materials employed for the development of ACF are poor renewable like cellulose (viscose rayon) fibers, polyacrylonitrile fibers, phenolic resin fibers, and pitch fibers. The price associated with the manufacture of ACF is the major limitation in its use as an adsorbent which can be offset by using rejects of commercial polymer fibers or coal pitch-based fibers as starting materials (Fuertes et al., 2003). The preparation of ACF requires the carbonization of organic fibers followed by activation with steam or carbon dioxide at 700–1000℃ (Tang et al., 2007). As compared to AC, ACF has a unique thin fiber shape complemented with straight and short micropores which assists in enhancing the adsorption kinetics as well as the rates of mass transfer (Zhu et al., 2020). Besides,

Table 5 Summary of applications of biochar on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Benzene	2.9	25 °C, 45 $mL.min^{-1}$, 10 ppmv	Vikrant et al. (2020)
Methyl Ethyl Ketone	43	25 °C, 45 $mL.min^{-1}$, 10 ppmv	Vikrant et al. (2020)
p-Xylene	130.21	25℃, P_0	Zhang et al. (2021)
Acetone	110.1	25 °C, 0.2 $mL.min^{-1}$, 200 ppmv	Rajabi et al. (2021)
Toluene	166	20 °C, 50 $mL.min^{-1}$, 1000 ppmv	David (2023)
Acetone	152	20 °C, 50 $mL.min^{-1}$, 1000 ppmv	David (2023)

it has a huge surface area accompanied by superb physical properties (Huo et al., 2021), and owing to its fibrous nature, the pressure drop across the adsorbent bed is also quite low (Meng et al., 2019). Undoubtedly, these advantages make ACF a potential adsorbent.

Usually, the textural properties of the porous adsorbent determine its adsorption capacity including ACF. It has been reported that ACFs formed by narrow micropores (< 1 nm) have greater adsorption ability compared to ACFs with wider pores especially at lower concentration of VOCs (Fuertes et al., 2003). Rodenas et al. (2011) also observed that a large volume of micropores (< 0.7 nm) was mainly responsible for the adsorption of benzene at low concentrations. Baur et al. (2015) found that ACF with ultra-micropores (< 1 nm) had better adsorption strength compared to one comprising semi-micropores (1–2 nm) for toluene in the 8 −10 ppmv concentration range. Liu et al. (2019) found that ACF cloth possesses a distinct micropore structure with a width of micropores lying between 0.61–0.69 nm. Hence, ACF with narrow micropores is considered to be one of the desired features for effective VOCs adsorption. The pore size distribution is depicted in Fig. 5.

The lesser concentration of oxygen groups on the ACF's surface makes ACF inherently hydrophobic. As reported, the concentration of oxygen groups on the ACF surface is between 735 to 865 μmol.g^{-1} whereas it is between 1570 to 4289 μmol.g^{-1} for AC (Huang et al., 2021). Hence, the adsorption capacity of ACF is influenced by the polarity of the VOCs. Non-polar and weak polar VOCs have good affinity for ACF while polar VOCs exhibit poor affinity towards ACF. Wang et al. (2021) prepared ACF by employing reductive carbonization owing to which its capacity to adsorb non-polar VOCs (benzene) increased by 8 times compared to ACF prepared by traditional methods. On the contrary, Gaur et al. (2006) noticed that the existence of any electronegative oxygen on the surface of ACF had an adverse impact on the adsorption of BTX (benzene, toluene, and m-xylene). Balanay et al. (2011) discovered that the capacity of ACF with surface areas similar to GAC (1500 $m^2.g^{-1}$) was high for airborne toluene (non-polar VOCs).

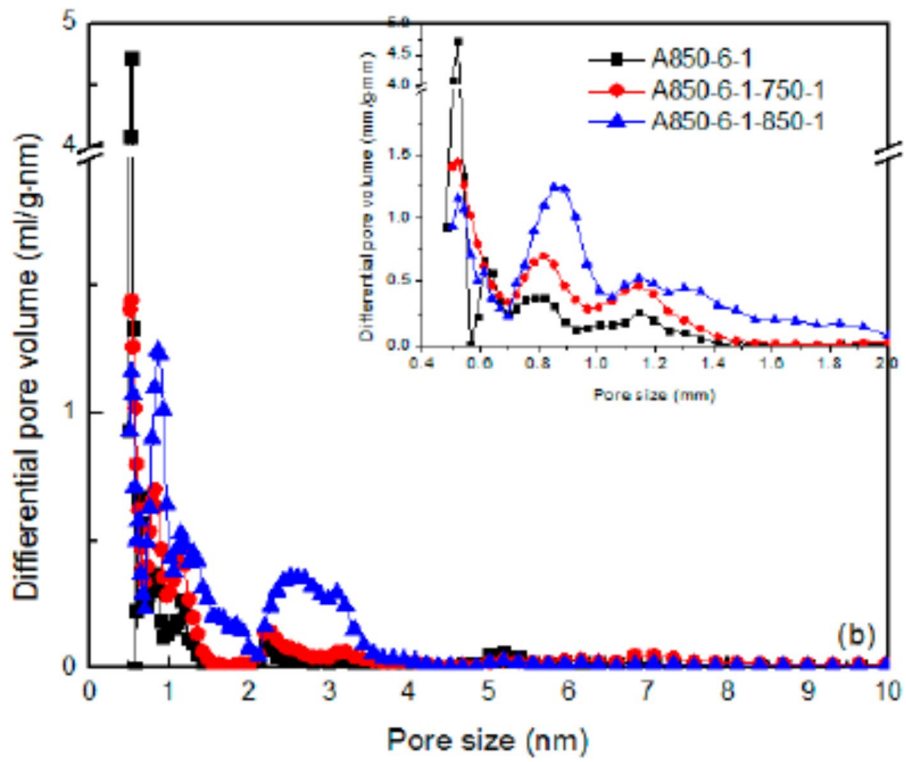

Fig. 5 Pore size distribution of ACF sample (Huang et al., 2016). Open access under the CC BY license

As discussed, the adsorption of polar VOCs on ACF is abysmal. Hence, there is a need to modify the surface of ACF to make it suitable for hydrophilic adsorbents. Usually, surface functional groups can be developed by modifying ACF with sulfuric acid, nitric acid, and phosphoric acid. Huo et al. (2021) prepared ACF with abundant functional groups by employing the steam secondary activation method and found that water facilitated the adsorption of ethanol vapors. Song et al. (2017) found the adsorptive capacity for toluene in the presence of water vapor on ACF activated with Fe_3O_4 and it was quite large when the same adsorbate composition was adsorbed on untreated ACF. The adsorption of polar VOCs can also be enhanced by impregnating metal oxide nanoparticles onto ACFs. Wang et al. (2021) carried out electrothermal desorption of ACF for regeneration by moderate electric power with complete recovery of adsorption capacity. Also, Huo et al. (2021) found ACF to have outstanding regeneration ability with recovery of 94% adsorption efficiency by nitrogen purging at room temperature. Notwithstanding the excellent adsorption capacity of ACFs its utility in the industries is quite limited. This is due to costly fiber precursors accompanied by high processing costs. The use of ACF as an adsorbent for the removal of VOCs is demonstrated in Table 6.

2.1.4 Carbon Nanotubes

The research and innovation in the field of nanotechnology led to the development of carbon nanotubes (CNTs) which was discovered by Iijima in 1991 (Iijima, 1991). CNTs are comprised of one or more graphene (allotrope of carbon) layers rolled coaxially in the form of a cylinder whose length is generally greater than 20 μm with a radius not more than 100 nm (Zhu et al., 2002). CNTs are synthesized by making use of the following techniques: (i) chemical vapor deposition, (ii) electric arc discharge, (iii) laser ablation, and (iv) plasma-enhanced chemical vapor deposition (Shoukat & Khan, 2021). The high yield of CNTs is obtained in the electric arc discharge method and laser ablation method. CNTs are prepared in two distinct varieties i.e., single-walled carbon nanotubes (SWCNT) comprising of one graphene layer and multi-walled carbon nanotubes (MWCNT) made up by rolling more than one graphene layer with an interspacing of 0.34 nm between two concentric cylinders (Zare et al., 2015). The properties that make CNTs a promising adsorbent are large specific surface area, inherent hydrophobicity, high aspect ratios, readily modified surfaces, and hollow cylindrical structure (Gupta et al., 2013). As an adsorbent it is widely employed for dye removal (Costa et al., 2023; Lee et al., 2023), removal of heavy metals (Krishna et al., 2023; Li et al., 2023), CO_2 removal (Omidfar et al., 2015; Sekiya et al., 2018), CH_4 removal (Feng et al., 2018; Shkolin et al., 2018), ammonia removal (Vikramaditya & Sumithra, 2014; Yan et al., 2015), hydrogen adsorption (Kaskun et al., 2020), adsorption of organic compounds (Anjum et al., 2019; Ersan, 2021; Han et al., 2022; Memetova et al., 2023), VOCs abatement (Dai et al., 2021; Diaz et al., 2007; Zheng et al., 2006).

It has been reported in the literature that polarizability is a key factor in deciding the adsorption strength of CNTs (Dai et al., 2021; Li et al., 2016a). The graphene layers naturally are hydrophobic which makes CNTs a suitable candidate for adsorption of non-polar or weakly polar VOCs molecules. Kupreenko et al. (2022) learnt, that with decreasing dipole moment of the adsorbate, the adsorptive strength of CNTs rose. Similarly, the adsorption

Table 6 Summary of applications of ACF on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Toluene	538.8	30℃, 86.5 ppmv	Kim et al. (2012)
Acetone	106.71	25℃, 150 $mL.min^{-1}$, 3000 $mg.m^{-3}$	Meng et al. (2019)
Methanol	133.06	25℃, 150 $mL.min^{-1}$, 3000 $mg.m^{-3}$	Meng et al. (2019)
Toluene	720	25℃, 7 $L.min^{-1}$, 500 ppmv	Balanay et al. (2011)
Ethanol	72.63	25℃, 150 $mL.min^{-1}$, 300 ppmv	Huo et al. (2021)
Toluene	569	25℃, 500 $mL.min^{-1}$, 1200 ppmv	Lin et al. (2013)
Benzene	310	25℃, 90 $mL.min^{-1}$, 200 ppmv	Rodenas et al. (2011)

of isopropyl alcohol onto CNTs was found to be decreasing at higher relative humidities suggesting the hydrophobic nature of the adsorbent (Hsu & Lu, 2009). Hence, to enhance the adsorptive capacity of polar VOCs molecules several modifications were made by the researchers namely, the oxidation of SWCNTs with NaOCl for the adsorption of isopropyl alcohol (Hsu & Lu, 2009), functionalization of CNTs via carboxylation and nitration increased breakthrough volume by 300% when ethanol vapors were adsorbed (Hussain et al., 2009). The mechanism of VOCs adsorption is primarily by physisorption for non-polar molecules and in general chemisorption for polar VOCs which is evident from the heat of adsorption studies done by various researchers. Shih and Li (2008) found that the magnitude of heat of adsorption for non-polar VOCs namely, trichloroethylene, benzene, and hexane indicated physical adsorption on MWCNTs while higher heat of adsorption in the case of acetone vapor reflected chemisorption as a governing mechanism. The heats of adsorption of organic vapors (MEK, toluene, hexane, and cyclohexane) were found to be 1–4 times their respective heats of vaporization which represented physical adsorption as the key mechanism (Agnihotri et al., 2005). The presence of amorphous carbon in CNTs facilitates the adsorption of organic vapors as it enhances the surface heterogeneity and Kupreenko et al. (2022) showed nitrogen doping as one of the techniques for increasing amorphous carbon. This fact was also corroborated by Shih and Li (2008) that amorphous carbon on the exterior layers results in greater sorption capacity for organic vapors. The topological defect is another vital factor that aids in the strong adsorption of oxygen and hydrogen molecules on the surface of CNTs (Grujicic et al., 2003; Mehmood et al., 2013; Mishra & Kundalwal, 2022). Shih and Li (2008) found that acetone got chemisorbed on topological defects present in CNTs indicating strong chemical interactions. The aggregation or bundling of CNTs is another challenge that needs to be addressed as it impairs its adsorption capacity by blocking the available adsorption sites. In aqueous solutions, the addition of anionic surfactants, proteins, or other chemicals etc.; improves the dispersion of CNTs (Gotovac et al., 2006; Ihsanullah et al., 2016; Pan & Xing, 2008) while in gas phase adsorption supporting method is generally employed to avoid bundling of CNTs. Tulaphol et al. (2016) embedded MWCNTs in SiO_2 particles to alleviate the effect of aggregation. Table 7 depicts the applications of CNTs for the adsorption of VOCs.

2.1.5 Graphene

Graphene (an allotropic form of carbon) is comprised of monolayered atoms in a two-dimensional structure in the form of a sheet packed in a hexagonal honeycomb matrix. The common methods for manufacturing graphene include micromechanical exfoliation, electrochemical exfoliation, pyrolysis, chemical vapor deposition, epitaxial growth, hydrothermal self-assembly, and nanotube slicing (Mbayachi et al., 2021; Peng et al., 2017). The adjacent carbon atoms are joined through sp^2 hybridization which is responsible for its superb properties such as high thermal conductivity, and great mechanical strength accompanied by excellent chemical stability. These properties make graphene a suitable candidate for its applications in various areas of science and engineering such as electronic gadgets, sensors, photonics, biomedicines, and energy storage (Fu et al., 2025; Kong et al., 2021). Graphene also exhibits high surface area owing to which it has wide applications in the environmental field as an adsorbent (Chen et al., 2019) for (i) heavy metals removal (Kong et al., 2021;

Table 7 Summary of applications of CNTs on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Formaldehyde	62.49	25℃, 2.6 $L.min^{-1}$, 1.5 $mg.m^{-3}$	Yang et al. (2017)
Isopropyl alcohol	83	25℃, 0.08$L.min^{-1}$, 500 ppmv	Hsu and Lu (2009)
Toluene	175	25℃, 5000 ppmv	Agnihotri et al. (2005)
Methyl ethyl ketone	120	25℃, 5000 ppmv	Agnihotri et al. (2005)
Benzene	218.4	30℃, 0.03 atm	Crespo and Yang (2006)

Peng et al., 2017), (ii) aromatic organic contaminants adsorption (Apul et al., 2013; Ma et al., 2020), and (iii) VOCs abatement (Bai et al., 2013; Kunaseth et al., 2017; Szczesniak et al., 2018a). The two varieties of graphene that are normally employed by researchers for the adsorption of VOCs are graphene oxide (GO) and reduced graphene oxide (rGO). The difference between these two is the oxygen groups that are available on their surface. GO is a result of the oxidation of graphene with carboxylic, hydroxyl, or epoxide groups; the oxygen-comprising groups. On the other hand, rGO is obtained by eliminating functional groups from GO by employing techniques such as chemical reduction, reduction via natural antioxidants, thermal annealing, microwave and photo reduction, and electrochemical reduction (Minale et al., 2020; Yu et al., 2016). The GO owing to the availability of oxygen functional groups is suited for the uptake of hydrophilic VOCs while the hydrophobic character of rGO facilitates the adsorption of aromatic VOCs. In one of the comparative studies made by Yu et al. (2018a), the adsorption capacities of GO and rGO were found to be 216.2 and 276.4 $mg.g^{-1}$, respectively, when a gas stream containing 50 ppm benzene concentration was made to flow through the adsorption column. Similarly, the capacity of rGO-SnO_2 (metal oxide/rGO composite material) for benzene was found to be 23.3 $mg.g^{-1}$, the maximum amongst other composites of metal oxides and graphene that were prepared (Khan et al., 2019). The other parameters that influence the VOCs adsorption on graphene-based materials are specific surface area, pore volume, and pore size distribution (Kumar et al., 2020). The specific surface area of graphene in composite form was reported to be more in comparison to graphene available in pristine form. In one of the studies undertaken by Sun et al. (2014), the surface area of MIL-101/GO composite was found to be 3502.2 $m^2. g^{-1}$ much more than 236.4 $m^2. g^{-1}$, the surface area reported for GO (Yu et al., 2018a). Consequently, the higher surface area of MIL-101/GO composite resulted in excellent hexane uptake of 1042.1 mg. g^{-1}. The reduction of GO to rGO also led to a marginal rise in the surface area from 236.4 $m^2. g^{-1}$ to 292.9 $m^2. g^{-1}$ (Yu et al., 2018a). One of the methods to enhance the surface area is through KOH activation as it results in the production of pores whose size is greater than 2 nm (Szczesniak et al., 2018b). Yu et al. (2018a) successfully regenerated rGO by application of heat at 150℃ and found it a promising adsorbent for VOCs under dynamic adsorption/desorption. Hence, graphene-based derivatives especially graphene in the composite form have been found to exhibit all the attributes of a good adsorbent for the abatement of VOCs. However, the synthesis of graphene, its tendency to aggregate, and the associated cost pose a great challenge for the researchers which need to be addressed before its implementation on an industrial scale. The adsorption capacities of graphene for different VOCs are shown in Table 8.

2.1.6 Carbon–Silica Composites

The synthesis of carbon–silica composite (CSCs) consists of impregnating precursor of carbon-bearing material into mesoporous silica followed by carbonization at high temperatures in the absence of oxygen (Fig. 6). For the first time, Glover et al. (2008) prepared CSC by impregnating furfuryl alcohol in MCM-41, a well-known siliceous material. The uniqueness of CSCs lies in the presence

Table 8 Summary of applications of graphene on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Benzene	276.4	10℃, 40 $mL.min^{-1}$, 50 ppmv	Yu et al. (2018a)
Toluene	304.4	10℃, 40 $mL.min^{-1}$, 50 ppmv	Yu et al. (2018a)
n-hexane	1042.1	25℃	Sun et al. (2014)
Toluene	183	25℃, 120 $mL.min^{-1}$, 1300 $mg.m^{-3}$	Dai et al. (2019)
Benzene	23	25℃, 50 $mL.min^{-1}$, 50 ppmv	Khan et al. (2019)
Benzene	289.8	20℃, $0.98P_0$	Guo et al. (2016)
Toluene	1.9	25℃, 30 ppmv	Kim et al., (2018a, 2018b)

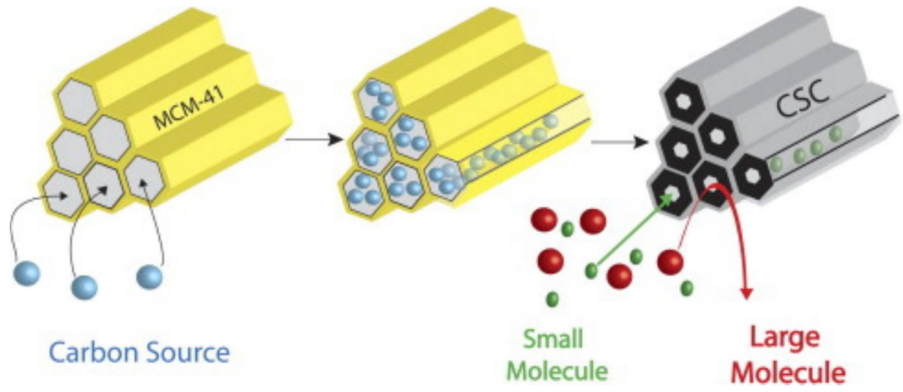

Fig. 6 Conceptual depiction of CSC creation. Reprinted with Permission from Glover et al. (2008). Copyright Elsevier 2008

of two discrete phases namely, carbonaceous (non-polar) and siliceous (polar). Since it is well established that the mutual interaction between adsorbent and adsorbate is influenced by their polarities. A non-polar surface (carbon) in nature readily adsorbs adsorbates of weak polarity while the polar surface (siliceous) has a high affinity towards polar adsorbates. CSCs that are equipped with both polar and non-polar surfaces as potential adsorption sites have an edge over single-phase adsorbents (Furtado et al., 2013). Moreover, the higher surface area with good adjustable pore size distribution are the other properties of this material. The filling of carbon precursor into mesopore silica also assists in reducing (i) large pores into micropores, and (ii) diffusional path. The amount of carbon loading determines the size of pores and it was reported by Clippel et al. (2010) that carbon loading of less than 5 wt% resulted in the generation of mesopores while carbon loading of more than 22 wt% led to the production of micropores and bi-porosity was observed for intermediate loadings. Similarly, Twumasi et al. (2012) observed that the generation of microporosity along with pore size distribution was chiefly dependent upon % carbon loading and method of synthesis. Carbonization temperature is also an important parameter that controls microporosity (Furtado et al., 2013). CSCs, owing to their typical pore size distribution, display higher VOCs adsorption capacity in comparison to the parent material. Lu et al. (2020) demonstrated that the adsorption capacity of CSC for toluene increased with the rise in carbon content, from 11.76 to 22.91 mg. g^{-1} increasing the % carbon content from 3.09 to 9.1. The adsorption capacity of CSC (22.91 mg. $g^{-1)}$ was also found to be more than that of the parent material, SiO_2 (1.63 mg. g^{-1}). Janus et al. (2011) obtained the sorption capacity of methyl ethyl ketone onto CSCs to be 257 mg. g^{-1}, more than that of parent material, MCM-41 (197 mg. g^{-1}). Twumasi et al. (2012) found enhanced uptake for toluene when CSC was prepared with 45 wt% carbon in comparison to 32 wt%. The uptake capacity of CSCs for adsorption of benzene was found to be 5.06 mmol. g^{-1}, greater than that of activated carbon, 4.37 mmol. g^{-1} (Dou et al., 2011). Similarly, in one of the studies, CSCs showed higher adsorption capacity for benzene and ethyl benzene in comparison to activated carbon (Mohammadi & Moghaddas, 2015). Glover et al. (2008) showed that CSCs reached equilibrium in less time in comparison to MCM-41. Janus et al. (2011) found high stability of carbon silica nanocomposite adsorbents in ten consecutive adsorption desorption runs indicating excellent reproducibility without any significant loss of adsorbent capacity. Mohammadi and Moghaddas (2015) found no noticeable change in the adsorption capacity of silica aerogel-activated carbon composites after regeneration. The lesser mass transfer resistance on account of a shorter diffusion path, and enhanced affinity towards VOCs; contribute to the higher rates of adsorption, hence making CSCs a promising adsorbent for abatement of VOCs. By considering a factor of fire hazard, the higher spontaneous ignition temperature of CSCs than AC enables them to be successfully utilized for commercial applications (Twumasi et al., 2012). Table 9 shows the applications of CSCs for the removal of VOCs.

Table 9 Summary of applications of CSCs on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Methyl Ethyl Ketone	257	10℃, 20 $mL.min^{-1}$, 93,757 ppmv	Janus et al. (2011)
Benzene	22.91	30℃, 166 $mL.min^{-1}$, 1000 $mg.m^{-3}$	Lu et al. (2020)
Benzene	394.68	45℃	Dou et al. (2011)
Ethyl Benzene	954.5	25℃, 85 $mL.min^{-1}$, 1115 ppmv	Mohammadi and Moghaddas (2015)

2.2 Oxygen-Containing Materials

2.2.1 Zeolites

Zeolites are crystalline aluminosilicates with well-organized distribution and evenly sized micropores with pore sizes usually less than 2 nm. It is a three-dimensional framework of TO_4 tetrahedron block, where T is either a Si^{4+} or Al^{3+} atom with T occupying the central position surrounded by four oxygen atoms. The adjacent tetrahedrons are connected through the sharing of oxygen atoms which leads to crosslinking and eventually creates cages and channels. The replacement of Al^{3+} with Si^{4+} tends to create a net negative charge over the entire framework that is neutralized by the presence of cations (Ca^{2+}, K^{+}, Na^{+}, etc.) located in the cavities or cages (Malamis & Katsou, 2013). To date, 250 different forms of zeolites are known with diverse pore topologies (Salmankhani et al., 2021). Zeolites can be applied as a molecular sieve, adsorbent, or catalyst for environmental remediation including the removal of VOCs (Jafari et al., 2018; Mekki & Boukoussa, 2019; Wu et al., 2021). Some of the desirable properties of zeolites that make them appropriate for these applications are their hydrophobicity, great surface area, nonflammability, and adjustable porosities. Moreover, zeolites exhibit outstanding hydrothermal and chemical stability that enables their regeneration at a temperature of 150℃ much lower than that for carbon-based materials where desorption is performed over 300℃ (Su et al., 2010; Yin et al., 2022). The applications of zeolites for the adsorption of VOCs have been comprehensively explored by the research community. It has been reported in the literature that the factors influencing the amount of VOCs adsorbed on zeolites are: (i) Si/Al ratio, (ii) pore characteristics, (iii) cation type, and (iv) specific surface area (Kim & Ahn, 2012; Li et al., 2021). Kim and Ahn (2012) studied the adsorption and desorption characteristics of VOCs (benzene, toluene, ethanol, methanol, etc.) on the physiochemical properties of mordenite and X- or Y-type faujasite zeolites. The adsorption capacity of faujasite-Y was found to be the highest and large mesopore volume along with the strong pore structure were found to be the influencing factors. Microwave heating was found to be more effective for the regeneration of zeolites compared to conventional heating. Li et al. (2021) reported that most VOCs waste gases are accompanied by water vapor where hydrophobicity of the adsorbent is a key parameter in enhancing the adsorption of VOCs. In view of this, the authors investigated the adsorptive properties of nine commercial zeolites for p-xylene under humid conditions. The results revealed the Si/Al ratio, indicative of surface hydrophobicity (large Si/Al ratio implies higher hydrophobicity), and pore diameter as the important parameters for p-xylene adsorption. The highest adsorptive capacity obtained was 100 $mg.g^{-1}$ after simultaneously optimizing both parameters. Adsorption capacity was further enhanced by 25% after subjecting zeolites to alkali treatment which also resulted in a decrease in desorption temperature. Kang et al. (2018) computed the adsorption capacity of dichloromethane vapor under a humid environment on ZSM-5 zeolites and found that zeolite containing the highest Si/Al ratio displayed the greatest capacity of 179.2 $mg.g^{-1}$. Huang et al. (2014) observed that ZSM-5 zeolite showed superior adsorption performance in adsorbing smaller VOCs molecules (acetone and benzene) than larger VOCs molecules (cyclohexane and cyclohexanone). Wu et al. (2021) investigated the adsorption behavior of cyclohexane, butyl acetate, toluene, MEK, and isopropanol, respectively, on binder-fee dealuminated Y/ZSM-5 composite. The adsorption capacities for toluene, butyl acetate, and

cyclohexane were found to be larger than MEK and isopropanol owing to higher surface area, wider pore diameter, and larger micropore volume of composites. The results also indicated that composites were suitable for the adsorption of larger VOCs molecules. The dealuminated composites on account of their higher hydrophobicity were found to be an appropriate candidate for adsorption under humid conditions. Moreover, the regeneration ability of composites was found to be better. Another research by Li et al. (2020) showed that ZSM-5/SBA-15 composites possessed excellent adsorption capacities in the absence of water vapor due to the availability of intercrystalline mesopores responsible for significantly reducing the toluene's diffusion pathway. These composites were also found suitable under humid conditions due to the incorporation of SBA-15. It is apparent from the literature review that zeolites are better adsorbents than conventional adsorbents due to their properties like excellent thermal stability, good pore network, good regeneration ability, and customized Si/Al ratio as per requirement. However, a few limitations need immediate attention to make zeolite a promising adsorbent in the field of VOCs removal: (i) a time-consuming and complex synthesis process, and (ii) precursors used in the preparation of zeolites are costly. Table 10 demonstrates the use of zeolite in the field of VOCs adsorption.

2.2.2 *Metal–Organic Framework*

Metal–organic frameworks (MOF), first synthesized in 1995 (Yaghi et al., 1995), are a kind of hybrid porous material. The structure of MOF consists of metal ions or clusters as the coordination centers which are linked through coordination bonds to organic ligands containing oxygen or nitrogen, eventually forming a three-dimensional crystalline framework (Fig. 7). The techniques applied for the synthesis of MOF include slow evaporation and diffusion method, solvo(hydro)-thermal and iono-thermal method, microwave-assisted method, mechanochemical method, electrochemical method, sonochemical method, microemulsion method (Raptopoulou, 2021). Some of the remarkable attributes that prompt the researchers to explore MOFs as potential adsorbents are high surface area, outstanding thermal stability, high porosity, open metal sites, and an adjustable pore network (Li et al., 2025; Wang et al., 2020). Moreover, the use of different combinations of metal centers and organic ligands results in the formation of diverse MOF structures and functionalities (Ghanbari et al., 2020). The MOF retains its original structure and crystallization order even after regeneration while conventional adsorbents do not exhibit this property (Zhao et al., 2018). There are various types of MOF reported in the literature that have been synthesized to capture VOCs: IRMOF, PCN, ZIF, MIL, and UiO etc. (Lu et al., 2024; Xie et al., 2022). Vellingiri et al. (2017) tested diverse MOF (UiO-66, UiO-66(NH_2), ZIF-67, MOF-199, MOF-5, and MIL-101(Fe)) for the adsorption of toluene. The equilibrium adsorption capacity was found to lie between 159 (MOF-199) to 252 mg.g^{-1} (UiO-66(NH_2)). The highest adsorption capacity of UiO-66(NH_2) was ascribed to the hydrogen bonding between toluene and micropores available in the framework. However, considerable reductions in adsorption capacities were found with the increase in humidity. UiO-66(NH_2) also maintained its adsorption capacity even after three cycles of adsorption–desorption processes while the adsorption capacities of other MOFs reduced to half after

Table 10 Summary of applications of zeolites on VOCS adsorption

Adsorbate	Adsorption capacity, mg.g^{-1}	Conditions	Reference
Mesitylene	184	100 ppmv, 10% humidity	Nien et al. (2017)
Benzene	1.72	10℃, 50 ppmv	Aziz and Kim (2017)
Butyl acetate	234	30℃, 250 mL.min^{-1}, 1000 ppmv	Wu et al. (2021)
Toluene	139	30℃, 250 mL.min^{-1}, 1000 ppmv	Wu et al. (2021)
p-xylene	100	35℃, 100 mL.min^{-1}, 50 ppmv	Li et al. (2021)
Toluene	100	40℃, 100 mL.min^{-1}, 400 ppmv	Li et al. (2020)
Acetone	165.88	25℃, 0.5P_0	Cosseron et al. (2013)

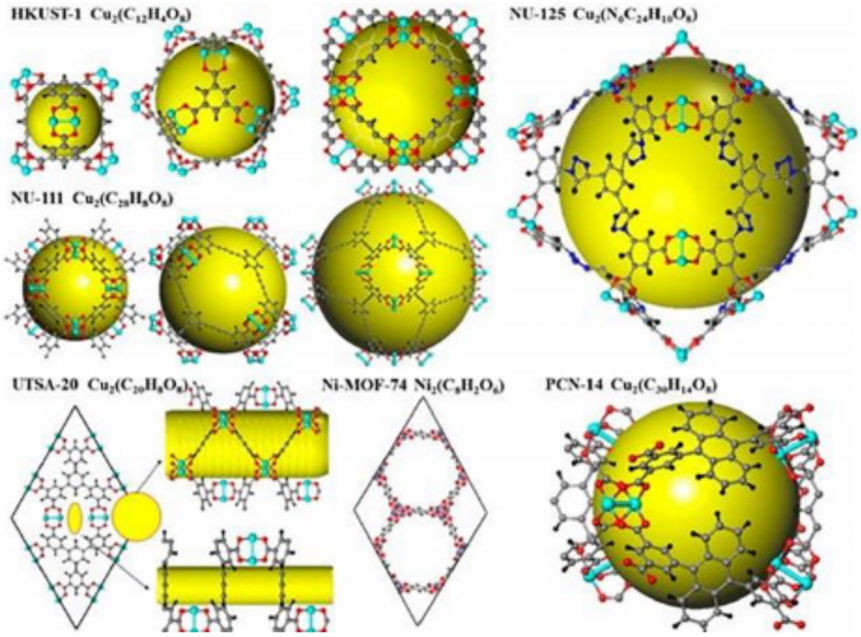

Fig. 7 Composition of MOFs nanocages and crystals. The empirical formulas for each MOF in the desolvated form are also indicated. Adapted from Ejeromedoghene et al. (2022). Under Creative Commons CC-BY-NC-ND license

three adsorption–desorption cycles. Pei et al. (2021) synthesized Fe-based MOF derivative (M-350), a partially carbonized material obtained by calcining MIL-100(Fe) at 350℃, for adsorbing oxygenated VOCs such as methanol, formaldehyde, and acetone. M-350 displayed 61.5% more breakthrough adsorption capacity than pure MIL-100(Fe) and it was also 24.7 and 6.5 times larger than commercial activated carbon and zeolite, respectively. The plentiful coordinatively unsaturated Fe sites acting as Lewis acid led to a strong affinity for oxygenated VOCs. Chevalier et al. (2019) utilized the HKUST-1 framework for adsorbing a mixture of VOCs (toluene, o-xylene, ethanol, acetone, and acetaldehyde) at extremely low concentrations (0.5–2.5 ppmv) under different humidity levels. The adsorption capacity was found to be highest for toluene (23.8 wt%) under mono-pollutant conditions. However, the results of the adsorption of five gas mixtures revealed the amount of toluene adsorption to be the least. Here, the selectivity was found to be dependent on steric activity and Cu-adsorbate interaction in large pores. Adsorption capacities dropped sharply with an increase in RH. The uptake capacity became stable after the first adsorption/desorption cycle. Yang et al. (2013) investigated synthesized MOF-177 for removing VOCs such as acetone, benzene, toluene, xylene, ethylbenzene, etc. present in air. The effect of humidity on VOCs adsorption was also taken into account. Excellent adsorption capacities of VOCs (> 200 $mg.g^{-1}$) were obtained even at higher humidity levels, with small-size VOCs molecules, for instance, benzene and acetone exhibited capacity as high as 800 and 589 $mg.g^{-1}$, respectively. The high adsorption capacity of MOF-177 was attributed to its high surface area and great pore volume (2970 $m^2.g^{-1}$ and 1.11 $cm^3.g^{-1}$). Adsorption of VOCs was found to be slightly hampered by the presence of moisture in air but performance of activated carbon gets highly affected at higher relative humidities. Yang et al. (2011) showed the saturation adsorption capacity of MIL-101 to be 1290 $mg.g^{-1}$ for benzene at $P/P_o = 0.55$ at 25℃, much higher than HY zeolite (258 $mg.g^{-1}$) for benzene under same conditions. The humidity plays a vital role, which severely affects the adsorption capacity of an MOF. Yang et al. (2013) found that increasing the relative humidity (RH) from 0 to 50% led to a sharp decrease in the toluene adsorption on MOF-177. It was attributed to the adsorption of water molecules on some of the sites which subsequently impedes the VOCs adsorption on the pores. The crystal structure of MOF-177 was found to be damaged after being exposed to air for more than 3 days. Vellingiri et al. (2017) reported shorter breakthrough times in the case of toluene adsorption on

MOF-199. Competitive adsorption between the VOCs molecules and water molecules at higher RH was the main reason cited for this behaviour. Chevalier et al. (2019) showed that the adsorption capacity of HKUST-1 framework fell by 43% and 97% at 20% and 40% RH, respectively. Undoubtedly, MOF is an excellent adsorbent for VOCs capture due to its tailored pore network and superb physicochemical properties. As a consequence of this, its adsorption capacity is well ahead of AC and zeolites. However, limitations like its powder form which restricts its application in dynamic conditions, and synthesis cost; make it unfeasible as well as unaffordable for its implementation in industries (Pauletto & Bandosz, 2022). The use of MOF for the adsorption of VOCs is shown in Table 11. The techno-economic comparison of MOFs with carbon-based adsorbents is summarized in Table 12.

Similar to MOF, Covalent organic framework (COF) is another class of porous materials composed of organic building blocks linked through strong covalent bonds. Issaka et al. (2025) successfully adsorbed per- and polyfluoroalkyl substances (PFAS) from various matrices on COFs. Jiang et al. (2018) synthesised PAF-110 with excellent structural and thermal stability for selectively separating acetylene from ethylene. He et al. (2021) prepared nitrogen-rich COF (SCU-COF-2) for the adsorption of elemental iodine and methyl iodide vapor.

2.2.3 Clay

Clay is a fine-grained naturally occurring particle on the surface of the earth which is mainly comprised of silica, alumina, water, and weathered rock. Hence, clays are known as hydrous aluminosilicates, a mixture of clay minerals, other minerals, and metal oxides. Clay minerals are known to occur in three forms, namely, kaolinite, montmorillonite, and illite. The following properties establish clay as a superior adsorbent compared to some of the commercially available adsorbents: (i) abundant availability, (ii) low cost, (iii) high specific surface area, and (iv) non-toxic nature (Adeyemo et al., 2017; Mojahedimotlagh et al., 2024). In some situations, pre-treatment of clays is also necessitated to improve their adsorption capacity. The favorable network of mesopores and micropores along with the high rate of mass transfer qualifies clay as a suitable adsorbent for VOCs removal (Zhu et al., 2020). Deng et al. (2017) calculated the adsorptive capacities, under dynamic conditions, of three different types of clay minerals (montmorillonite, kaolinite, and halloysite) by taking benzene as a model VOCs. The maximum adsorption capacity of

Table 11 Summary of applications of MOF on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Toluene	224	25℃, 0.0379 bar	Vellingiri et al. (2017)
Benzene	227.3	25℃, 2 ppm, 5% humidity	Zhu et al. (2017a)
Toluene	250	25℃, $0.4P_0$, 30% humidity	Yang et al. (2013)
Benzene	1290	25℃, $0.55P_0$	Yang et al. (2011)
Methanol	114.24	15℃	Chen et al. (2020)
Toluene	238	23℃, 750 $mL.min^{-1}$, 2.5 ppm	Chevalier et al. (2019)
Acetaldehyde	14	23℃, 750 $mL.min^{-1}$, 2.5 ppm	Chevalier et al. (2019)
Ethanol	165	23℃, 750 $mL.min^{-1}$, 2.5 ppm	Chevalier et al. (2019)

Table 12 Techno-economic comparison of MOFs with carbon-based adsorbents (Gargiulo et al., 2020)

S.NO	Parameter	MOFs compared to carbon-based adsorbents
1	Cost	High cost of preparation
2	Adsorption capacity	Reasonably good
3	Selectivity	Highly selective towards adsorption of specific VOCs
4	Regeneration capacity	Regeneration capacity is quite high
5	Industrial implementation	Limited

141.2 mg.g^{-1} was obtained for montmorillonite while the lowest uptake of 56.7 mg.g^{-1} was found for kaolinite. The availability of interlayer micropores was chiefly responsible for the higher adsorption capacity of montmorillonite and in kaolinite, there was no interlayer space available. Dammak et al. (2014) made a comparison of the adsorption capacity of raw clay and organoclay (modified clay) for removing o-xylene vapors. The organoclay's adsorption capacity was found to be 604 mg.g^{-1}, much higher compared to raw clay (310 mg.g^{-1}). The modification of raw clay primarily resulted in changing the surface properties from hydrophilic to organophilic owing to which organoclay exhibited higher adsorption capacity. Yang et al. (2019b) concluded that different desorption techniques, depending upon the type of VOCs, are necessary for the effective regeneration of clay.

Hence, raw clay can be employed as an effective adsorbent for VOCs removal on account of its excellent thermal stability and affordable price. The undeveloped pore structure and occurrence of silanol groups on the surface of the clay are some of the drawbacks that restrict its use in the field of VOCs adsorption. These limitations can be offset by modifying the surface of clay with acid which in turn enhances its adsorptive capacity and hydrophobicity. Table 13 depicts the use of clay for VOCs adsorption.

2.2.4 Silica Gel

Silica gel is a polymeric inorganic substance with an amorphous structure. It is comprised of silanol groups (Si–OH) dispersed on its surface with siloxane groups (Si–O-Si) present in the inner core (Shokoohi et al., 2015). Silica gel is conventionally prepared by using alkoxysilanes i.e., tetramethylorthosilicate and tetraethylorthosilicate; as precursor materials (Flores-Lopez et al., 2020). Nowadays, the sol–gel method is one of the widely used techniques for the preparation of silica gel. Its successful application as an adsorbent is attributed to its superb mechanical and thermal stability, presence of functional groups on its pore surface, and high surface area (Benvenutia et al., 2019). To date, the use of silica gel as an adsorbent for VOCs control is quite limited. Sui et al. (2019) tested silica gels with different pore size distributions for the adsorption of o-xylene vapors. Microporous silica gel displayed higher breakthrough time and a greater percentage of adsorbent utilization compared to mesoporous silica gel. The favorable isotherm and steep concentration front observed in the case of microporous silica gel were found to be the deciding factors. Kim et al. (2017) performed continuous adsorption experiments and compared the adsorption capacity of silica xerogel with commercially available silica gel and activated carbon for acetaldehyde removal. The silica xerogel exhibited more surface area than commercial silica gel. Moreover, its adsorption capacity and lifetime were almost double that of activated carbon at low concentrations of acetaldehyde. It was ascribed to the plentiful silanol and siloxane groups present on the surface of the synthesized silica xerogel, responsible for the selective acetylene adsorption. Sigot et al. (2015) employed silica gel for the removal of octamethylcyclotetrasiloxane, a VOCs containing silicon (VOSiC) present in the biogas. The adsorption capacity of 222 mg.g^{-1} was obtained when a synthetic N_2 gas + VOCs mixture containing 30 ppm VOCs was processed. Sui et al. (2017) reported much more complete desorption of toluene from silica gel as compared to activated carbon.

Table 13 Summary of applications of Clay on VOCS adsorption

Adsorbate	Adsorption capacity, mg.g^{-1}	Conditions	Reference
Toluene	90.4	60℃, 50 mL.min^{-1}, 2000 ppm	Zhu et al. (2017b)
Benzene	141.2	25℃, 3 mL.min^{-1}	Deng et al. (2017)
o-Xylene	604	20℃, 0.7P_0	Dammak et al. (2014)
Toluene	320	23℃, 0.75 P_0	Cortes et al. (2008)
o-Xylene	6.869	20℃, 630 mL.min^{-1}, 6.4 g.m^{-3}	Fakhfakh et al. (2018)
Toluene	122.92	25℃, 300 mL.min^{-1}, 1000 ppm	Yang et al. (2019b)
Carbon tetrachloride	530	25℃, 0.4 P_0	Zhu et al. (2005)

Sui et al. (2019) observed lesser heel formation and faster desorption rate of xylene due to weak interaction between silica gel and xylene. Silica gel was also reported to be the most appropriate adsorbent for the removal of VOSiC vapor compared to zeolite and activated carbon. However, the use of silica gel as an adsorbent for the removal of VOCs still requires greater insights for a comprehensive understanding of the adsorption mechanism. The applications of silica gel for adsorbing VOCs are shown in Table 14.

2.3 Organic Polymer

Organic polymers are distinct types of materials that are connected by covalent bonds and exhibit high porosity. The frameworks are interlinked with light non-metallic elements such as C, H, N, O, and B; eventually leading to the structure with features like superb stability, low density, and great surface area (Liu et al., 2025; Lu et al., 2021). There are vast applications of organic polymers reported in literature like gas adsorption, catalysis, chemical sensors, and energy storage (Chakraborty et al., 2023; Chowdhury et al., 2022; Kaur et al., 2011; Kou et al., 2011; Kundu et al., 2016; Ma et al., 2019; Modak et al., 2012). Hypercrosslinked polymer (HCP) and macroporous polymer are the two broad categories of organic polymers. The microporous organic material, a low-cost material, upon undergoing Friedel- Crafts alkylation reaction results in the formation of HCPs (Wang et al., 2015a). The involvement of a large number of cross-linking reactions does not allow polymer chains to collapse into a dense and non-porous state owing to which HCP possesses a permanent porosity of 0.5–2 nm. The macroporous polymer, on the other hand, comprises mainly mesopores and macropores. Some of the desirable properties of HCP like tailorable porosity, outstanding thermal stability, flexible regenerability, and hydrophobic properties under humid environments; make it a prominent candidate for the removal of VOCs. Wang et al. (2015a) synthesized hydrophobic HCPs with a surface area of 1394 $m^2.g^{-1}$, pore volume of 1.55 $m^3.g^{-1}$, and average pore diameter of 4.4 nm for the removal of benzene. Static adsorption experiments revealed the adsorption capacity of HCPs to be better than most of the traditional adsorbents. The dynamic adsorption experiments exhibited almost the same breakthrough times under dry conditions as well as under humid conditions (RH = 80%), thus indicating high selectivity towards benzene even in the presence of water vapor. Vinodh et al. (2015) also concluded that HCPs to better adsorbents for VOCs such as toluene, chloroform, and ethyl methyl ketone under humid conditions. Ghafari and Atkinson (2018) modified styrenic polymers by one step hyper cross-linking method to boost adsorption capacity due to the addition of micropores. Wang et al. (2016) synthesized cost-effective HCP with a surface area of 1345 $m^2.g^{-1}$ which displayed superhydrophobic nature and superb adsorbing power for benzene. Feng et al. (2024) developed HCP from waste polystyrene foam for the adsorption of monocyclic aromatic hydrocarbons. The adsorption capabilities of o-xylene, toluene, and benzene were found to be 422, 283, and 116 $mg.g^{-1}$, respectively. Zhu et al. (2024) synthesized a superhydrophobic polymer with a rich pore structure and a high specific surface area of 1780 $m^2.g^{-1}$ for adsorption of benzene at a relative humidity of 90% and found a 10% (insignificant) decrease in adsorption, indicating its application at high humidity levels. Yu et al. (2024) developed novel hydrophobic porous HCP for adsorbing toluene vapors with an adsorption capacity of 322.05 $mg.g^{-1}$. The adsorption was found to be unchanged even under high humidity levels (70%). The large surface area and outstanding hydrophobic nature of HCP make it an excellent adsorbent for the removal of VOCs both under dry and humid environments.

Table 14 Summary of applications of silica gel on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
o-Xylene	650	25℃, 400 Pa	Sui et al. (2019)
Octamethylcyclotetrasiloxane	222	25℃, 400 $mL.min^{-1}$, 30 ppmv	Sigot et al. (2015)
Toluene	325	25℃, 1.5 kPa	Sui et al. (2017)
Toluene	205	25℃, 450 $mL.min^{-1}$, 12,000 ppmv	Sui et al. (2017)

However, the complex synthesis process of HCP is the main challenge, the area in which a lot of work needs to be done. Table 15 illustrates a few studies that employed organic polymer for the removal of VOCs.

2.4 MXenes

MXenes belong to the family of two-dimensional transition metal carbide/nitride and have recently received attention from researchers in the field of environmental remediation. Their large surface area, highly adjustable structure, hydrophilic nature, and abundant active sites make them suitable for the adsorption of a large number of environmental pollutants (Liao et al., 2024; Solangi et al., 2023). They are widely employed for the adsorption of heavy metal ions, organic dyes, radionuclides, etc. Kim et al., (2018a, 2018b) synthesised a $Ti_3C_2T_x$ MXene gas sensor for detecting VOCs (acetone, ethanol, and propanal) at parts per billion (ppb) level in the range of 50–100 ppb. Chlikhy and Mazroui (2024) employed Ti_2CO_2 MXene for the detection of VOCs, and the results suggested its high sensitivity and selectivity towards isopropanol. To date, there are limited studies available in the literature related to the adsorption of VOCs on MXenes. Hence, MXenes can be further explored as a potential candidate for the adsorption of VOCs in the future owing to its unique characteristics.

2.5 Composite Materials

The inability of the adsorbent made by a single material to meet all the features of a good adsorbent prompted researchers to design a composite material with excellent adsorption capacity in treating multicomponent mixtures under high humidity conditions. Composite materials have been reported to be applied successfully in various fields like chemical sensors, gas storage, catalysis, adsorption, etc. (Falcaro et al., 2016; Ojha et al., 2019). Several studies have described the growing interest in the fabrication of MOF- and zeolite-based composites for the removal of VOCs. MOF is known to be a potential adsorbent in the field of VOCs treatment owing to its properties already mentioned under "Metal–organic framework" heading. MOFs are found to be inadequate for capturing light VOCs due to the absence of strong dispersive forces. This is attributed to the larger space occupied by the voids, restricted unsaturated metallic centres, and unlocked framework (Kumar et al., 2017). These shortcomings were overcome by coating the surface of MOFs with a dense array of atoms which eventually led to the development of MOF/carbon (MOF-C), MOF/metal oxide, MOF/silica, and MOF/organic polymer. Zheng et al. (2018) developed MIL-101/GrO and found its adsorption capacity for carbon tetrachloride to be 2368.1 $mg.g^{-1}$, 16% higher in comparison to the adsorption on MIL-101. Higher surface area, strong dispersive forces, and the addition of crystal defects; were the main reasons cited for the increase in uptake. Also, the uptake capacity of MIL-101/GrO was reported to be far above AC and zeolites (600 and 430 $mg.g^{-1}$). Li et al. (2016b) prepared Cu-BTC@GO composites and applied them for toluene adsorption. This composite material exhibited a surface area of 1362.7 $m^2.g^{-1}$ and an adsorption capacity of 9.1 $mmol.g^{-1}$, 47% more than Cu-BTC. The water stability of Cu-BTC@GO composites was found to be enhanced in comparison to Cu-BTC as

Table 15 Summary of applications of organic polymer on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Benzene	1392.3	25℃, $0.8P_0$	Wang et al. (2016)
Benzene	149	25℃, 50 $mL.min^{-1}$, 550 ppmv	Wang et al. (2016)
Benzene	1494.4	25℃, $0.9P_0$	Wang et al. (2015a)
Benzene	132.6	25℃, 50 $mL.min^{-1}$, 530 ppmv	Wang et al. (2015a)
Chlorobenzene	520	30℃, 2.5 kPa	Long et al. (2010)
Pentane	484.6	20℃, 60 kPa	Wu et al. (2012)
Cyclohexane	1736	25℃, 0.06 MPa	Gao et al. (2016)
Ethyl Methyl Ketone	217	18℃, 4000 $mL.min^{-1}$, 5000 ppmv	Vinodh et al. (2015)

the latter completely lost its structure when soaked in water for 10 h. The availability of carbonaceous material also prevents the poisoning of empty Lewis metal sites inside MOF, thus increasing interactions with small-sized VOCs molecules (Liu et al., 2016).

Zeolite is regarded as one of the potential adsorbents for the removal of VOCs due to its properties like great surface area, hydrophobic character, and excellent thermal stability (Zhang et al., 2012). Still, two drawbacks limit its adsorptive capacity: (i) nanoparticle agglomeration results in reduced effective surface area, and (ii) nanoparticles exhibit a microporosity smaller than 1 nm resulting in greater mass transfer resistance to macromolecules such as o- and m- xylene. Hence, to address these problems, a strategy was devised to develop hierarchically porous composite materials with a coating of zeolites on macroporous supports. It aids in eliminating the effects of agglomeration and at the same time diffusion path is shortened (Yuan et al., 2016). Diatomite (Dt) is one of the supports that is favored by the researchers on account of its low cost and well-developed porosity. Yu et al. (2015a) prepared a diatomite/MFI-type zeolite hierarchically porous composite followed by desilication for 1 h which led to the distribution of mesoporosity concentrated at 7 nm. The benzene uptake on this composite material was found to be 62.5 $mg.g^{-1}$, much higher than the Dt (11.1 $mg.g^{-1}$). The high capacity was ascribed to the terminal silanol group formation upon desilication and increase in porosity. Yuan et al. (2016) fabricated a diatomite/silicalite-1 composite for the adsorption of benzene vapors. It demonstrated an adsorption capacity of 246 $mg.g^{-1}$ much higher than silicalite-1nanoparticles and commercial zeolite. The introduction of macroporosity due to Dt helped in lowering the mass transfer resistance offered by silicalite particles and greater points through which benzene could enter into the composite finally led to the enhanced adsorption capacity of a composite material. Yuan et al. (2016) showed steady reversibility of composite materials after 4 adsorption/desorption cycles.

It is concluded that the extra cost incurred on account of the pre-treatment steps involved in the preparation of hierarchically porous composites makes the overall process expensive. Hence, there is a need to discover relatively simple and flexible synthesis routes for their preparation on which future research should be focussed. The use of composite materials in the field of VOCs adsorption is shown in Table 16.

2.6 Magnetic Composite Materials

Magnetite (Fe_3O_4), a nanoadsorbent, exhibits a unique magnetic property known as superparamagnetism. Its stability, along with unparalleled physical/chemical properties, is one of the characteristics of Fe_3O_4, which can be utilized in the field of adsorption. Kutluay et al. (2025) synthesized a novel magnetic nanoadsorbent (MNA), $Fe_3O_4@SiO_2$, containing p-aminobenzoic acid (p-AMBA) as functional groups for the adsorption of toluene. The adsorption capacity of 555 $mg.g^{-1}$ was found in comparison to 188 $mg.g^{-1}$ for Fe_3O_4 and 321 $mg.g^{-1}$ for $Fe_3O_4@SiO_2$. Ece et al. (2025) developed $Fe_3O_4@SiO_2@4$-PCA core–shell magnetic nanocomposite for the removal of xylene with an adsorption capacity of 649 $mg.g^{-1}$ much higher than Fe_3O_4 (251 $mg.g^{-1}$) and $Fe_3O_4@SiO_2$ (372 $mg.g^{-1}$). Ok et al. (2023) designed perlite-supported $Fe_3O_4@SiO_2@$8-hydroxyquinoline-5-sulfonic acid (perlite-$Fe_3O_4@SiO_2@$8-HQ-5-SA) to

Table 16 Summary of applications of composite materials on VOCS adsorption

Adsorbate	Adsorption capacity, $mg.g^{-1}$	Conditions	Reference
Toluene	837.2	25℃, $0.9P_0$	Li et al. (2016b)
Benzene	246	25℃, 3 $mL.min^{-1}$	Yuan et al. (2016)
Benzene	62.5	25℃	Yu et al. (2015a)
Benzene	82.68	25℃, 1 $mL.min^{-1}$, 1.51 $mmol.L^{-1}$	Yu et al. (2015b)
Carbon tetrachloride	2368	25℃, 150 mbar	Zheng et al. (2018)
Toluene	116	30℃, 15 $mL.min^{-1}$	Chu et al. (2018)
Acetone	1165.8	15℃, 161.8 mbar	Zhou et al., (2014)

investigate the competitive adsorption of toluene, ethylbenzene, and xylene. The adsorption capacities for these VOCs were found to be 558 $mg.g^{-1}$, 680 $mg.g^{-1}$ and 716 $mg.g^{-1}$, respectively. Magnetic composite materials emerged as a promising adsorbent for the abatement of VOCs in recent years and are considered a sustainable material for the protection of the environment.

3 Factors Affecting VOCs Adsorption

3.1 Characteristics of Adsorbent

The properties of adsorbent such as specific surface area, pore structure, and surface functional groups greatly affect the adsorption of VOCs which are discussed in this section.

3.1.1 Specific Surface Area

Specific surface area is supposed to be one of the essential properties of any adsorbent as it determines the sites available for the adsorption of VOCs to take place (Tan et al., 2025). Usually, it is said that the higher the surface area higher the adsorption capacity of any adsorbent which has also been documented in the literature. Xiang et al. (2020) enhanced the specific surface area by 1.4–29.1 times by subjecting biochar to the ball milling operation and found the adsorption capacity to increase by 1.3–13 folds. Similarly, on comparing activated carbon fibers for benzene adsorption having surface areas 1826 and 1026 $m^2.g^{-1}$ the adsorption capacities were found to be 310 and 200 $mg.g^{-1}$, respectively (Rodenas et al., 2011).

The higher surface area of an adsorbent can only be achieved by either generating new pores or by making unreachable pores accessible. The various techniques that are generally employed for the surface modification of adsorbent include treatment with acid, base, ozone, plasma, etc. (Bhatnagar et al., 2013). Biochar produced at greater pyrolytic temperatures results in higher surface area owing to the opening of clogged micropores. Physical methods such as steam activation or CO_2 activation are other widely used techniques to enhance the surface area of the adsorbent. Romero-Anaya et al. (2010) produced a series of spherical activated carbon by employing steam and CO_2 as an activating agent. A surface area of 1880 $m^2.g^{-1}$ was obtained when the adsorbent was treated with steam at 840℃ for 6 h, while a surface area of 2586 $m^2.g^{-1}$ was obtained when the adsorbent was treated with CO_2 at 880℃ for 24 h. The toluene adsorption capacities for these adsorbents were found to be in the range of 430–460 $mg.g^{-1}$ much higher than commercial activated carbon (310 $mg.g^{-1}$). Similarly, Huo et al. (2021) employed a steam secondary activation method for improving the surface area of activated carbon fiber. Kim et al. (2006) prepared modified activated carbons by impregnating them with various acids and bases. The activated carbon impregnated with 1 wt% H_3PO_4 showed the maximum specific surface area of 1109 $m^2.g^{-1}$ and the greatest adsorption capacities for benzene, toluene, p-xylene, methanol, and ethanol. The specific surface area is not the sole criterion that determines the adsorption capacity of the adsorbent. Gil et al. (2014) prepared a variety of microporous activated carbon from biocollagenic wastes of vegetable tanning after chemical activation by alkaline agents such as KOH, NaOH, and K_2CO_3. The activated carbon with specific surface areas of 798 and 729 $m^2.g^{-1}$ displayed adsorption capacity for toluene to be 656 and 431 mg,g^{-1}, respectively, while one having the highest surface area of 2719 $m^2.g^{-1}$ exhibited the lowest adsorption capacity of 346 mg,g^{-1}. Similarly, Bansode et al. (2003) found 59.9% adsorption for bromo dichloromethane on the phosphoric acid-activated almond shell (1340 $m^2.g^{-1}$) while 85.4% adsorption was obtained on steam-activated peacan shell (917 $m^2.g^{-1}$). Hence it can be concluded that the adsorption phenomenon is a complex process with several other factors that also play a decisive role in the determination of adsorption capacity.

3.1.2 Pore Size

The porosity of an adsorbent along with a favorable pore size distribution is one of the vital characteristics in determining its ability to capture VOCs. Three types of pores exist depending upon the pore diameters, namely, macropores (pore diameter > 50 nm), mesopores (pore diameter ranging between 2 to 50 nm), and micropores (pore diameter < 2 nm). The micropores act as the main sites where adsorption of VOCs eventually occurs. Mesopores act as the transport channels between macropores and micropores that facilitate the movement of VOCs molecules

and thus help in reducing the adsorption time. Usually, macropores are only available on the external surface of the porous adsorbents. The percentage contribution of these pores to the total surface area is (i) macropores (around 5%), and (ii) meso- and micropores (about 95%). The well-evolved micropore structure is chiefly responsible for the good adsorptive capacity of an adsorbent. Notably, the narrower micropores (pore diameter < 0.7 nm) engender higher diffusion resistance leading to lower adsorption rates. Yu et al. (2018b) employed activated carbon treated with HNO_3 and H_2O_2 at high temperatures to produce adsorbents with different pore structures and functional groups for acetone adsorption. It was found that AC-N (activated carbon with HNO_3 modification), despite its lower total surface area of 382 $m^2.g^{-1}$ than AC-T (activated carbon with heat treatment) with 399 $m^2.g^{-1}$, displayed a higher adsorption capacity of 5.49 $mmol.g^{-1}$ compared to 4.35 $mmol.g^{-1}$ of AC-T. The higher capacity was attributed to the higher microporous surface area of AC-N (329 $m^2.g^{-1}$) along with a well-developed pore structure. It was concluded that for physical adsorption to occur, micropore structure was one of the important factors. Shu et al. (2016) prepared Fe-loaded activated carbon with ultrasonic assistance to prepare adsorbents with different textures. It was found that micropores in the range of 0.7–2 nm contributed significantly to the enhanced adsorption capacity. Qi et al. (2018) synthesized porous carbon spheres of 1.2 mm diameter and reported that favorable micro/meso/macro hierarchal pore structure is a desirable property for the concurrent removal of benzene and H_2S. Qian et al. (2015) produced activated carbon microspheres with a BET surface area of 1104 $m^2.g^{-1}$ with micropores ranging between 0.4–1.5 nm, believed to be chiefly responsible for the overall surface area. The adsorption capacity of the chloromethanes in $mL.g^{-1}$ was found to be almost equal to the micropore volume of the adsorbent. Mao et al. (2016) successfully fitted the Dubinin–Radushkevich adsorption isotherm for the adsorption of toluene and acetone on activated carbon synthesized from agricultural residues, the isotherm mainly employed for microporous adsorbents. Rodenas et al. (2005) highlighted that narrow micropores (< 0.7 nm) governed the overall adsorption process for VOCs, especially benzene, at low concentrations. Although, the microporous volume corresponding to narrow micropores is extremely important for the adsorption of VOCs but at the same time it slows down the rate of adsorption. The higher intra-particle diffusion rate in the mesopores leads to enhanced rates of adsorption in mesopores compared to micropores. Horng et al. (2008) evaluated the micropore diffusion coefficients of chloroform, acetonitrile, and acetone on sludge adsorbent and activated carbon fiber. The diffusion coefficient in sludge adsorbent was found to be 10^{-4} $cm^2.s^{-1}$ higher than activated carbon fiber (10^{-8} to 10^{-7} $cm^2.s^{-1}$). It was attributed to the higher mesopore fraction with a pore diameter of 2.65 nm in sludge adsorbent and mainly micropore with a pore diameter of 1.72 nm in activated carbon fiber. Wang et al. (2015b) found rapid diffusion along with excellent adsorption capacity of benzene, cyclohexane, and hexane on ordered mesoporous carbon. The favorable pore size distribution (bimodal-like) with 5 and 1.8 nm pore sizes caused a higher diffusion rate of adsorbates in ordered mesoporous carbon compared to conventional adsorbents. Similarly, Wang et al. (2014) concluded that mesopores played a vital part in augmenting the adsorptive capacity for intermediate to high-concentration VOCs on cross-linked micro-mesoporous polymeric adsorbents. The effective adsorption of VOCs onto the adsorbent is found to be dependent upon the size of the pore and the size of the VOCs molecule. Based upon their sizes three cases can occur: (i) size of the VOCs molecule > pore size, no adsorption due to steric hindrance. (ii) size of the VOCs molecule = pore size, strong adsorption of VOCs but hard to desorb. (iii) size of the VOCs molecules < pore size, enhanced adsorption capacity due to capillary condensation. VOCs tend to desorb readily in case the size of the VOCs molecule is much smaller than the pore diameter. In light of these three cases, it was reported by Kim et al. (2006) that the adsorption of large VOCs molecules like o-xylene, m-xylene, and MEK was suppressed with a decrease in pore size while the adsorption of small molecules like ethanol and methanol got enhanced. Contrary to the fact that the size of VOCs molecule should be smaller than pore size, in some cases it was also observed that even smaller VOCs molecules in comparison to pore diameter are not able to enter the pores. Kim and Ahn (2012) reported that adsorption of small non-aromatic molecules (3.8–5.3 Aº) in comparison to large aromatic molecules (5.8–6.8 Aº) on mordenite and faujasite occurred easily even though the size of

micropores was greater than the molecular size of adsorbate molecules. The amount of VOCs adsorbed was found to be dependent upon the mesopore volume rather than the total pore volume. As a rule of thumb, the ratio of pore diameter to the size of the VOCs molecules should lie between 1.7 −3 for effective adsorption. The size of the majority of VOCs, in general, is almost comparable to that of the narrow micropores excluding BTEX molecules. Sometimes it is not possible to study the influence of pore sizes by experimental techniques. In those cases, molecular dynamics (MD) simulation or density functional theory (DFT), a computational tool, explains the adsorption mechanism at the molecular level by developing an idealized model (Nasab et al., 2023). Chen et al. (2022) employed MD simulation to estimate the adsorption capacities of ordered mesoporous silica for VOCs such as acetone, ethyl acetate, and toluene. It was done by simulating various pore sizes of 2 nm, 3 nm, and 4 nm, respectively. This study also revealed the adsorption mechanism in which the interaction energy effect between the adsorbent and VOCs played a major role. The quantitative structure–activity relationship (QSAR) is another method to predict VOCs removal as a function of physico-chemical properties. Hung and Lin (2007) predicted the saturation adsorption capacity of VOCs at higher relative pressures on activated carbon. The QSAR-based k and pore size distribution estimated W_0, the two parameters used in the Dubinin-Radushkevich (D-R) equation, were employed to determine the adsorption capacities. Somer et al. (2024) elucidated the use of statistical molecular design (SMD) with QSAR to estimate the removal of unanalysed VOCs from plastic waste.

3.1.3 Surface Chemical Functional Groups

The surface chemistry of the adsorbent surface is known to be one of the significant factors that influence VOCs adsorption. The type of functional groups present on the adsorbent's surface depends upon the kind of raw material used and the modification techniques the adsorbent is subjected to. The surface modification is generally performed after the activation step. The modification can be done by making use of physical, chemical, or electrochemical techniques aiming to insert or eliminate functional groups of activated carbon like carboxylic, phenolic, amine, hydroxyl, etc. (Bhatnagar et al., 2013; Yu et al., 2018b). Surface chemistry is mainly governed by the availability of the heteroatoms of surface functional groups like oxygen, nitrogen, halogen, sulfur, etc. The vital species considered for adsorption on porous carbon are reported to be oxygen and nitrogen. The treatment of adsorbent with N-containing compounds aids in the introduction of nitrogen which further imparts basic properties to the adsorbent. The oxygen groups on the other hand are introduced via oxidation. Oxygen groups contribute to the surface acidity and hence such adsorbents facilitate the adsorption of hydrophilic VOCs. In general, acidic treatment or treatment with ozone are the two methods for introducing surface oxygen groups on the carbon-based material. The acid modification employs sulfuric acid, nitric acid, phosphoric acid, hydrochloric acid, etc. as the commonly used reagents for this purpose (Bhatnagar et al., 2013). During treatment with acids, both dehydration and oxidation take place simultaneously which retains the framework of the adsorbent but alters its physical and chemical properties (Hu et al., 2016). Aguayo-Villarreal et al. (2017) modified biomass residue by using phosphoric acid as an activating agent to enable the introduction of phosphate groups that subsequently enhanced its adsorptive capacity (237.3 $mg.g^{-1}$) for 1-butanol due to the interaction of hydroxyl groups and phosphate groups. Yu et al. (2018b) prepared HNO_3-modified AC which owing to abundant surface carboxylic groups readily adsorbs acetone, a well-known strong polar VOCs, with an outstanding uptake capacity of 318.42 $mg.g^{-1}$. It might be attributed to the interaction between acetone and main active site. Jaramillo et al. (2010) changed the basic character of the activated carbon to an acidic character by subjecting it to ozone treatment with the value of pH_{pzc} (pH of the point of zero charge) as low as 3.6 by conducting the zeta potential experiments (Peng et al., 2025). However, the availability of the surface oxygen groups hinders the interaction between hydrophobic VOCs and the π-electron rich zone of carbon-based adsorbent materials. Hence, hydrophobic or non-polar VOCs tend to adsorb on the surface which does not hold surface oxygen. Li et al. (2011) discovered that the capacity of coconut shell-derived activated carbon after treatment with acids for capturing o-xylene (hydrophobic VOCs) was 21.6% less than the unmodified one. Hence, appropriate modification methods need to be applied to enable higher adsorption capacity for hydrophobic VOCs.

There are two modification methods, namely, thermal treatment and alkali treatment, which are extensively used to improve the adsorption of hydrophobic VOCs. Thermal treatment involves the decomposition of surface functional groups when adsorbent is exposed to higher temperatures for activated carbon it was reported that at 150–300℃: carboxylic groups decompose, at 300–500℃: acid anhydride and lactone decompose, and at 500–800℃: groups such as ethers, hydroxyl and carbonyl decompose (Ding et al., 2016; Jaramillo et al., 2010). In one of the studies, activated carbon was subjected to thermal treatment under an inert atmosphere of helium at 900℃ to eliminate surface functional groups (Rodenas et al., 2005). The treatment of activated carbon with alkali, the second method, has also been employed by various researchers. The decrease in concentration of surface oxygen after alkali treatment is attributed to the occurrence of redox reaction between porous adsorbent and alkali reagents at high temperatures that causes the O/C ratio to decrease. To date, various studies have established that alkali-treated activated carbon is a potential candidate for adsorbing hydrophobic VOCs (benzene, toluene, o-xylene) and on the other hand, demonstrates lower adsorption capacity for hydrophilic VOCs (ethanol and acetone). Contrarily, there are some studies available that indicate that surface functional groups alone are not an important factor that affects the adsorption capacity of polar or non-polar VOCs. Horng et al. (2008) found that the adsorption capacity of chloroform (low dipole moment) on polar AC was 146 $mg.g^{-1}$ much higher than 74 $mg.g^{-1}$ on a non-polar AC. Hence, the inference drawn from this work was that oxygenated surface functional groups were not the sole criteria for determining the affinity between adsorbate and adsorbent and it was the physical properties of the adsorbent which played a pivotal role and can't be ignored. Similar results were also reported by Diaz et al. (2005). In the same line, Gil et al. (2014) also reported that no definite correlation existed between adsorbents'textural properties and surface functional groups on the VOCs adsorption capacity and the balance between various adsorbent properties should be properly considered to explain the high adsorption capacities of various adsorbents. X-ray photoelectron spectroscopy (XPS) analysis is performed to determine the concentration of oxygen-containing groups on activated carbon adsorbent. Yang et al. (2024) observed an O1s peak at 532.5 eV for C-O and found oxygen concentration to be 14.11 at% after surface modification with nitric acid in comparison to 4.87 at% in the raw sample. Deryło-Marczewska et al. (2019) noticed O1s signals with the peak position at 532–533 eV for carbonyl and carboxylic groups, increasing the atomic concentration of oxygen from 3.6 to 5.8%. Drewniak et al. (2016) confirmed the oxidation of graphene through Fourier Transform Infrared Spectroscopy (FTIR) spectra. The widest peak occurred in the range of 3320–3430 cm^{-1} on account of C–OH stretching vibrations of a hydroxyl group. Aragaw (2020) observed the FTIR spectrum of graphene oxide with an intense peak occurring at 3457 cm^{-1} due to stretching vibrations of –OH group from different alkoxy and carboxy functional groups.

4 Characteristics of Adsorbates

The properties of VOCs such as molecular structure, polarity, and boiling point also influence the adsorption capacity of an adsorbent.

4.1 Molecular Structure

The adsorption capacity of carbon-based adsorbent materials is highly dependent upon the molecular structure of a VOCs in terms of its accessibility to adsorption sites available on the adsorbent. Smaller VOCs can enter into the pores more easily than larger VOCs molecules. The size of the VOCs refers to the cross-sectional area of the VOCs molecules. The uptake capabilities of AC and metal–organic frameworks for VOCs were found to be inversely related to the molecular sizes of VOCs (Qian et al., 2015). Besides, the molecular size, the shape of the VOCs molecules also affects the adsorption capacity. Notwithstanding, the cross-sectional areas of o-, m-, and p-xylene are almost the same (0.375, 0.379, and 0380 nm^2, respectively), the adsorption capacity of p-xylene onto carbonaceous adsorbent is more than other forms of xylene. It is the methyl-directing groups present at different positions owing to which these three forms of xylene acquire different molecular shapes. It was highlighted by Yang et al. (2011), that methyl groups interact with the adsorption sites of the carbon adsorbent prior to the benzene ring. The greater distance between the methyl groups in

the case of m-xylene, and o-xylene compared to the pore size of the adsorbent was the reason cited due to which their entry into the pores was restricted. On the other hand, two methyl groups in the case of p-xylene which are aligned to the benzene ring at an angle of 180º enabled its entry into the pores. The influence of molecular shapes entering MIL-pores is shown in Fig. 8.

4.2 Molecular Polarity

The polarity of the VOCs molecules determines the extent of adsorption onto the surface of the carbonaceous adsorbent material. Usually, polar VOCs molecules tend to adsorb readily on adsorbents carrying polar groups while non-polar molecules get easily adsorbed on adsorbents with non-polar groups. The activated carbon is largely considered to be a non-polar adsorbent but owing to the occurrence of some oxygen groups and inorganic impurities, it imparts some polarity. Given its non-polar surface, carbon-based adsorbent is not an appropriate choice for treating humid gas mixtures. Bansode et al. (2003) observed higher percentage adsorption of non-polar VOCs, CCl_4 on activated carbons derived from various sources (77.5%, 86.2%, and 81.2%) in comparison to acid-treated AC with polar groups (39.6%). Likewise, Horng et al. (2008) reported higher adsorption capacity for weakly polar $CHCl_3$ (205 $mg.g^{-1}$) on commercial activated carbon relative to 151 $mg.g^{-1}$ on ACF which exhibited polarity due to the presence of carbonyl groups. Carbonaceous materials possess polarity to some extent either inherently or it is introduced by treating adsorbent with ozone or nitric acid. The favorable dipole–dipole interaction among VOCs molecules and adsorbent leads to the reduction in intermolecular potential energy that eventually assists the adsorption process. Qian et al. (2015) employed activated carbon microspheres for the adsorption of CH_2Cl_2, $CHCl_3$, CCl_4, and CH_3I. The adsorption capacity for polar VOCs, CH_2Cl_2 and CH_3I with dipole moments of 1.8 and 1.59 respectively, were found to be higher than weak- and non-polar VOCs, $CHCl_3$ and CCl_4 with dipole moments of 1.1 and 0, respectively.

4.3 Boiling Point

The physical adsorption is analogous to vapor–liquid transition in the sense that it is easier for high boiling point species to convert into liquid than one with low boiling point on account of greater intermolecular forces. Hence, VOCs having high boiling points preferentially adsorb onto carbonaceous material in comparison to VOCs with low boiling points (Guo et al., 2013). Besides, liquid-like condensation is known to be an important phenomenon in the adsorption of VOCs over adsorbent material which also makes the boiling point of VOCs a vital parameter (Chiang et al., 2001). Gupta et al. (2015) found longer

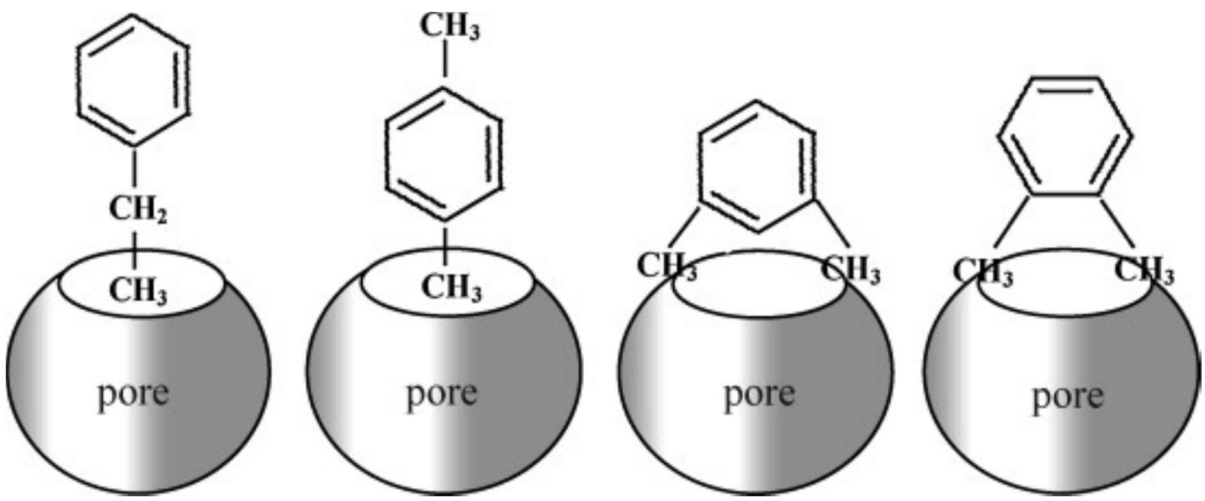

Fig. 8 Scheme of ethylbenzene, p-xylene, o-xylene and m-xylene entering into MIL-101 pores. Reprinted with Permission from Yang et al. (2011). Copyright Elsevier 2011

breakthrough times when xylene was adsorbed onto GAC compared to toluene adsorption under the same conditions. It was due to the higher molecular boiling of xylene. Giraudet et al. (2014) reported adsorption capacities of low boiling VOCs, dichloromethane and ethanethiol were 0.21 and 0.18 mol.kg^{-1}, respectively, lower than the high boiling point VOCs, siloxane D4 (1.23 mol.kg^{-1}). Oh et al. (2010) adsorbed seven VOCs on AC and found that higher boiling point VOCs exhibited higher adsorption capacities. An empirical formula was also obtained between the adsorbent capacity and VOCs boiling point. The uptake capacities of other porous adsorbents such as clay were also found to have influenced the boiling point of VOCs in the same manner (Qu et al., 2009). The strong affinity of high boiling point VOCs with the adsorbents tends to displace the already adsorbed lower boiling point VOCs. Wang et al. (2012) noticed this phenomenon when the authors adsorbed a mixture of eight organic compounds on beaded activated carbon. The dislodgement of low boiling point VOCs by the high boiling point VOCs caused higher concentrations of low boiling point species in the effluent gas after the breakthrough. Giraudet et al. (2014) conducted dynamic multi-component adsorption experiments and found concentrations of dichloromethane, ethanethiol, and isopropanol at the exit of the column to be greater than their corresponding inlet concentrations. It was attributed to the favorable interaction between siloxane D4 (high boiling point VOCs) and adsorbent that replaced adsorbed lower boiling point VOCs. The stronger affinity makes desorption of high boiling point VOCs difficult in comparison to low boiling point species. The complete desorption of low boiling compounds such as dichloromethane and isopropanol were observed while siloxane D4 was found to be partially desorbed at a temperature of 420 K (Giraudet et al., 2014).

5 Conclusion and Outlook

The VOCs, undoubtedly, are the most undesired species present in the air which causes severe damage to human beings and the environment. There are various control techniques reported in the literature for their abatement but they suffer from one or the other drawback related to cost, efficiency, energy, and harmful byproducts. Adsorption of VOCs emerges as the most favored technique for the removal of VOCs. The variety of porous materials that are available as adsorbents, their adsorption performance, interaction mechanism along modification methods have been reviewed in this work. The pros, cons, and applications of various adsorbents are summarized below, which can act as a guideline for future researchers in the selection of an adsorbent:

Undoubtedly, activated carbon exhibits higher adsorption capacity owing to high surface area, and pore volume but its flammable nature, hygroscopicity are some of the challenges that restrict its application on the industrial scale.

Biochar is a low-cost adsorbent with superb adsorption capacity. But its production is accompanied by the release of VOCs. Moreover, the complex interactions between VOCs molecules and biochar's surface groups require in-depth investigation for the efficient use of biochar.

ACF exhibits excellent adsorption capacity, but being hydrophobic, it is not suitable for treating polar VOCs. Notably, the main constraint of the use of ACF in the industries is attributed to the high cost of fibre precursors and processing.

The main challenge faced by CNTs is their tendency to aggregate, which leads to a reduction in their adsorption capacity. It is known to be a good adsorbent for the removal of non-polar VOCs. Similarly, graphene is also found to be prone to severe aggregation, and further, its complicated synthesis associated with high cost confines its use on an industrial scale.

The ability to readily adsorb both polar and non-polar VOCs is one of the unique attributes of CSCs. Its higher spontaneous ignition temperature than AC facilitates its widespread use in commercial applications.

The higher adsorption capacity, excellent thermal stability, and easy reproducibility are some of the characteristics of zeolite that make it a conventional adsorbent for the removal of VOCs. But its complex synthesis process and high cost are some of the limitations that need to be addressed by the researchers.

MOF is an excellent adsorbent due to its tailored pore network and superb physicochemical properties with adsorption capacity much greater than AC and zeolite. Its high cost makes it an unaffordable option for the industries. Humidity is also a key limitation in the case of MOFs.

The low price and good thermal stability make raw clay an alternative option for VOCs adsorption. Its drawbacks include (i) an undeveloped pore structure, and (ii) the presence of silanol groups on the surface of the clay.

Greater insights are still required in the case of silica gel for VOCs adsorption, although it is regarded as a good adsorbent for capturing VOSiC vapors.

Organic polymer is considered a promising adsorbent under both dry and humid conditions. Its complex synthesis process hinders its application on a large scale.

Though composite materials possess great adsorption capacity. But the cost of pretreatment steps involved in developing hierarchically porous structured composite materials is an additional expense. In recent years, the application of magnetic composite materials has gained momentum, but still, a lot of research is going on in this area.

Out of the various adsorbents investigated, MOF-based composites can be employed as an alternative to the prevalent adsorbents such as zeolites and AC, as they offer high surface area, controllable porosity, and good hydrophobicity. The surface chemistry along with the adsorbent's textural properties markedly influences the adsorption process. Large surface area and pore volume significantly improve the adsorption capacity of the adsorbent. The surface functional groups, polarity, and boiling point of the adsorbate greatly influence the adsorption behavior. However, there is no quantitative correlation exists between surface chemistry, textural properties, and adsorptive capacity. The surface chemistry of the adsorbent can be varied by introducing functional groups which is achieved by treating it with acid or alkali.

Despite a good amount of work that has been done in the field of VOCs adsorption, still there are grey areas in which focused research is required: (i) increase in adsorption capacity and selectivity through appropriate modification techniques, (ii) improvement in hydrophobic property of adsorbents under humid environment, (iii) development of low-cost adsorbents with outstanding stability like MOF based composites, (iv) improvement in adsorption of low boiling point VOCs, and (v) suitable method for the desorption of high boiling point VOCs.

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Declarations

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References

Adeyemo, A. A., Adeoye, I. O., & Bello, O. S. (2017). Adsorption of dyes using different types of clay: A review. *Applied Water Science, 7*, 543–568. https://doi.org/10.1007/s13201-015-0322-y

Agnihotri, S., Rood, M. J., & Rostam-Abadi, M. (2005). Adsorption equilibrium of organic vapors on single-walled carbon nanotubes. *Carbon, 43*(11), 2379–2388. https://doi.org/10.1016/j.carbon.2005.04.020

Aguayo-Villarreal, I. A., Montes-Moran, M. A., Hernandez-Montoya, V., Bonilla-Petriciolet, A., Concheso, A., Rojas-Mayorga, C. K., & Gonzalez, J. (2017). Importance of iron oxides on the carbons surface vs the specific surface for VOCs's adsorption. *Ecological Engineering, 106*, 400–408. https://doi.org/10.1016/j.ecoleng.2017.05.043

Ahmad, M., Lee, S. S., Rajapaksha, A. U., Vithanage, M., Zhang, M., Cho, J. S., Lee, S. E., & Ok, Y. S. (2013). Trichloroethylene adsorption by pine needle biochars produced at various pyrolysis temperatures. *Bioresource Technology, 143*, 615–622. https://doi.org/10.1016/j.biortech.2013.06.033

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, SS., & Ok, YS. (2014). Biochar as a sorbent for contaminant management in soil and water: A review. *Chemosphere, 99*, 19–33. https://doi.org/10.1016/j.chemosphere.2013.10.071

Akbar Ali, A. M., Karthikeyan, R. K., Sentamil, S. M., Rai, M. K., Priyadarshini, M., Maheswari, N., Janani, S. G., Padmanaban, V. C., & Singh, R. S. (2020). Removal of Reactive Orange 16 by adsorption onto activated carbon prepared from rice husk ash: Statistical modelling and adsorption kinetics. *Separation Science and Technology, 55*(1), 23–64. https://doi.org/10.1080/01496395.2018.1559856

Amalina, F., Razak, A. S. A., Krishnan, S., Sulaiman, H., Zularisam, A. W., & Nasrullah, M. (2022). Biochar production techniques utilizing biomass waste-derived materials and environmental applications –A review. *Journal of Hazardous Materials Advances, 7*(8), Article 100134. https://doi.org/10.1016/j.hazadv.2022.100134

Anfruns, A., Martin, M. J., & Montes-Moran, M. A. (2011). Removal of odourous VOCs using sludge-based adsorbents. *Chemical Engineering Journal, 166*(3), 1022–1031. https://doi.org/10.1016/j.cej.2010.11.095

Anjum, H., Johari, K., Gnanasundaram, N., Appusamy, A., & Thanabalan, M. (2019). Investigation of green functionalization of multiwall carbon nanotubes and its application in adsorption of benzene, toluene & p-xylene from aqueous solution. *Journal of Cleaner Production, 221*(6), 323–338. https://doi.org/10.1016/j.jclepro.2019.02.233

Apul, O. G., Wang, Q., Zhou, Y., & Karanfil, T. (2013). Adsorption of aromatic organic contaminants by graphene nanosheets: Comparison with carbon nanotubes and activated carbon. *Water Research, 47*(4), 1648–1654. https://doi.org/10.1016/j.watres.2012.12.031

Aragaw, B. A. (2020). Reduced graphene oxide-intercalated graphene oxide nano-hybrid for enhanced photoelectrochemical water reduction. *Journal of Nanostructure in Chemistry, 10*(3), 9–18. https://doi.org/10.1007/s40097-019-00324-x

Aziz, A., & Kim, K. S. (2017). Adsorptive volatile organic removal from air onto NaZSM-5 and HZSM-5: Kinetic and equilibrium studies. *Water, Air, and Soil Pollution, 228*(8), 319. https://doi.org/10.1007/s11270-017-3497-z

Azzouni, D., Baragh, F., Mahmoud, A. M., Alanazi, M. M., Rais, Z., & Taleb, M. (2023). Optimization of methylene blue removal from aqueous solutions using activated carbon derived from coffee ground pyrolysis: A response surface methodology (RSM) approach for natural and cost-effective adsorption. *Journal of the Saudi Chemical Society, 27*(5), Article 101695. https://doi.org/10.1016/j.jscs.2023.101695

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, Y., Huang, Z. H., & Kang, F. (2013). Synthesis of reduced graphene oxide/phenolic resin-based carbon composite ultrafine fibers and their adsorption performance for volatile organic compounds and water. *Journal of Materials Chemistry A, 33*, 9536–9543. https://doi.org/10.1039/C3TA10545H

Bajwa, A., Balakrishnan, M., Svensson, G., & Batra, V. S. (2016). Removal of volatile organic compounds over bagasse ash derived activated carbons and monoliths. *Journal of Environmental Chemical Engineering, 4*(2), 1561–1573. https://doi.org/10.1016/j.jece.2016.02.022

Balanay, J. A. G., Crawford, S. A., & Lungu, C. T. (2011). Comparison of toluene adsorption among granular activated carbon and different types of activated carbon fibers (ACFs). *Journal of Occupational and Environmental Hygiene, 8*(10), 573–579. https://doi.org/10.1080/15459624.2011.613346

Bansode, R. R., Losso, J. N., Marshall, W. E., Rao, R. M., & Portier, R. J. (2003). Adsorption of volatile organic compounds by pecan shell- and almond shell-based granular activated carbons. *Bioresource Technology, 90*(2), 175–184. https://doi.org/10.1016/S0960-8524(03)00117-2

Baur, G. B., Yuranov, I., Renken, A., & Kiwi-Minsker, L. (2015). Activated carbon fibers for efficient VOCs removal from diluted streams: The role of surface morphology. *Adsorption, 21*(5), 471–488. https://doi.org/10.1007/s10450-015-9667-7

Bedane, A. H., Guo, T., Eic, M., & Xiao, H. (2019). Adsorption of volatile organic compounds on peanut shell activated carbon. *The Canadian Journal of Chemical Engineering, 97*(1), 238–246. https://doi.org/10.1002/cjce.23330

Benvenutia, J., Fischb, A., Santos, J. H. Z., & Gutterres, M. (2019). Silica-based adsorbent material with grape bagasse encapsulated by the solgel method for the adsorption of Basic Blue 41 dye. *Journal of Environmental Chemical Engineering, 7*(5), 103342. https://doi.org/10.1016/j.jece.2019.103342

Bhatnagar, A., Hogland, W., Marques, M., & Sillanpaa, M. (2013). An overview of the modification methods of activated carbon for its water treatment applications. *Chemical Engineering Journal, 219*(3), 499–511. https://doi.org/10.1016/j.cej.2012.12.038

Bozaci, G., & Acarali, N. (2023). Chemical production of activated carbon from green coffee with adsorption isotherm support by Taguchi model. *Journal of the Indian Chemical Society, 100*(1), 100864. https://doi.org/10.1016/j.jics.2022.100864

Cabrita, I., Ruiz, B., Mestre, A. S., Fonseca, I. M., Carvalho, A. P., & Ania, C. O. (2010). Removal of an analgesic using activated carbons prepared from urban and industrial residues. *Chemical Engineering Journal, 163*(3), 249–255. https://doi.org/10.1016/j.cej.2010.07.058

Cal, M. P., Rood, M. J., & Larson, S. M. (1996). Removal of VOCs from humidified gas streams using activated carbon cloth. *Gas Separation & Purification, 10*(2), 117–121. https://doi.org/10.1016/0950-4214(96)00004-7

Canales-Flores, R. A., & Prieto-Garcia, F. (2020). Taguchi optimization for production of activated carbon from phosphoric acid impregnated agricultural waste by microwave heating for the removal of methylene blue. *Diamond and Related Materials, 109*(11), 108027. https://doi.org/10.1016/j.diamond.2020.108027

Cansado, I. P. P., Mourao, P. A. M., Nabais, J. M. V., Tita, B., Batista, T., Rocha, T., Borges, C., & Matos, G. (2022). Use of dirty plastic waste as precursors for activated carbon production – A contribution to the circular economy. *Water and Environmental Journal, 36*(1), 96–104. https://doi.org/10.1111/wej.12762

Cao, L., Li, Y., Mo, X., Li, J., Wu, Q., & Yao, S. (2020). Adsorption behavior and mechanism of 2,4,6-trichlorophenol on nut shell activated carbon. *Bio Resources, 15*(4), 8800–8812. https://doi.org/10.15376/biores.15.4.8800-8812

Cardenas, C., Latifi, A. M., Vallieres, C., & Marsteau, S. (2023). Multiscale modeling of ammonia adsorption on zinc sulfate-doped activated carbon: Sensitivity analysis, parameter identification, and model validation. *Separation and Purification Technology, 322*(10), 124173. https://doi.org/10.1016/j.seppur.2023.124173

Cardoso, B., Mestre, A. S., Carvalho, A. P., & Pires, J. (2008). Activated carbon derived from cork powder waste by KOH activation: Preparation, characterization, and VOCs adsorption. *Industrial & Engineering Chemistry Research, 47*(16), 5841–5846. https://doi.org/10.1021/ie800338s

Chakraborty, D., Chatterjee, R., Mondal, S., Das, S. K., Amoli, V., Cho, M., & Bhaumik, A. (2023). Construction of N-rich aminal-linked porous organic polymers for outstanding precombustion CO_2 capture and H_2 purification: A combined experimental and theoretical study. *ACS Applied Materials & Interfaces, 15*(41), 48326–48335. https://doi.org/10.1021/acsami.3c11732

Chaukura, N., Murimba, E. C., & Gwenzi, W. (2017). Synthesis, characterisation and methyl orange adsorption capacity of ferric oxide–biochar nano-composites derived from pulp and paper sludge. *Applied Water Science, 7*(9), 2175–2186. https://doi.org/10.1007/s13201-016-0392-5

Chen, B., Zhou, D., & Zhu, L. (2008). Transitional adsorption and partition of non-polar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environmental Science & Technology, 42*(14), 5137–5143. https://doi.org/10.1021/es8002684

Chen, K., Xiao, C., Liu, H., & Zhao, J. (2019). Graphene adsorption and separation functional materials. *Chemical Engineering & Technology, 42*(2), 266–286. https://doi.org/10.1002/ceat.201800358

Chen, R., Yao, Z., Han, N., Ma, X., Li, L., Liu, S., Sun, H., & Wang, S. (2020). Insights into the adsorption of VOCs on a Cobalt-Adeninate Metal−Organic Framework (Bio-MOF-11). *ACS Omega, 5*(25), 15402–15408. https://doi.org/10.1021/acsomega.0c01504

Chen, H., Mu, X., Ma, J., Yao, M., & Liu, F. (2022). Performance evaluation of functionalized ordered mesoporous silica for VOCs adsorption by molecular dynamics simulation. *Arabian Journal of Chemistry, 15*(11), 104192. https://doi.org/10.1016/j.arabjc.2022.104192

Cheng, H., Liu, Y., & Li, X. (2021). Adsorption performance and mechanism of iron-loaded biochar to methyl orange in the presence of Cr^{6+} from dye wastewater. *Journal of Hazardous Materials, 415*(8), 125749. https://doi.org/10.1016/j.jhazmat.2021.125749

Chevalier, V., Martin, J., Peralta, D., Roussey, A., & Tardif, F. (2019). Performance of HKUST-1 metal-organic framework for a VOCs mixture adsorption at realistic concentrations ranging from 0.5 to 2.5 ppmv under different humidity conditions. *Journal of Environmental Chemical Engineering, 7*(3), Article 103131. https://doi.org/10.1016/j.jece.2019.103131

Chiang, Y. C., Chiang, P. C., & Huang, C. P. (2001). Effects of pore structure and temperature on VOCs adsorption on activated carbon. *Carbon, 39*(4), 523–534. https://doi.org/10.1016/S0008-6223(00)00161-5

Chiang, H. L., Huang, C. P., & Chiang, P. C. (2002). The adsorption of benzene and methylethylketone onto activated carbon: Thermodynamic aspects. *Chemosphere, 46*(1), 143–152. https://doi.org/10.1016/S0045-6535(01)00126-6

Ching, S. L., Yusoff, M. S., Aziz, H. A., & Umar, M. (2011). Influence of impregnation ratio on coffee ground activated carbon as landfill leachate adsorbent for removal of total iron and orthophosphate. *Desalination, 279*(1–3), 225–234. https://doi.org/10.1016/j.desal.2011.06.011

Chlikhy, Y., & Mazroui, M. (2024). Adsorption of typical VOCs onto Ti_2CO_2 MXene with implications in early-stage lung cancer diagnosis: A DFT study. *Advanced Theory and Simulations, 7*(12), Article 2400583. https://doi.org/10.1002/adts.202400583

Chowdhury, A., Bhattacharjee, S., Chatterjee, R., & Bhaumik, A. (2022). A new nitrogen rich porous organic polymer for ultra-high CO_2 uptake and as an excellent organocatalyst for CO_2 fixation reactions. *Journal of CO2 Utilization, 65(11),* 102236. https://doi.org/10.1016/j.jcou.2022.102236

Chu, F., Zheng, Y., Wen, B., Zhou, L., Yan, J., & Chen, Y. (2018). Adsorption of toluene with water on zeolitic imidazolate framework-8/graphene oxide hybrid nanocomposites in a humid atmosphere. *RSC Advances, 8*(5), 2426–2432. https://doi.org/10.1039/C7RA12931A

Clippel, F. D., Harkiolakis, A., Ke, X., Vosch, T., Tendeloo, G. V., Baron, G., Jacobs, P., Denayer, J., & Sels, B. (2010). Molecular sieve properties of mesoporous silica with intra-porous nanocarbon. *Chemical Communications, 46*(6), 928–930. https://doi.org/10.1039/B918864A

Cortes, C. L., Revilla, G. O., Velazquez, T. G., & Cardenas, S. A. (2008). Adsorption of vapor-phase VOCs (benzene and toluene) on modified clays and its relation with surface properties. *Canadian Journal of Chemistry, 86*(4), 305–311. https://doi.org/10.1139/v08-017

Cosseron, A. F., Daou, T. J., Tzanis, L., Nouali, H., Deroche, I., Coasne, B., & Tchamber, V. (2013). Adsorption of Volatile Organic Compounds in pure silica CHA, *BEA, MFI and STT-type zeolites. *Microporous and Mesoporous Materials, 173*(6), 147–154. https://doi.org/10.1016/j.micromeso.2013.02.009

Costa, J. S., Desouza, J. F., Santos, D. R. S., & Fajardo, A. R. (2023). Composite aerogels of alginate/poly(acrylamide)/carbon nanotubes with enhanced performance for cationic dyes adsorption. *Materials Science and Engineering: B, 298*(12), Article 116820. https://doi.org/10.1016/j.mseb.2023.116820

Crespo, D., & Yang, R. T. (2006). Adsorption of organic vapors on single-walled carbon nanotubes. *Industrial & Engineering Chemistry Research, 45*(16), 5524–5530. https://doi.org/10.1021/ie051106b

Cruz, F. R., Jr., Gomez, I. C., Rodriguez-Reinoso, F., Silvestre-Albero, J., Rambo, C. R., & Martinez-Escandell, M. (2023). Activated carbons with high micropore volume obtained from polyurethane foams for enhanced CO_2 adsorption. *Chemical Engineering Science, 273*(6),

Article 118671. https://doi.org/10.1016/j.ces.2023.118671

Dai, Y., Li, M., Liu, F., Xue, M., Wang, Y., & Zhao, C. (2019). Graphene oxide wrapped copper-benzene-1,3,5-tricarboxylate metal organic framework as efficient absorbent for gaseous toluene under ambient conditions. *Environmental Science and Pollution Research, 26*(1), 2477–2491. https://doi.org/10.1007/s11356-018-3657-8

Dai, Z., Li, D., Ao, Z., Wang, S., & An, T. (2021). Theoretical exploration of VOCs removal mechanism by carbon nanotubes through persulfate-based advanced oxidation processes: Adsorption and catalytic oxidation. *Journal of Hazardous Materials, 405*(3), Article 124684. https://doi.org/10.1016/j.jhazmat.2020.124684

Dammak, N., Ouledltaief, O., Fakhfakh, N., & Benzina, M. (2014). Adsorption equilibrium studies for O-xylene vapour and modified clays system. *Surface and Interface Analysis, 46*(7), 457–464. https://doi.org/10.1002/sia.5534

Danish, M., Pin, Z., Ziyang, L., Ahma, T., Majeed, S., Yahya, A. N. H., Khanday, W. A. H., & Abdul Khalil, H. P. S. (2022). Preparation and characterization of banana trunk activated carbon using H_3PO_4 activation: A rotatable central composite design approach. *Materials Chemistry and Physics, 282*(4), Article 125989. https://doi.org/10.1016/j.matchemphys.2022.125989

David, E. (2023). Production of Activated Biochar Derived from Residual Biomass for Adsorption of Volatile Organic Compounds. *Materials, 16*(1), 389. https://doi.org/10.3390/ma16010389

Dehamani, Y., Franco, D. S. P., Georgin, J., Lamhasni, T., Brahmi, Y., Oukhrib, R., Youcef, H. B., & Sadik, A. (2023). Towards experimental and theoretical understanding of the adsorption behavior of phenol on a new activated carbon prepared from oak wood. *Journal of Water Process Engineering, 54*(8), Article 103936. https://doi.org/10.1016/j.jwpe.2023.103936

Deng, L., Yuan, P., Liu, D., Annabi-Bergaya, F., Zhou, J., Chen, F., & Liu, Z. (2017). Effects of microstructure of clay minerals, montmorillonite, kaolinite and halloysite, on their benzene adsorption behaviors. *Applied Clay Science, 143*(7), 184–191. https://doi.org/10.1016/j.clay.2017.03.035

Deryło-Marczewska, A., Skrzypczynska, K., Kusmierek, K., Swiatkowski, A., & Zienkievoicz-Stzalka, M. (2019). The adsorptive properties of oxidized activated carbons and their applications as carbon paste electrode modifiers. *Adsorption, 25*(1), 357–366. https://doi.org/10.1007/s10450-019-00016-6

Diaz, E., Ordonez, S., Vega, A., & Coca, J. (2005). Comparison of adsorption properties of a chemically activated and a steam-activated carbon, using inverse gas chromatography. *Microporous and Mesoporous Materials, 82*(1–2), 173–181. https://doi.org/10.1016/j.micromeso.2005.03.010

Diaz, E., Ordonez, S., & Vega, A. (2007). Adsorption of volatile organic compounds onto carbon nanotubes, carbon nanofibers, and high-surface-area graphites. *Journal of Colloid and Interface Science, 305*(1), 7–16. https://doi.org/10.1016/j.jcis.2006.09.036

Ding, Z., Wan, Y., Hu, X., Wang, S., Zimmerman, A. R., & Gao, B. (2016). Sorption of lead and methylene blue onto hickory biochars from different pyrolysis temperatures: Importance of physicochemical properties. *Journal of Industrial and Engineering Chemistry, 37*(5), 261–267. https://doi.org/10.1016/j.jiec.2016.03.035

Dobre, T., Parvulescu, O. C., Lavorschi, G., Stroescu, M., & Stoica, A. (2014). Volatile organic compounds removal from gas streams by adsorption onto activated carbon. *Industrial & Engineering Chemistry Research, 53*(9), 3622–3628. https://doi.org/10.1021/ie402504u

Dolas, H. (2023). Activated carbon synthesis and methylene blue adsorption from pepper stem using microwave assisted impregnation method: Isotherm and kinetics. *Journal of King Saud University-Science, 35*(3), Article 102559. https://doi.org/10.1016/j.jksus.2023.102559

Dou, B., Li, J., Wang, Y., Wang, H., Ma, C., & Hao, Z. (2011). Adsorption and desorption performance of benzene over hierarchically structured carbon–silica aerogel composites. *Journal of Hazardous Materials, 196*(11), 194–200. https://doi.org/10.1016/j.jhazmat.2011.09.019

Drewniak, S., Muzyka, R., Stolarezyk, A., Pustelny, T., Kotyczka-Moranska, M., & Setkiewicz, M. (2016). Studies of reduced graphene oxide and graphite oxide in the aspect of their possible application in gas sensors. *Sensors (Basel), 16*(1), 103. https://doi.org/10.3390/s16010103

Ece, M. S., Kutluay, S., & Sahin, O. (2025). Facile synthesis and characterization of Fe_3O_4@SiO_2 core–shell magnetic nanocomposite functionalized with 4-piperidinecarboxylic acid for dynamic adsorption of xylene. *Journal of Industrial and Engineering Chemistry, 147*(7), 448–460. https://doi.org/10.1016/j.jiec.2024.12.035

Ejeromedoghene, O., Oderinde, O., Okoye, C. O., Oladipo, A., & Alli, Y. A. (2022). Microporous metal-organic frameworks based on deep eutectic solvents for adsorption of toxic gases and volatile organic compounds: A review. *Chemical Engineering Journal Advances, 12*(11), 100361. https://doi.org/10.1016/j.ceja.2022.100361

El Mouchtari, E. M., Daou, C., Rafqah, S., Najjar, F., Anane, H., Piram, A., Hamade, A., Briche, S., & Chung, P. W. W. (2020). TiO_2 and activated carbon of Argania Spinosa tree nutshells composites for the adsorption photocatalysis removal of pharmaceuticals from aqueous solution. *Journal of Photochemistry and Photobiology a: Chemistry, 388*(2), 112183. https://doi.org/10.1016/j.jphotochem.2019.112183

El-Nemr, M. A., Hassaan, M. A., & Ashour, I. (2023). Formation of self-nitrogen-doping activated carbon from fish/sawdust/$ZnCl_2$ by hydrothermal and pyrolysis for toxic chromium adsorption from wastewater. *Scientific Reports, 13*, 11556. https://doi.org/10.1038/s41598-023-38697-3

Ersan, G. (2021). Adsorption modeling of organic compounds (OCs) by carbon nanotubes (CNTs): Role of OC and CNT properties on the linear solvation energy relationship. *Water Science and TechnOlogy, 84*(7), 1635–1647. https://doi.org/10.2166/wst.2021.346

Fakhfakh, N., Dammak, N., & Benzina, M. (2018). Breakthrough modeling and experimental design for o-xylene dynamic adsorption onto clay material. *Environmental*

Science and Pollution Research, 25(7), 18263–18277. https://doi.org/10.1007/s11356-017-9386-6

Falcaro, P., Ricco, R., Yazdi, A., Imaz, I., Furukawa, S., Maspoch, D., Ameloot, R., Evans, J. D., & Doonan, C. J. (2016). Application of metal and metal oxide nanoparticles at MOFs. *Coordination Chemistry Reviews, 307*(2), 237–254. https://doi.org/10.1016/j.ccr.2015.08.002

Feng, Y., Li, Y., Yang, W., Yang, D., Ye, G., & Zhang, S. (2018). Open-tip carbon nanotubes for enhanced methane adsorption performance: A comparative study. *Journal of Nanotechnology, 2018*, 1–8. https://doi.org/10.1155/2018/8905204

Feng, Z., Zhang, X., Wang, Y., Yu, H., Xu, Z., & Wang, J. (2024). Superacid-catalyzed waste foamed polystyrene plastics-based hypercrosslinked polymers for adsorption of monocyclic aromatic hydrocarbons. *Sustainable Chemistry and Pharmacy, 42*(12), 101857. https://doi.org/10.1016/j.scp.2024.101857

Fernandes, J. A., Bernardino, C. A. R., Mahler, C. F., Santelli, R. E., Braz, B. F., Borges, R. C., Veloso, M. C. D. C., Romeeiro, G. A., & Cincotto, F. H. (2021). Biochar generated from agro-industry sugarcane residue by low temperature pyrolysis utilized as an adsorption agent for the removal of thiamethoxam pesticide in wastewater. *Water, Air, & Soil Pollution, 232*, 67–79. https://doi.org/10.1007/s11270-021-05030-5

Flores-Lopez, S. L., Villanuevaa, S. F., Montes-Morana, M. A., Cruzb, G., Garridob, J. J., & Arenillas, A. (2020). Advantages of microwave-assisted synthesis of silica gels. *Colloids and Surfaces a: Physicochemical and Engineering Aspects, 604*(11), 125248. https://doi.org/10.1016/j.colsurfa.2020.125248

Fu, X., Niu, Z., Peng, C., Han, H., Sun, W., & Yue, T. (2025). Quantitative synergistic adsorption affinity of Ca(II) and sodium oleate to predict the surface reactivity of hematite and quartz. *Separation and Purification Technology, 360*(3), 131196. https://doi.org/10.1016/j.seppur.2024.131196

Fuertes, A. B., Marban, G., & Nevskaia, D. M. (2003). Adsorption of volatile organic compounds by means of activated carbon fibre-based monoliths. *Carbon, 41*(1), 87–96. https://doi.org/10.1016/S0008-6223(02)00274-9

Furtado, A. M. B., Wang, Y., & LeVan, M. D. (2013). Carbon silica composites for sulfur dioxide and ammonia adsorption. *Microporous and Mesoporous Materials, 165*(1), 48–54. https://doi.org/10.1016/j.micromeso.2012.07.032

Gao, H., Ding, L., Li, W. Q., Ma, G. F., Bai, H., & Li, L. (2016). Hyper-cross-linked organic microporous polymers based on alternating copolymerization of bismaleimide. *ACS Macro Letters, 5*(3), 377–381. https://doi.org/10.1021/acsmacrolett.6b00015

Gargiulo, N., Peluso, A., & Caputo, D. (2020). MOF-based adsorbents for atmospheric emission control: A review. *Processes, 8*(5), 613. https://doi.org/10.3390/pr8050613

Gaur, V., Sharma, A., & Verma, N. (2006). Preparation and characterization of ACF for the adsorption of BTX and SO_2. *Chemical Engineering and Processing - Process Intensification, 45*(1), 1–13. https://doi.org/10.1016/j.cep.2005.04.006

Geng, X., Lv, S., Yang, J., Cui, S., & Zhao, Z. (2021). Carboxyl-functionalized biochar derived from walnut shells with enhanced aqueous adsorption of sulfonamide. *Journal of Environmental Management, 280*(2), 111749. https://doi.org/10.1016/j.jenvman.2020.111749

Ghafari, M., & Atkinson, J. D. (2018). Impact of styrenic polymer one-step hyper-cross-linking on volatile organic compound adsorption and desorption performance. *Journal of Hazardous Materials, 351*(6), 117–123. https://doi.org/10.1016/j.jhazmat.2018.02.051

Ghanbari, T., Abnisa, F., & Daud, W. M. A. W. (2020). A review on production of metal organic frameworks (MOF) for CO_2 adsorption. *Science of the Total Environment, 707*(3), 135090. https://doi.org/10.1016/j.scitotenv.2019.135090

Gil, R.R., Ruiz, B., Lozan,o M.S., Martin, M.J., & Fuente, E. (2014). VOCs removal by adsorption onto activated carbons from biocollagenic wastes of vegetable tanning. *Chemical Engineering Journal, 245(6),* 80–88. https://doi.org/10.1016/j.cej.2014.02.012

Giraudet, S., Boulinguiez, B., & Cloirec, P. L. (2014). Adsorption and electrothermal desorption of volatile organic compounds and siloxanes onto an activated carbon fiber cloth for biogas purification. *Energy & Fuels, 28*(6), 3924–3932. https://doi.org/10.1021/ef500600b

Gironi, F., & Piemonte, V. (2011). VOCs removal from dilute vapor streams by adsorption onto activated carbon. *Chemical Engineering Journal, 172*(2–3), 671–677. https://doi.org/10.1016/j.cej.2011.06.034

Glover, T. G., Dunne, K. I., Davis, R. J., & LeVan, M. D. (2008). Carbon–silica composite adsorbent: Characterization and adsorption of light gases. *Microporous and Mesoporous Materials, 111*(1–3), 1–11. https://doi.org/10.1016/j.micromeso.2007.07.012

Gotovac, S., Hattori, Y., Noguchi, D., Miyamoto, J., Kanamaru, M., Utsumi, S., Kanoh, H., & Kaneko, K. (2006). Phenanthrene adsorption from solution on single wall carbon nanotubes. *The Journal of Physical Chemistry B, 110*(33), 16219–16224. https://doi.org/10.1021/jp061830

Grigoras, C. G., Simion, A. I., Favier, L., & Gavrila, L. (2020). Congo red removal from aqueous effluents by adsorption on cherry stones activated carbon. *Environmental Engineering and Management Journal, 19*(2), 247–254. https://doi.org/10.30638/eemj.2020.023

Gorzin, F., & Abadi, M. M. B. R. (2017). Adsorption of Cr (VI) from aqueous solution by adsorbent prepared from paper mill sludge: Kinetics and thermodynamics studies. *Adsorption Science & Technology, 36*(1–2), 149–169. https://doi.org/10.1177/0263617416686976

Grujicic, M., Cao, G., & Singh, R. (2003). The effect of topological defects and oxygen adsorption on the electronic transport properties of single-walled carbon-nanotubes. *Applied Surface Science, 211*(1–4), 166–183. https://doi.org/10.1016/S0169-4332(03)00224-1

Guo, Y., Li, Y., Zhu, T., & Ye, M. (2013). Effects of concentration and adsorption product on the adsorption of SO_2 and no on activated carbon. *Energy & Fuels, 27*(1), 360–366. https://doi.org/10.1021/EF3016975

Guo, Z., Huang, J., Xue, Z., & Wang, X. (2016). Electrospun graphene oxide/carbon composite nanofibers with well-developed mesoporous structure and their adsorption performance for benzene and butanone. *Chemical*

Engineering Journal, 306(12), 99–106. https://doi.org/10.1016/j.cej.2016.07.048

Guo, W., Ai, Y., Men, B., & Wang, S. (2017). Adsorption of phenanthrene and pyrene by biochar produced from the excess sludge: Experimental studies and theoretical analysis. *International Journal of Environmental Science and Technology, 14*(9), 1889–1896. https://doi.org/10.1007/s13762-017-1272-8

Gupta, K. N., & Kumar, R. (2020). Kinetic modeling and optimization of fraction of bed utilized for the gaseous phase removal of toluene in fixed bed adsorption column: Response surface methodology. *Separation Science and Technology, 55*(6), 1062–1077. https://doi.org/10.1080/01496395.2019.1583252

Gupta, V. K., Kumar, R., Nayak, A., Saleh, T. A., & Barakat, M. A. (2013). Adsorptive removal of dyes from aqueous solution onto carbon nanotubes: A review. *Advances in Colloid and Interface Science, 193–194*(6), 24–34. https://doi.org/10.1016/j.cis.2013.03.003

Gupta, K. N., Rao, N. J., & Agarwal, G. K. (2015). Gaseous phase adsorption of volatile organic compounds on granular activated carbon. *Chemical Engineering Communications, 202*(3), 384–401. https://doi.org/10.1080/00986445.2013.840827

Han, Y., Wang, N., Guo, X., Jiao, T., & Ding, H. (2022). Influence of ultrasound on the adsorption of single-walled carbon nanotubes to phenol: A study by molecular dynamics simulation and experiment. *Chemical Engineering Journal, 427*(1), 131819. https://doi.org/10.1016/j.cej.2021.131819

He, C., Cheng, J., Zhang, X., Douthwaite, M., Pattisson, S., & Hao, Z. (2019). Recent advances in the catalytic oxidation of volatile organic compounds: A review based on pollutant sorts and sources. *Chemical Reviews, 119*(7), 4471–4568. https://doi.org/10.1021/acs.chemrev.8b00408

He, L., Chen, L., Dong, X., Zhang, S., Zhang, M., Dai, X., Liu, X., Liu, P., Li, K., Chen, C., Pan, T., Ma, F., Chen, J., Yuan, M., Zhang, Y., Chen, L., Zhou, R., Han, Y., & Chai, Z. (2021). A nitrogen-rich covalent organic framework for simultaneous dynamic capture of iodine and methyl iodide. *Chem, 7*(3), 699–714. https://doi.org/10.1016/j.chempr.2020.11.024

Horng, T. J., Mei, C. H., Yinag, H. G., & Lung, C. H. (2008). Adsorption characteristics of acetone, chloroform and acetonitrile on sludge-derived adsorbent, commercial granular activated carbon and activated carbon fibers. *Journal of Hazardous Materials, 154*(1–3), 1183–1191. https://doi.org/10.1016/j.jhazmat.2007.11.065

Hsu, S. C., & Lu, C. (2009). Adsorption kinetic, thermodynamic, and desorption studies of isopropyl alcohol vapor by oxidized single-walled carbon nanotubes. *Journal of the Air & Waste Management Association, 59*(8), 990–997. https://doi.org/10.3155/1047-3289.59.8.990

Hu, L., Cheng, W., Zhang, W., Wu, F., Peng, S., & Li, J. (2016). Monolithic bamboo-based activated carbons for dynamic adsorption of toluene. *Journal of Porous Materials, 24*(4), 541–549. https://doi.org/10.1007/s10934-016-0289-6

Huang, H. F., Rong, W. J., Gu, Y. Y., Chang, R. Q., & Lu, H. F. (2014). Adsorption and desorption of VOCs on the ZSM-5 zeolite. *Acta Scientiae Circumstantiae, 34*, 3144–3151. https://doi.org/10.13671/j.hjkxxb.2014.0739

Huang, Y., Ma, E., & Zhao, G. (2016). Optimizing the pore structure of bio-based ACFs through a simple KOH–steam reactivation. *Materials, 9*(6), 432. https://doi.org/10.3390/ma9060432

Huang, Y., Yu, O., Li, M., Jin, S., Fan, J., Zhao, L., & Yao, Z. (2021). Surface modification of activated carbon fiber by low-temperature oxygen plasma: Textural property, surface chemistry, and the effect of water vapor adsorption. *Chemical Engineering Journal, 418*(8), 129474. https://doi.org/10.1016/j.cej.2021.129474

Hung, H. W., & Lin, T. F. (2007). Prediction of the adsorption capacity for volatile organic compounds onto activated carbons by the Dubinin–Radushkevich–Langmuir model. *Journal of the Air & Waste Management Association, 57*(4), 497–506. https://doi.org/10.3155/1047-3289.57.4.497

Huo, P., Zhang, Y., Zhang, L., Yang, M., Wei, W., Zhang, X., Yang, J., & Zhang, Y. (2021). Insight into the adsorption process of ethanol and water on the pore structure and surface chemistry properties engineered activated carbon fibers. *Industrial & Engineering Chemistry Research, 60*(30), 11141–11150. https://doi.org/10.1021/acs.iecr.1c02005

Hussain, C. M., Saridara, C., & Mitra, S. (2009). Modifying the sorption properties of multi-walled carbon nanotubes via covalent functionalization. *The Analyst, 134*(9), 1928–1933. https://doi.org/10.1039/b823316k

Ihsanullah Abbas, A., Al-Amer, A. M., Laoui, T., Al-Marri, M. J., Nasser, M. S., Khraisheh, M., & Atieh, M. A. (2016). Heavy metal removal from aqueous solution by advanced carbon nanotubes: Critical review of adsorption applications. *Separation and Purification Technology, 157*(1), 141–161. https://doi.org/10.1016/j.seppur.2015.11.039

Iijima, S. (1991). Helical microtubules of graphitic carbon. *Nature, 354*, 56–58. https://doi.org/10.1038/354056a0

Issaka, E., Adams, M., Baffoe, J., Danso-Boateng, E., Melville, L., & Fazal, A. (2025). Covalent organic frameworks: A review of synthesis methods, properties and applications for per- and poly-fluoroalkyl substances removal. *Clean Technologies and Environmental Policy, 27*(2), 833–860. https://doi.org/10.1007/s10098-024-03102-8

Jacobs, J. H., Chou, N., Lesage, K. L., Xiao, Y., Hil, J. M., & Marriott, R. A. (2023). Investigating activated carbons for SO_2 adsorption in wet flue gas. *Fuel, 353*(12), 129239. https://doi.org/10.1016/j.fuel.2023.129239

Jafari, S., Ghorbani-Shahna, F., Bahrami, A., & Kazemian, H. (2018). Adsorptive removal of toluene and carbon tetrachloride from gas phase using Zeolitic Imidazolate Framework-8: Effects of synthesis method, particle size, and pretreatment of the adsorbent. *Microporous and Mesoporous Materials, 268*(9), 58–68. https://doi.org/10.1016/j.micromeso.2018.04.013

Jahandar Lashaki, M., Atkinson, J. D., Hashisho, Z., Phillips, J. H., Anderson, J. E., & Nichols, M. (2016). The role of beaded activated carbon's pore size distribution on heel formation during cyclic adsorption/desorption of organic vapors. *Journal of Hazardous Materials, 315*(9), 42–51. https://doi.org/10.1016/j.jhazmat.2016.04.071

Janus, R., Kustrowski, P., Dudek, B., Piwowarska, Z., Kochanowski, A., Michalik, M., & Cool, P. (2011). Removal of methyl–ethyl ketone vapour on polyacrylonitrile-derived carbon/mesoporous silica nanocomposite adsorbents. *Microporous and Mesoporous Materials, 145*(1–3), 65–73. https://doi.org/10.1016/j.micromeso.2011.04.029

Jaramillo, J., Alvarez, P. M., & Gomez-Serrano, V. (2010). Preparation and ozone-surface modification of activated carbon. Thermal stability of oxygen surface groups. *Applied Surface Science, 256*(17), 5232–5236. https://doi.org/10.1016/j.apsusc.2009.12.109

Jaria, G., Lourenco, M. A. O., Silva, C. P., Ferreira, P., Otero, M., Calisto, V., & Esteves, V. I. (2020). Effect of the surface functionalization of a waste-derived activated carbon on pharmaceuticals' adsorption from water. *Journal of Molecular Liquids, 299*(2), 112098. https://doi.org/10.1016/j.molliq.2019.112098

Jawad, H., Bardhan, M., Islam, M.A., Syed-Hassan, S.S.A., Surip, S.N., ALOthman, Z.A., & Khan, M.R. (2020). Insights and modeling, characterization and adsorption performance of mesoporous activated carbon from corn cob residue via microwave-assisted H_3PO_4 activation. *Surfaces and Interfaces*, *21*(12), 100688. https://doi.org/10.1016/j.surfin.2020.100688

Jellali, S., Azzaz, A. A., Al-Harrasi, M., Charabi, Y., Al-Sabahi, J. N., Al-Raeesi, A., Usman, M., Al-Nasiri, N., Al-Abri, M., & Jeguirim, M. (2022). Conversion of industrial sludge into activated biochar for effective cationic dye removal: Characterization and adsorption properties assessment. *Water, 14*(14), 2206. https://doi.org/10.3390/w14142206

Jiang, L., Tian, Y., Sun, T., Zhu, Y., Ren, H., Zou, X., Ma, Y., Meihaus, K. R., Long, J. R., & Zhu, G. (2018). A crystalline polyimide porous organic framework for selective adsorption of acetylene over ethylene. *Journal of the American Chemical Society, 140*(46), 15724–15730. https://doi.org/10.1021/jacs.8b08174

Kalluri, R. R., Cahela, D. R., & Tatarchuk, B. J. (2008). Microfibrous entrapped small particle adsorbents for high efficiency heterogeneous contacting. *Separation and Purification Technology, 62*(2), 304–316. https://doi.org/10.1016/j.seppur.2008.01.021

Kang, S., Ma, J., Wu, Q., & Deng, H. (2018). Adsorptive removal of dichloromethane vapor on FAU and MFI zeolites: Si/Al ratio effect and mechanism. *Journal of Chemical and Engineering Data, 63*(6), 2211–2218. https://doi.org/10.1021/acs.jced.8b00174

Karimi, M., Zafanelli, L. F. A. S., Almeida, J. P. P., Stroher, G. R., Rodrigues, A. E., & Silva, J. A. C. (2020). Novel insights into activated carbon derived from municipal solid waste for CO_2 uptake: Synthesis, adsorption isotherms and scale-up. *Journal of Environmental Chemical Engineering, 8*(5), 104069. https://doi.org/10.1016/j.jece.2020.104069

Karri, R. R., & Sahu, J. N. (2018). Modeling and optimization by particle swarm embedded neural network for adsorption of zinc (II) by palm kernel shell based activated carbon from aqueous environment. *Journal of Environmental Management, 206*(1), 178–191. https://doi.org/10.1016/j.jenvman.2017.10.026

Kaskun, S., Akinay, Y., & Kayfeci, M. (2020). Improved hydrogen adsorption of ZnO doped multi-walled carbon nanotubes. *International Journal of Hydrogen Energy, 45*(60), 34949–34955. https://doi.org/10.1016/j.ijhydene.2020.06.304

Kaur, P., Hupp, J. T., & Nguyen, S. T. (2011). Porous organic polymers in catalysis: Opportunities and challenges. *ACS Catalysis, 1*(7), 819–835. https://doi.org/10.1021/cs200131g

Khan, F. I., & Ghoshal, A. K. (2000). Removal of volatile organic compounds from polluted air. *Journal of Loss Prevention in the Process Industries, 13*(6), 527–545. https://doi.org/10.1016/S0950-4230(00)00007-3

Khan, A., Szulejko, J. E., Samaddar, P., Kim, K., Eom, W., Ambade, S. B., & Han, T. H. (2019). The effect of diverse metal oxides in graphene composites on the adsorption isotherm of gaseous benzene. *Environmental Research, 172*(5), 367–374. https://doi.org/10.1016/j.envres.2019.01.050

Kim, K. J., & Ahn, H. G. (2012). The effect of pore structure of zeolite on the adsorption of VOCs and their desorption properties by microwave heating. *Microporous and Mesoporous Materials, 152*(4), 78–83. https://doi.org/10.1016/j.micromeso.2011.11.051

Kim, K. J., Kang, C. S., You, Y. J., Chung, M. C., Woo, M. W., Jeong, W. J., Park, N. C., & Ahn, H. J. (2006). Adsorption-desorption characteristics of VOCs over impregnated activated carbons. *Catalysis Today, 111*(3–4), 223–228. https://doi.org/10.1016/j.cattod.2005.10.030

Kim, M., Kim, S., Lim, C. S., & Seo, B. (2017). Adsorption of acetaldehyde at room temperature in a continuous system using silica synthesized by the sol-gel method. *Korean Journal of Chemical Engineering, 34*(10), 2773–2779. https://doi.org/10.1007/s11814-017-0170-6

Kim, J. M., Kim, J. H., Lee, C. Y., Jerng, D. W., & Ahn, H. S. (2018a). Toluene and acetaldehyde removal from air on to graphene-based adsorbents with micro sized pores. *Journal of Hazardous Materials, 344*(2), 458–465. https://doi.org/10.1016/j.jhazmat.2017.10.038

Kim, S. J., Koh, H. J., Ren, C. E., Kwon, O., Maleski, K., Cho, S. Y., Anasori, B., Kom, C. K., Choi, Y. K., Kim, J., Gogotsi, Y., & Jung, H. T. (2018b). Metallic $Ti_3C_2T_x$ MXene gas sensors with ultrahigh signal-to-noise ratio. *ACS Nano, 12*(2), 986–993. https://doi.org/10.1021/acsnano.7b07460

Kim, K.D., Park, E.J., Seo, H.O., Jeong, M.G., Kim, Y.D., Lim, & D.C. (2012). Effect of thin hydrophobic films for toluene adsorption and desorption behavior on activated carbon fiber under dry and humid conditions. *Chemical Engineering Journal, 200–202(8),* 133–139. https://doi.org/10.1016/j.cej.2012.06.044

Kong, Q., Shi, X., Ma, W., Zhang, F., Yu, T., Zhao, F., Zhao, D., & Wei, C. (2021). Strategies to improve the adsorption properties of graphene-based adsorbent towards heavy metal ions and their compound pollutants: A review. *Journal of Hazardous Materials, 415*(8), 125690. https://doi.org/10.1016/j.jhazmat.2021.125690

Kou, Y., Xu, Y. H., Guo, Z. Q., & Jiang, D. L. (2011). Super capacitive energy storage and electric power supply using an aza-fused pi-conjugated microporous framework.

Angewandte Chemie International Edition, 50(37), 8753–8757. https://doi.org/10.1002/anie.201103493

Krishna, R. H., Chandraprabha, M. N., Samrat, K., Murthy, T. P. K., Manjunatha, C., & Kumar, S. G. (2023). Carbon nanotubes and graphene-based materials for adsorptive removal of metal ions – A review on surface functionalization and related adsorption mechanism. *Applied Surface Science Advances, 16*(8), 100431. https://doi.org/10.1016/j.apsadv.2023.100431

Kumar, P., Vellingiri, K., Kim, K., Brown, R. J. C., & Manos, M. J. (2017). Modern progress in metal-organic frameworks and their composites for diverse applications. *Microporous and Mesoporous Materials, 253*(11), 251–265. https://doi.org/10.1016/j.micromeso.2017.07.003

Kumar, A., Singh, E., Khapre, A., Bordoloi, N., & Kumar, S. (2019). Sorption of volatile organic compounds on non-activated biochar. *Bioresource Technology, 297*(2), 122469. https://doi.org/10.1016/j.biortech.2019.122469

Kumar, V., Lee, Y. S., Shin, J. W., Kim, K. H., Kukkar, D., & Tsang, Y. F. (2020). Potential applications of graphene-based nanomaterials as adsorbent for removal of volatile organic compounds. *Environmental International, 135*(2), 105356. https://doi.org/10.1016/j.envint.2019.105356

Kunaseth, M., Poldorn, P., Junkeaw, A., Meeprasert, J., Rungnim, C., Namuangruk, S., Kungwan, N., Inntam, C., & Jungsuttiwong, S. (2017). A DFT study of volatile organic compounds adsorption on transition metal deposited graphene. *Applied Surface Science, 396*(2), 1712–1718. https://doi.org/10.1016/j.apsusc.2016.11.238

Kundu, S. K., & Bhaumik, A. (2016). Novel nitrogen and sulfur rich hyper-cross-linked microporous poly-triazine-thiophene copolymer for superior CO_2 capture. *ACS Sustainable Chemistry & Engineering, 4*(7), 3697–3703. https://doi.org/10.1021/acssuschemeng.6b00262

Kupreenko, S.Y., Strokova, N.E., IIgova, E.A., Ivanov, A.S., Arkhipova, E.A., & Savilov, S.V. (2022). Adsorption of organic solvent vapours on carbon nanotubes, few-layer graphene nanoflakes and their nitrogen-doped counterparts. *Adsorption 28(12),* 55-66 https://doi.org/10.1007/s10450-021-00349-1

Kutluay, S., & Ece, M. S. (2025). Exploring enhanced gas-phase toluene adsorption by engineered a novel magnetic nanoadsorbent modified with p-aminobenzoic acid: Insights on characterization, performance, kinetics, isotherm, mechanism and reusability. *Separation and Purification Technology, 359*(3), 130874. https://doi.org/10.1016/j.seppur.2024.130874

Lashaki, M. J., Kamravaei, S., Hashisho, Z., Phillips, J. H., Crompton, D., Anderson, J. E., & Nichols, M. (2023). Adsorption and desorption of a mixture of volatile organic compounds: Impact of activated carbon porosity. *Separation and Purification Technology, 314*(6), 123530. https://doi.org/10.1016/j.seppur.2023.123530

Lee, S. M., Yusop, M. F. M., Ng, W. L., Ahmad, M. A., & Tan, S. H. (2023). Synthesis of polyethylene terephthalate/multi-walled carbon nanotubes adsorbent for methylene blue adsorption. *International Journal of Environmental Science and Technology, 20*(8), 9111–9128. https://doi.org/10.1007/s13762-022-04583-0

Li, Y., Lee, C., & Gullett, B. (2002). The effect of activated carbon surface moisture on low temperature mercury adsorption. *Carbon, 40*(1), 65–72. https://doi.org/10.1016/S0008-6223(01)00085-9

Li, L., Liu, S., & Liu, J. (2011). Surface modification of coconut shell based activated carbon for the improvement of hydrophobic VOCS removal. *Journal of Hazardous Materials, 192*(2), 683–690. https://doi.org/10.1016/j.jhazmat.2011.05.069

Li, M., Wu, S. C., & Shih, Y. (2016a). Characterization of volatile organic compound adsorption on multi wall carbon nanotubes under different levels of relative humidity using linear solvation energy relationship. *Journal of Hazardous Materials, 315*(7), 35–41. https://doi.org/10.1016/j.jhazmat.2016.04.004

Li, Y., Miao, J., Sun, X., Xiao, J., Li, Y., Wang, H., Xia, Q., & Li, Z. (2016b). Mechanochemical synthesis of Cu-BTC@go with enhanced water stability and toluene adsorption capacity. *Chemical Engineering Journal, 298*(8), 191–197. https://doi.org/10.1016/j.cej.2016.03.141

Li, R., Xue, T., Li, Z., & Wang, Q. (2020). Hierarchical structure ZSM-5/SBA-15 composite with improved hydrophobicity for adsorption-desorption behavior of toluene. *Chemical Engineering Journal, 392*(7), 124861. https://doi.org/10.1016/j.cej.2020.124861

Li, X., Wang, J., Guo, Y., Zhu, T., & Xu, W. (2021). Adsorption and desorption characteristics of hydrophobic hierarchical zeolites for the removal of volatile organic compounds. *Chemical Engineering Journal, 411*(5), 128558. https://doi.org/10.1016/j.cej.2021.128558

Li, Y., Li, Z., Qu, G., Li, R., Liang, S., Zhou, J., Ji, W., & Tang, H. (2023). Mechanism, behaviour and application of iron nitrate modified carbon nanotube composites for the adsorption of arsenic in aqueous solutions. *Chinese Journal of Chemical Engineering, 60*(8), 26–36. https://doi.org/10.1016/j.cjche.2023.01.010

Li, F., Cheng, Z., Li, X., Zhao, X., Sheng, S., & He, J. (2025). Facile and scalable method to synthesize MOFs/PET composite fibers for indoor VOCs adsorption. *Separation and Purification Technology, 357*(5), 130007. https://doi.org/10.1016/j.seppur.2024.130007

Liao, M., Zheng, Z., Jiang, H., Ma, M., Wnag, L., Wang, Y., & Zhuang, S. (2024). MXenes as emerging adsorbents for removal of environmental pollutants. *Science of the Total Environment, 912*(2), 169014. https://doi.org/10.1016/j.scitotenv.2023.169014

Lim, C., Jeong, S. G., Ha, S., Ha, N., Myeong, S., & Lee, Y. S. (2023). Unique CO_2 adsorption of pine needle biochar-based activated carbons by induction of functionality transition. *Journal of Industrial and Engineering Chemistry, 124*(8), 201–210. https://doi.org/10.1016/j.jiec.2023.04.008

Lin, C. L., Cheng, Y. H., Liu, Z. S., & Chen, J. Y. (2013). Adsorption and oxidation of high concentration toluene with activated carbon fibers. *Journal of Porous Materials, 20*(8), 883–889. https://doi.org/10.1007/s10934-012-9665-z

Liu, J., Yan, Y., & Zhang, H. (2011). Adsorption dynamics of toluene in composite bed with microfibrous entrapped

activated carbon. *Chemical Engineering Journal, 173*(2), 456–462. https://doi.org/10.1016/j.cej.2011.08.004

Liu, X. W., Sun, T. J., Hu, J.-L., & Wang, S. D. (2016). Composites of metal–organic frameworks and carbon-based materials: Preparations, functionalities and applications. *Journal of Materials Chemistry A, 4*(10), 3584–3616. https://doi.org/10.1039/C5TA09924B

Liu, Y., Mallouk, K., Emamipour, H., Rood, M. J., Liu, X., & Yan, Z. (2019). Isobutane adsorption with carrier gas recirculation at different relative humidities using activated carbon fiber cloth and electrothermal regeneration. *Chemical Engineering Journal, 360*(3), 1011–1019. https://doi.org/10.1016/j.cej.2018.02.095

Liu, B., Liu, H., Xi, Y., Huang, Y., Su, Z., Zhang, Z., Peng, Z., Xu, W., Zhang, C., & Li, X. (2023). Adsorption of lead ions by activated carbon doped sodium alginate/sodium polyacrylate hydrogel beads and their in-situ recycle as sustainable photocatalysts. *Journal of Colloid and Interface Science, 645*(9), 133–145. https://doi.org/10.1016/j.jcis.2023.04.091

Liu, Y., Wang, Y., Fu, Y., Wang, N., Liu, Q., Zhao, S., Yang, H. U., & Liu, C. (2025). Fabrication of temperature and pH dual-sensitive semi-interpenetrating network hydrogel with enhanced adhesion and antibacterial properties. *Polymer, 326*(5), 128343. https://doi.org/10.1016/j.polymer.2025.128343

Long, C., Li, Q., Li, Y., Liu, Y., Li, A., & Zhang, Q. (2010). Adsorption characteristics of enzene–chlorobenzene vapor on hypercrosslinked polystyrene adsorbent and a pilot-scale application study. *Chemical Engineering Journal, 160*(2), 723–728. https://doi.org/10.1016/j.cej.2010.03.074

Lu, X., He, J., Xie, J., Zhou, Y., Liu, S., Zhu, Q., & Lu, H. (2020). Preparation of hydrophobic hierarchical pore carbon–silica composite and its adsorption performance toward volatile organic compounds. *Journal of Environmental Sciences, 87*(1), 39–48. https://doi.org/10.1016/j.jes.2019.05.003

Lu, S., Liu, Q., Han, R., Guo, M., Shi, J., Song, C., Ji, N., Lu, X., & Ma, D. (2021). Potential applications of porous organic polymers as adsorbent for the adsorption of volatile organic compounds. *Journal of Environmental Sciences, 105*(7), 184–203. https://doi.org/10.1016/j.jes.2021.01.007

Lu, L., Cao, S., Li, Z., Huang, J., Jiang, Y., Deng, C., Liu, Z., & Liu, Z. (2023). Adsorption and desorption of flavonoids on activated carbon impregnated with different metal ions. *RSC Advances, 13*, 19235–19242. https://doi.org/10.1039/d3ra03476c

Lu, Y., Wu, S., Xu, H., Li, N., Liu, Q., Wang, H., Zou, Y., Jiang, Q., & Amirkhanian, S. (2024). Simulation of inhibition and targeted adsorption of rubberized asphalt VOCs by UiO-66 based on molecular dynamics. *Journal of Cleaner Production, 447*(4), 141541. https://doi.org/10.1016/j.jclepro.2024.141541

Ma, T. T., Zhao, X., Matsuo, Y., Song, J., Zhao, R., Faheem, M., Chen, M., Zhang, Y., Tian, Y., & Zhu, G. (2019). Fluorescein- based fluorescent porous aromatic framework for Fe 3 + detection with high sensitivity. *Journal of Materials Chemistry C, 7*(8), 2327–2332. https://doi.org/10.1039/C8TC06288A

Ma, L., Li, K., Wang, C., Liu, B., Peng, H., Mei, Y., & Ning, P. (2020). Enhanced adsorption of hydrophobic organic contaminants by high surface area porous graphene. *Environmental Science and Pollution Research, 27*(3), 7309–7317. https://doi.org/10.1007/s11356-019-07439-2

Malamis, S., & Katsou, E. (2013). A review on zinc and nickel adsorption on natural and modified zeolite, bentonite and vermiculite: Examination of process parameters, kinetics and isotherms. *Journal of Hazardous Materials, 252–253*(5), 428–461. https://doi.org/10.1016/j.jhazmat.2013.03.024

Maneechakr, P., & Mongkollertlop, S. (2020). Investigation on adsorption behaviors of heavy metal ions (Cd^{2+}, Cr^{3+}, Hg^{2+} and Pb^{2+}) through low-cost/active manganese dioxide-modified magnetic biochar derived from palm kernel cake residue. *Journal of Environmental Chemical Engineering, 8*(6), 104467. https://doi.org/10.1016/j.jece.2020.104467

Mao, H., Huang, R., Hashisho, Z., Wang, S., Chen, H., Wang, H., & Zhou, D. (2016). Adsorption of toluene and acetone vapors on microwave-prepared activated carbon from agricultural residues: Isotherms, kinetics, and thermodynamics studies. *Research on Chemical Intermediates, 42*(4), 3359–3371. https://doi.org/10.1007/s11164-015-2217-9

Mbayachi, B., Ndayiragije, E., Sammani, T., Taj, S., Mbuta, E. R., & Khan, A. (2021). Graphene synthesis, characterization and its applications: A review. *Results in Chemistry, 3*(1), 100163. https://doi.org/10.1016/j.rechem.2021.100163

Mehmood, F., Pachter, R., Lu, W., & Boeckl, J. J. (2013). Adsorption and diffusion of oxygen on single-layer graphene with topological defects. *The Journal of Physical Chemistry C, 117*(20), 10366–10374. https://doi.org/10.1021/jp312159v

Mekki, A., & Boukoussa, B. (2019). Structural, textural and toluene adsorption properties of microporous–mesoporous zeolite omega synthesized by different methods. *Journal of Materials Science, 54*(6), 8096–8107. https://doi.org/10.1007/s10853-019-03450-7

Memetova, A. E., Burakova, I. V., Burakov, A. E., Memetov, N. R., & Tkachev, A. G. (2023). Effective adsorption of toluene and benzene on coconut activated carbon modified with carbon nanotubes: Kinetics, isotherms and thermodynamics. *Adsorption, 29*(8), 335–349. https://doi.org/10.1007/s10450-023-00405-y

Meng, F., Song, M., Wei, Y., & Wang, Y. (2019). The contribution of oxygen-containing functional groups to the gas-phase adsorption of volatile organic compounds with different polarities onto lignin-derived activated carbon fibers. *Environmental Science and Pollution Research, 26*(3), 7195–7204. https://doi.org/10.1007/s11356-019-04190-6

Minale, M., Gu, Z., Guadie, A., Kabtamu, D. M., Li, Y., & Wang, X. (2020). Application of graphene-based materials for removal of tetracyclines using adsorption and photocatalytic-degradation: A review. *Journal of Environmental Management, 276*(12), 111310. https://doi.org/10.1016/j.jenvman.2020.111310

Mishra, S., & Kundalwal, S. I. (2022). Topological defects embedded large-sized single-walled carbon nanotubes

for hydrogen storage: A molecular dynamics study. *International Journal of Hydrogen Energy, 47*(86), 36605–36621. https://doi.org/10.1016/j.ijhydene.2022.08.212

Modak, A., Nandi, M., Mondal, J., & Bhaumik, A. (2012). Porphyrin based porous organic polymers: Novel synthetic strategy and exceptionally high CO_2 adsorption capacity. *Chemical Communications, 48*(2), 248–250. https://doi.org/10.1039/C1CC14275E

Mohammadi, A., & Moghaddas, J. (2015). Synthesis, adsorption and regeneration of nanoporous silica aerogel and silica aerogel-activated carbon composites. *Chemical Engineering Research and Design, 94*(2), 475–484. https://doi.org/10.1016/j.cherd.2014.09.003

Mohan, N., Kannan, G. K., Upendra, S., Subha, R., & Kumar, N. S. (2009). Breakthrough of toluene vapors in granular activated carbon filled packed bed reactor. *Journal of Hazardous Materials, 168*(2–3), 777–781. https://doi.org/10.1016/j.jhazmat.2009.02.079

Mojahedimotlagh, F., Nasab, E. A., Foroutan, R., Vakilabadi, D. R., Dobaradaran, S., & Azamateslamtalab, B. (2024). Azithromycin decomposition from simple and complex waters by H_2O_2 activation over a recyclable catalyst of clay modified with nanofiltration process brine. *Environmental Technology & Innovation, 33*(2), Article 103512. https://doi.org/10.1016/j.eti.2023.103512

Muller, J. F. (1992). Geographical distribution and seasonal variation of surface emissions and deposition velocities of atmospheric trace gases. *Journal of Geophysical Research-Atmospheres, 97*(D4), 3787–3804. https://doi.org/10.1029/91JD02757

Nasab, E. A., Nasseh, N., Damavandi, S., Amarzadeh, M., Ghahrchi, M., Hoseinkhani, A., Alver, A., Khan, N. A., Farhadi, A., & Danaee, I. (2023). Efficient purification of aqueous solutions contaminated with sulfadiazine by coupling electro-Fenton/ultrasound process: Optimization, DFT calculation, and innovative study of human health risk assessment. *Environmental Science and Pollution Research, 30*(7), 84200–84218. https://doi.org/10.1007/s11356-023-28235-z

Nien, K. C., Chang, F. T., & Chang, M. B. (2017). Adsorption of mesitylene via mesoporous adsorbents. *Journal of the Air & Waste Management Association, 67*(12), 1319–1327. https://doi.org/10.1080/10962247.2017.1359701

Oh, K. J., Park, D. W., Kim, S. S., & Park, S. W. (2010). Breakthrough data analysis of adsorption of volatile organic compounds on granular activated carbon. *Korean Journal of Chemical Engineering, 27*(3), 632–638. https://doi.org/10.1007/s11814-010-0079-9

Ojha, D. P., Song, J. H., & Kim, H. J. (2019). Facile synthesis of graphitic carbon-nitride supported antimony-doped tin oxide nanocomposite and its application for the adsorption of volatile organic compounds. *Journal of Environmental Sciences, 79*(5), 35–42. https://doi.org/10.1016/j.jes.2018.10.008

Ok, R. A., & Kutluay, S. (2023). Designing novel perlite-Fe_3O_4@SiO_2@8-HQ-5-SA as a promising magnetic nanoadsorbent for competitive adsorption of multicomponent VOCs. *Chemosphere, 338*(10), 139636. https://doi.org/10.1016/j.chemosphere.2023.139636

Omidfar, N., Mohamadalizadeh, A., & Mousavi, S. H. (2015). Carbon dioxide adsorption by modified carbon nanotubes. *Asia-Pacific Journal of Chemical Engineering, 10*(6), 885–892. https://doi.org/10.1002/apj.1925

Pan, B., & Xing, B. (2008). Adsorption mechanisms of organic chemicals on carbon nanotubes. *Environmental Science & Technology, 42*(24), 9005–9013. https://doi.org/10.1021/es801777n

Pauletto, P. S., & Bandosz, T. J. (2022). Activated carbon versus metal-organic frameworks: A review of their PFAS adsorption performance. *Journal of Hazardous Materials, 425*(3), 127810. https://doi.org/10.1016/j.jhazmat.2021.127810

Pei, Y., Qin, J., Wang, J., & Hu, Y. (2021). Fe-based metal organic framework derivative with enhanced Lewis acidity and hierarchical pores for excellent adsorption of oxygenated volatile organic compounds. *Science of the Total Environment, 790*(10), Article 148132. https://doi.org/10.1016/j.scitotenv.2021.148132

Peng, W., Li, H., Liu, Y., & Song, S. (2017). A review on heavy metal ions adsorption from water by graphene oxide and its composites. *Journal of Molecular Liquids, 230*(3), 496–504. https://doi.org/10.1016/j.molliq.2017.01.064

Peng, C., Fu, X., Niu, Z., Sun, W., & Yue, T. (2025). Protonation behavior study of the active sites on typical sulfide minerals surface using surface complexation model. *Colloids and Surfaces a: Physicochemical and Engineering Aspects, 710*(4), 136307. https://doi.org/10.1016/j.colsurfa.2025.136307

Qi, J., Wei, G., Li, Y., Li, J., Sun, X., Shen, J., Han, W., & Wang, L. (2018). Porous carbon spheres for simultaneous removal of benzene and H_2S. *Chemical Engineering Journal, 339*(5), 499–508. https://doi.org/10.1016/j.cej.2018.01.157

Qian, Q., Gong, C., Zhang, Z., & Yuan, G. (2015). Removal of VOCs by activated carbon microspheres derived from polymer: A comparative study. *Adsorption, 21*(5), 333–341. https://doi.org/10.1007/s10450-015-9673-9

Qu, F., Zhu, L., & Yang, K. (2009). Adsorption behaviors of volatile organic compounds (VOCs) on porous clay heterostructures (pch). *Journal of Hazardous Materials, 170*(1), 7–12. https://doi.org/10.1016/j.jhazmat.2009.05.027

Rajabi, H., Mosleh, M. H., Prakoso, T., Ghaemi, N., Mandal, P., Langton, A. L., & Sedighi, M. (2021). Competitive adsorption of multicomponent volatile organic compounds on biochar. *Chemosphere, 283*(11), 131288. https://doi.org/10.1016/j.chemosphere.2021.131288

Ramos, M. E., Bonelli, P. R., Cukierman, A. L., Carrott, M. M. L. R., & Carrott, P. J. M. (2010). Adsorption of volatile organic compounds onto activated carbon cloths derived from a novel regenerated cellulosic precursor. *Journal of Hazardous Materials, 177*(1–3), 175–182. https://doi.org/10.1016/j.jhazmat.2009.12.014

Raptopoulou, C. P. (2021). Metal-organic frameworks: Synthetic methods and potential applications. *Materials, 14*(2), 310. https://doi.org/10.3390/ma14020310

Rodenas, M. A. L., Cazorla-Amoros, D., & Linares-Solano, A. (2005). Behavior of activated carbons with different pore size distributions and surface oxygen groups for benzene and toluene adsorption at low concentrations. *Carbon, 43*(8), 1758–1767. https://doi.org/10.1016/j.carbon.2005.02.023

Rodenas, M. A. L., Amoros, D. C., & Solano, A. L. (2011). Benzene and toluene adsorption at low concentration on activated carbon fibres. *Adsorption, 17*(6), 473–481. https://doi.org/10.1007/s10450-010-9301-7

Romero-Anaya, A. J., Lillo-Rodenas, M. A., & Linares-Solano, A. (2010). Spherical activated carbons for low concentration toluene adsorption. *Carbon, 48*(9), 2625–2633. https://doi.org/10.1016/j.carbon.2010.03.067

Saghir, S., Pu, C., Fu, E., Wang, Y., & Xiao, Z. (2022). Synthesis of high surface area porous biochar obtained from pistachio shells for the efficient adsorption of organic dyes from polluted water. *Surfaces and Interfaces, 34*(11), 102357. https://doi.org/10.1016/j.surfin.2022.102357

Saifurrehman, M., Kim, I., Rashid, N., Umer, M.A., Sajid, M., & Han, J. (2016). Adsorption of brilliant green dye on biochar prepared from lignocellulosic bioethanol plant waste. *Clean – Soil Air Water, 44(1),* 55–62. https://doi.org/10.1002/clen.201300954

Salmankhani, A., Khadem, S. S. M., Seidi, F., Mashhadzadeh, A. H., Zarrintaj, P., Habibzadeh, S., Mohaddespour, A., Rabiee, N., Lima, E. C., Shokouhimehr, M., Varma, R. S., & Saeb, M. R. (2021). Adsorption onto zeolites: Molecular perspective. *Chemical Papers, 75*(12), 6217–6239. https://doi.org/10.1007/s11696-021-01817-2

Sangon, S., Hunt, A. J., Attard, T. M., Mengchang, P., Ngernyen, Y., & Supanchaiyamat, N. (2018). Valorisation of waste rice straw for the production of highly effective carbon-based adsorbents for dyes removal. *Journal of Cleaner Production, 172*(1), 1128–1139. https://doi.org/10.1016/j.jclepro.2017.10.210

Sekiya, Y., Sugiyama, H., Sagisaka, K., Kondo, A., & Hattori, Y. (2018). Restricted adsorption of carbon dioxide gas in fluorinated single-walled carbon nanotubes. *Fullerenes, Nanotubes and Carbon Nanostructures, 26*(11), 746–750. https://doi.org/10.1080/1536383X.2018.1493460

Sewu, D., Boakye, P., & Woo, S. H. (2017). Highly efficient adsorption of cationic dye by biochar produced with Korean cabbage waste. *Bioresource Technology, 224*(1), 206–213. https://doi.org/10.1016/j.biortech.2016.11.009

Shan, R., Shi, Y., Gu, J., Wang, Y., & Yuan, H. (2020). Single and competitive adsorption affinity of heavy metals toward peanut shell-derived biochar and its mechanisms in aqueous systems. *Chinese Journal of Chemical Engineering, 28*(5), 1375–1383. https://doi.org/10.1016/j.cjche.2020.02.012

Shih, Y., & Li, M. (2008). Adsorption of selected volatile organic vapors on multiwall carbon nanotubes. *Journal of Hazardous Materials, 154*(1–3), 21–28. https://doi.org/10.1016/j.jhazmat.2007.09.095

Shin, W. S. (2017). Adsorption characteristics of phenol and heavy metals on biochar from *Hizikia fusiformis*. *Environmental Earth Sciences, 76*, 782. https://doi.org/10.1007/s12665-017-7125-4

Shiue, A., Kang, Y. H., Hu, S. C., Jou, G., Lin, C. H., & Hu, M. C. (2010). Vapor adsorption characteristics of toluene in an activated carbon adsorbent-loaded nonwoven fabric media for chemical filters applied to cleanrooms. *Building and Environment, 45*(10), 2123–2131. https://doi.org/10.1016/j.buildenv.2010.03.008

Shkolin, A. V., Fomkin, A. A., Yakovlev, V. Y., & Men'shchikov, I. E. (2018). Model nanoporous supramolecular structures based on carbon nanotubes and hydrocarbons for methane and hydrogen adsorption. *Colloid Journal, 80*(11), 739–750. https://doi.org/10.1134/S1061933X18060157

Shokoohi, T., Khosravan, M., & Nejad, F. K. (2015). Adsorption of metal ions under chemically modified silica gel with the presence of aza crown ether at physiological pH. *Toxin Reviews, 34*(4), 210–214. https://doi.org/10.3109/15569543.2015.1132469

Shoukat, R., & Khan, M. I. (2021). Carbon nanotubes: A review on properties, synthesis methods and applications in micro and nanotechnology. *Microsystem Technologies, 27*(12), 4183–4192. https://doi.org/10.1007/s00542-021-05211-6

Shu, S., Guo, J., Liu, X., Wang, X., Yin, H., & Luo, D. (2016). Effects of pore sizes and oxygen-containing functional groups on desulfurization activity of Fe/NAC prepared by ultrasonic-assisted impregnation. *Applied Surface Science, 360(Part B),* 684–692. https://doi.org/10.1016/j.apsusc.2015.11.046

Sigot, L., Ducom, G., & Germain, P. (2015). Adsorption of octamethylcyclotetrasiloxane (D4) on silica gel (SG): Retention mechanism. *Microporous and Mesoporous Materials, 213*(9), 118–124. https://doi.org/10.1016/j.micromeso.2015.04.016

Singh, H. B., Tabazadeh, A., Evans, M. J., Field, B. D., Jacob, D. J., Sachse, G., Crawford, J. H., Shetter, R., & Brune, W. H. (2003). Oxygenated volatile organic chemicals in the oceans: Inferences and implications based on atmospheric observation sand air-sea exchange models. *Geophysical Research Letters, 30*(16), 1–5. https://doi.org/10.1029/2003GL017933

Singh, V. K., Soni, A. B., & Singh, R. K. (2016). Process optimization studies of malachite green dye adsorption onto eucalyptus (*Eucalyptus globulus*) wood biochar using response surface methodology. *Oriental Journal of Chemistry, 32*(5), 2621–2631. https://doi.org/10.13005/ojc/320534

Solangi, N. H., Mubarak, N. M., Karri, R. R., Mazari, S. A., Kailasa, S. K., & Alfantazi, A. (2023). Applications of advanced MXene-based composite membranes for sustainable water desalination. *Chemosphere, 314*(2), 137643. https://doi.org/10.1016/j.chemosphere.2022.137643

Somer, T. D., Minh, T. N. L., Roosen, M., Nachtergaele, P., Manhaeghe, D., Laere, T. V., Schlummer, M., Geem, K. M. V., & Meester, S. D. (2024). Application of chemometric tools in the QSAR development of VOCS removal in plastic waste recycling. *Chemosphere, 350*(2), 141069. https://doi.org/10.1016/j.chemosphere.2023.141069

Song, M., Zhang, W., Chen, Y., Luo, J., & Crittenden, J. C. (2017). The preparation and performance of lignin-based activated carbon fiber adsorbents for treating gaseous streams. *Frontiers of Chemical Science and Engineering, 11*(9), 328–337. https://doi.org/10.1007/s11705-017-1646-y

Srikhaow, A., Chaengsawang, W., Kiatsiriroat, T., Kajitvichyanukul, P., & Smith, S. M. (2022). Adsorption kinetics of imidacloprid, acetamiprid and methomyl pesticides in aqueous solution onto eucalyptus woodchip derived

biochar. *Minerals, 12*(5), 528. https://doi.org/10.3390/min12050528

Su, Y. C., Kao, H. M., & Wang, J. L. (2010). Mesoporous silicate MCM-48 as an enrichment medium for ambient volatile organic compound analysis. *Journal of Chromatography A, 1217*(36), 5643–5651. https://doi.org/10.1016/j.chroma.2010.06.065

Sui, H., Liu, H., An, P., He, L., Li, X., & Cong, S. (2017). Application of silica gel in removing high concentrations toluene vapor by adsorption and desorption process. *Journal of the Taiwan Institute of Chemical Engineers, 74*(5), 218–224. https://doi.org/10.1016/j.jtice.2017.02.019

Sui, H., Wang, Z., He, L., Han, Z., & Li, X. (2019). Piecewise loading bed for reversible adsorption of VOCs on silica gels. *Journal of the Taiwan Institute of Chemical Engineers, 102*(9), 51–60. https://doi.org/10.1016/j.jtice.2019.05.025

Sulaiman, N. S., Hashim, R., Amini, M. H. M., Danish, M., & Sulaiman, O. (2018). Optimization of activated carbon preparation from cassava stem using response surface methodology on surface area and yield. *Journal of Cleaner Production, 198*(10), 1422–1430. https://doi.org/10.1016/j.jclepro.2018.07.061

Sun, X., Xia, Q., Zhao, Z., Li, Y., & Li, Z. (2014). Synthesis and adsorption performance of MIL-101(Cr)/graphite oxide composites with high capacities of n-hexane. *Chemical Engineering Journal, 239*(3), 226–232. https://doi.org/10.1016/j.cej.2013.11.024

Sun, L., Jiang, Z., Yuan, B., Zhi, S., Zhang, Y., Li, J., & Wu, A. (2021). Ultralight and superhydrophobic perfluorooctyltrimethoxysilane modified biomass carbonaceous aerogel for oil-spill remediation. *Chemical Engineering Research and Design, 174*(10), 71–78. https://doi.org/10.1016/j.cherd.2021.08.002

Szczesniak, B., Choma, J., & Jaroniec, M. (2018a). Gas adsorption properties of hybrid graphene-MOF materials. *Journal of Colloid and Interface Science, 514*(3), 801–813. https://doi.org/10.1016/j.jcis.2017.11.049

Szczesniak, B., Choma, J., & Jaroniec, M. (2018b). Effect of graphene oxide on the adsorption properties of ordered mesoporous carbons toward H_2, C_6H_6, CH_4 and CO_2. *Microporous and Mesoporous Materials, 261*(5), 105–110. https://doi.org/10.1016/j.micromeso.2017.10.054

Tan, X., Ma, X., Li, X., & Li, Y. (2025). An adsorption model considering fictitious stress. *Fractal and Fractional, 9*(1), 17. https://doi.org/10.3390/fractalfract9010017

Tang, D., Zheng, Z., Lin, K., Luan, J., & Zhang, J. (2007). Adsorption of p-nitrophenol from aqueous solutions onto activated carbon fiber. *Journal of Hazardous Materials, 143*(1–2), 49–56. https://doi.org/10.1016/j.jhazmat.2006.08.066

Tulaphol, S., Bunsan, S., Kanchanatip, E., Miao, H. Y., & Grisdanurak, N. (2016). Influence of chlorine substitution on adsorption of gaseous chlorinated phenolics on multi-walled carbon nanotubes embedded in SiO_2. *International Journal of Environmental Science and Technology, 13*(6), 1465–1474. https://doi.org/10.1007/s13762-016-0984-5

Twumasi, E., Forslund, M., Norberg, P., & Sjostrom, C. (2012). Carbon–silica composites prepared by the precipitation method. Effect of the synthesis parameters on textural characteristics and toluene dynamic adsorption. *Journal of Porous Materials, 19*(6), 333–343. https://doi.org/10.1007/s10934-011-9479-4

Vellingiri, K., Kumar, P., Deep, A., & Kim, K. H. (2017). Metal-organic frameworks for the adsorption of gaseous toluene under ambient temperature and pressure. *Chemical Engineering Journal, 307*(1), 1116–1126. https://doi.org/10.1016/j.cej.2016.09.012

Viegas, R. M. C., Mestre, A. S., Mesquita, E., Campinas, M., Andrade, M. A., Carvalho, A. P., & Rosa, M. J. (2020). Assessing the applicability of a new carob waste-derived powdered activated carbon to control pharmaceutical compounds in wastewater treatment. *Science of the Total Environment, 743*(11), 140791. https://doi.org/10.1016/j.scitotenv.2020.140791

Vikramaditya, T., & Sumithra, K. (2014). Effect of substitutionally boron-doped single-walled semiconducting zigzag carbon nanotubes on ammonia adsorption. *Journal of Computational Chemistry, 35*(7), 586–594. https://doi.org/10.1002/jcc.23526

Vikrant, K., Kim, K. H., Peng, W., Ge, S., & Ok, Y. S. (2020). Adsorption performance of standard biochar materials against volatile organic compounds in air: A case study using benzene and methyl ethyl ketone. *Chemical Engineering Journal, 387*(5), 123943. https://doi.org/10.1016/j.cej.2019.123943

Vinodh, R., Jung, E. M., Ganesh, M., Peng, M. M., Abidov, A., Palanichamy, M., Cha, W. S., & Jang, H. T. (2015). Novel microporous hypercross-linked polymers as sorbent for volatile organic compounds and CO_2 adsorption. *Journal of Industrial and Engineering Chemistry, 21*(1), 1231–1238. https://doi.org/10.1016/j.jiec.2014.05.039

Wang, H., Lashaki, M. J., Fayaz, M., Hashisho, Z., Philips, J. H., Anderson, J. E., & Nichols, M. (2012). Adsorption and desorption of mixtures of organic vapors on beaded activated carbon. *Environmental Science & Technology, 46*(15), 8341–8350. https://doi.org/10.1021/es3013062

Wang, S., Sun, H., Ang, H. M., & Tade, M. O. (2013). Adsorptive remediation of environmental pollutants using novel graphene-based nanomaterials. *Chemical Engineering Journal, 226*(6), 336–347. https://doi.org/10.1016/j.cej.2013.04.070

Wang, S., Zhang, L., Long, C., & Li, A. (2014). Enhanced adsorption and desorption of VOCs vapor on novel micro-mesoporous polymeric adsorbents. *Journal of Colloid and Interface Science, 428*(8), 185–190. https://doi.org/10.1016/j.jcis.2014.04.055

Wang, G., Dou, B., Zhang, Z., Wang, J., Liu, H., & Hao, Z. (2015a). Adsorption of benzene, cyclohexane and hexane on ordered mesoporous carbon. *Journal of Environmental Sciences, 30*(4), 65–73. https://doi.org/10.1016/j.jes.2014.10.015

Wang, W. Q., Wang, J., Chen, J. G., Fan, X. S., Liu, Z. T., Liu, Z. W., Jiang, J., & Hao, Z. (2015b). Synthesis of novel hyper-cross-linked polymers as adsorbent for removing organic pollutants from humid streams. *Chemical Engineering Journal, 281*(12), 34–41. https://doi.org/10.1016/j.cej.2015.06.095

Wang, J., Wang, W. Q., Hao, Z., Wang, G., Li, Y., Chen, J. G., Li, M., Cheng, J., & Liu, Z. T. (2016). A

superhydrophobic hyper-cross-linked polymer synthesized at room temperature used as an efficient adsorbent for volatile organic compounds. *RSC Advances, 6*(99), 97048–97054. https://doi.org/10.1039/C6RA18687D

Wang, Z., Lai, C., Qin, L., Fu, Y., He, J., Huan, D., Li, B., Zhang, M., Liu, S., Li, L., Zhang, W., Yi, H., Liu, X., & Zhou, X. (2020). ZIF-8-modified $MnFe_2O_4$ with high crystallinity and superior photo-Fenton catalytic activity by Zn-O-Fe structure for TC degradation. *Chemical Engineering Journal, 392*(7), 124851. https://doi.org/10.1016/j.cej.2020.124851

Wang, H., Bayatpour, S., Qian, X., Frigo-Vaz, B., & Wang, P. (2021). Activated carbon fibers via reductive carbonization of cellulosic biomass for adsorption of nonpolar volatile organic compounds. *Colloids and Surfaces a: Physicochemical and Engineering Aspects, 612*(3), 125908. https://doi.org/10.1016/j.colsurfa.2020.125908

Wang, Z., Liu, L., Tian, G., Ren, T., Qi, Z., & Li, G. K. (2023). Effect of isopropanol on CO_2 capture by activated carbon: Adsorption performance and regeneration capacity. *Chemical Engineering Research and Design, 196*(8), 632–641. https://doi.org/10.1016/j.cherd.2023.06.056

Worku, Z., Tibebu, S., Nure, J. F., Tibebu, S., Moyo, W., Ambaye, A. D., & Nkambule, T. T. I. (2023). Adsorption of chromium from electroplating wastewater using activated carbon developed from water hyacinth. *BMC Chemistry, 17*, 85–101. https://doi.org/10.1186/s13065-023-00993-4

Wu, L., & Yang, L. (2023). A novel micro-sphere activated carbon synthesized from waste cigarette butts for ammonia adsorption. *Waste Management, 168*(8), 396–405. https://doi.org/10.1016/j.wasman.2023.06.017

Wu, J., Zhang, L., Long, C., & Zhang, Q. X. (2012). Adsorption characteristics of pentane, hexane, and heptane: Comparison of hydrophobic hypercrosslinked polymeric adsorbent with activated carbon. *Journal of Chemical and Engineering Data, 57*(12), 3426–3433. https://doi.org/10.1021/je300550x

Wu, S., Wang, Y., Sun, C., Zhao, T., Zhao, J., Wang, Z., Liu, W., Lu, J., Shi, M., Zhao, A., Bu, L., Wang, Z., Yang, M., & Zhi, Y. (2021). Novel preparation of binder-free Y/ZSM-5 zeolite composites for VOCs adsorption. *Chemical Engineering Journal, 417*(8), Article 129172. https://doi.org/10.1016/j.cej.2021.129172

Xiang, W., Zhang, X., Chen, K., Fang, J., He, F., Hu, X., Tsang, D. C. W., Ok, Y. S., & Gao, B. (2020). Enhanced adsorption performance and governing mechanisms of ball-milled biochar for the removal of volatile organic compounds (VOCs). *Chemical Engineering Journal, 385*(4), 123842. https://doi.org/10.1016/j.cej.2019.123842

Xie, Y., Lyu, S., Zhang, Y., & Cai, C. (2022). Adsorption and degradation of volatile organic compounds by metal-organic frameworks (MOFs): A review. *Materials, 15*(21), 7727. https://doi.org/10.3390/ma15217727

Xing, L., Yang, F., Zhong, X., Liu, Y., Lu, H., Guo, Z., Lv, G., Yang, J., Yuan, A., & Pan, J. (2023). Ultra-microporous cotton fiber-derived activated carbon by a facile one-step chemical activation strategy for efficient CO_2 adsorption. *Separation and Purification Technology, 324*(11), 124470. https://doi.org/10.1016/j.seppur.2023.124470

Xu, C., Ruan, C. Q., Li, Y., Lindh, J., & Stromme, M. (2017). High-performance activated carbons synthesized from nanocellulose for CO_2 capture and extremely selective removal of volatile organic compounds. *Advanced Sustainable Systems, 2*(2), 1700147. https://doi.org/10.1002/adsu.201700147

Yaghi, O. M., Li, G. M., & Li, H. L. (1995). Selective binding and removal of guests in a microporous metal-organic framework. *Nature, 378*, 703–706. https://doi.org/10.1038/378703a0

Yan, T., Li, T. X., Wang, R. Z., & Jia, R. (2015). Experimental investigation on the ammonia adsorption and heat transfer characteristics of the packed multi-walled carbon nanotubes. *Applied Thermal Engineering, 77*(2), 20–29. https://doi.org/10.1016/j.applthermaleng.2014.12.001

Yan, Y., Peng, L., Li, R., Li, Y., Li, L., & Bai, H. (2017). Concentration, ozone formation potential and source analysis of volatile organic compounds (VOCs) in a thermal power station centralized area: A study in Shuozhou. *Environmental Pollution, 223*(4), 295–304. https://doi.org/10.1016/j.envpol.2017.01.026

Yang, T., & Lua, A. C. (2003). Characteristics of activated carbons prepared from pistachio-nut shells by potassium hydroxide activation. *Microporous and Mesoporous Materials, 63*(1–3), 113–124. https://doi.org/10.1016/S1387-1811(03)00456-6

Yang, K., Sun, Q., Xue, F., & Lin, D. (2011). Adsorption of volatile organic compounds by metal–organic frameworks MIL-101: Influence of molecular size and shape. *Journal of Hazardous Materials, 195*(11), 124–131. https://doi.org/10.1016/j.jhazmat.2011.08.020

Yang, K., Xue, F., Sun, Q., Yue, R., & Lin, D. (2013). Adsorption of volatile organic compounds by metal-organic frameworks MOF-177. *Journal of Environmental Chemical Engineering, 1*(4), 713–718. https://doi.org/10.1016/j.jece.2013.07.005

Yang, Y., Lin, X., Wei, B., Zhao, Y., & Wang, J. (2014). Evaluation of adsorption potential of bamboo biochar for metal-complex dye: Equilibrium, kinetics and artificial neural network modelling. *International Journal of Environmental Science and Technology, 11*(5), 1093–1100. https://doi.org/10.1007/s13762-013-0306-0

Yang, G., Wu, L., Xian, Q., Shen, F., Wu, J., & Zhang, Y. (2016). Removal of Congo red and methylene blue from aqueous solutions by vermicompost-derived biochars. *PLoS ONE, 11*(5), e0154562. https://doi.org/10.1371/journal.pone.0154562

Yang, S., Zhu, Z., Wei, F., & Yang, X. (2017). Enhancement of formaldehyde removal by activated carbon fiber via in situ growth of carbon nanotubes. *Building and Environment, 126*(12), 27–33. https://doi.org/10.1016/j.buildenv.2017.09.025

Yang, C., Miao, G., Pi, Y., Xia, Q., Wu, J., Li, Z., & Xiao, J. (2019a). Abatement of various types of VOCs by adsorption/catalytic oxidation: A review. *Chemical Engineering Journal, 370*(8), 1128–1153. https://doi.org/10.1016/j.cej.2019.03.232

Yang, P., Song, M., Kim, D., Jung, S. P., & Hwang, Y. (2019b). Synthesis conditions of porous clay heterostructure (PCH) optimized for volatile organic compounds (VOCS) adsorption. *Korean Journal of Chemical*

Engineering, 36(11), 1806–1813. https://doi.org/10.1007/s11814-019-0369-9

Yang, Z., Hu, W., Yao, B., Shen, L., Jiang, F., Zhou, Y., & Nunez-Delgado, A. (2021). A novel manganese-rich pokeweed biochar for highly efficient adsorption of heavy metals from wastewater: Performance, mechanisms, and potential risk analysis. *Processes, 9*(7), 1209. https://doi.org/10.3390/pr9071209

Yang, S. Y., Bai, B. C., & Kim, Y. R. (2024). Effective Surface Structure Changes and Characteristics of Activated Carbon with the Simple Introduction of Oxygen Functional Groups by Using Radiation Energy. *Surfaces, 7*(1), 12–25. https://doi.org/10.3390/surfaces7010002

Yao, H., Lu, J., Wu, J., Lu, Z., Wilson, P. C., & Shen, Y. (2013). Adsorption of Fluoroquinolone Antibiotics by Wastewater Sludge Biochar: Role of the Sludge Source. *Water, Air, & Soil Pollution, 224*, 1370–1378. https://doi.org/10.1007/s11270-012-1370-7

Yin, T., Meng, X., Wang, S., Yao, X., Liu, N., & Shi, L. (2022). Study on the adsorption of low-concentration VOCs on zeolite composites based on chemisorption of metal-oxides under dry and wet conditions. *Separation and Purification Technology, 280*(1), 119634. https://doi.org/10.1016/j.seppur.2021.119634

Yu, W., Deng, L., Yuan, P., Liu, D., Yuan, W., & Chen, F. (2015a). Preparation of hierarchically porous diatomite/MFI-type zeolite composites and their performance for benzene adsorption: The effects of desilication. *Chemical Engineering Journal, 270*(6), 450–458. https://doi.org/10.1016/j.cej.2015.02.065

Yu, W., Yuan, P., Liu, D., Deng, L., Yuan, W., Tao, B., Cheng, H., & Chen, F. (2015b). Facile preparation of hierarchically porous diatomite/MFI-type zeolite composites and their performance of benzene adsorption: The effects of NaOH etching pretreatment. *Journal of Hazardous Materials, 285*(3), 173–181. https://doi.org/10.1016/j.jhazmat.2014.11.034

Yu, F., Li, Y., Han, S., & Ma, J. (2016). Adsorptive removal of antibiotics from aqueous solution using carbon materials. *Chemosphere, 153*(6), 365–385. https://doi.org/10.1016/j.chemosphere.2016.03.083

Yu, L., Wang, L., Xu, W., Chen, L., Fu, M., Wu, J., & Ye, D. (2018a). Adsorption of VOCs on reduced graphene oxide. *Journal of Environmental Sciences, 67*(5), 171–178. https://doi.org/10.1016/j.jes.2017.08.022

Yu, X., Liu, S., Lin, G., Zhu, X., Zhang, S., Qu, R., Zheng, C., & Gao, X. (2018b). Insight into the significant roles of microstructures and functional groups on carbonaceous surfaces for acetone adsorption. *RSC Advances, 8*(38), 21541–21550. https://doi.org/10.1039/C8RA03099E

Yu, M., Ren, Y., Guo, M., Ren, B., Xiong, G., Ding, F., You, L., & Sun, Y. (2024). Hydrophobic hypercrosslinked polymers prepared by secondary pore-forming method as excellent toluene adsorbents. *Separation and Purification Technology, 351*(12), 128115. https://doi.org/10.1016/j.seppur.2024.128115

Yuan, W., Yuan, P., Liu, D., Deng, L., Zhou, J., Yu, W., & Chen, F. (2016). A hierarchically porous diatomite/silicalite-1 composite for benzene adsorption/desorption fabricated via a facile pre-modification in situ synthesis route. *Chemical Engineering Journal, 294*(6), 333–342. https://doi.org/10.1016/j.cej.2016.02.099

Yuan, J., Amano, Y., & Machida, M. (2021). Surface characterization of mesoporous biomass activated carbon modified by thermal chemical vapor deposition and adsorptive mechanism of nitrate ions in aqueous solution. *Colloids and Surfaces a: Physicochemical and Engineering Aspects, 616*(5), 126213. https://doi.org/10.1016/j.colsurfa.2021.126213

Yue, Z., Vakili, A., & Wang, J. (2017). Activated carbon fibers from meltblown isotropic pitch fiber webs for vapor phase adsorption of volatile organic compounds. *Chemical Engineering Journal, 330*(12), 183–190. https://doi.org/10.1016/j.cej.2017.07.150

Yuvaraj, P., Rao, J. R., Fathima, N. S., Natchimuthu, N., & Mohan, R. (2018). Complete replacement of carbon black filler in rubber sole with CaO embedded activated carbon derived from tannery solid waste. *Journal of Cleaner Production, 170*(1), 446–450. https://doi.org/10.1016/j.jclepro.2017.09.188

Zare, K., Gupta, V. K., Moradi, O., Makhlouf, A. S. H., Sillanpaa, M., Nadagouda, M. N., Sadegh, H., Shahryari-ghoshekandi, R., Pal, A., Wang, Z., Tyagi, I., & Kazemi, M. (2015). A comparative study on the basis of adsorption capacity between CNTs and activated carbon as adsorbents for removal of noxious synthetic dyes: A review. *Journal of Nanostructure in Chemistry, 5*(6), 227–236. https://doi.org/10.1007/s40097-015-0158-x

Zavyalova, U., Nigrovski, B., Pollok, K., Langenhorst, F., Müller, B., Scholz, P., & Ondruschka, B. (2008). Gel-combustion synthesis of nanocrystalline spinel catalysts for VOCs elimination. *Applied Catalysis B: Environmental, 83*(3–4), 221–228. https://doi.org/10.1016/j.apcatb.2008.02.015

Zeng, F., Liao, X., Pan, D., & Shi, H. (2020). Adsorption of dissolved organic matter from landfill leachate using activated carbon prepared from sewage sludge and cabbage by $ZnCl_2$. *Environmental Science and Pollution Research, 27*(2), 4891–4904. https://doi.org/10.1007/s11356-019-07233-0

Zhang, K., Lively, R. P., Noel, J. D., Dose, M. E., McCool, B. A., Chance, R. R., & Koros, W. J. (2012). Adsorption of water and ethanol in MFI-type zeolites. *Langmuir, 28*(23), 8664–8673. https://doi.org/10.1021/la301122h

Zhang, Z., Lei, Y., Li, D., Zhao, J., Wang, Y., Zhou, G., Yan, C., & He, Q. (2020). Sudden heating of H_3PO_4-loaded coconut shell in CO_2 flow to produce super activated carbon and its application for benzene adsorption. *Renewable Energy, 153*(6), 1091–1099. https://doi.org/10.1016/j.renene.2020.02.059

Zhang, X., Miao, X., Xiang, W., Zhang, J., Cao, C., Wang, H., Hu, X., & Gao, B. (2021). Ball milling biochar with ammonia hydroxide or hydrogen peroxide enhances its adsorption of phenyl volatile organic compounds (VOCs). *Journal of Hazardous Materials, 403*(2), 123540. https://doi.org/10.1016/j.jhazmat.2020.123540

Zhang, T., Zhang, X., & Li, H. (2023). Kinetics and equilibrium study of phenol adsorption by activated carbon derived from pig blood. *Carbon Trends, 12*(9), 100281. https://doi.org/10.1016/j.cartre.2023.100281

Zhao, Y. T., Yu, L. Q., Xia, X., Yang, X. Y., Hu, W., & Lv, Y. K. (2018). Evaluation of the adsorption and desorption properties of zeolitic imidazolate framework-7 for volatile organic compounds through thermal desorption-gas chromatography. *Analytical Methods, 10*(40), 4894–4901. https://doi.org/10.1039/C8AY01856A

Zheng, F., Baldwin, D. L., Fifield, L. S., Anheier, N. C., Aardahl, C. L., & Grate, J. W. (2006). Single-walled carbon nanotube paper as a sorbent for organic vapor preconcentration. *Analytical Chemistry, 78*(7), 2442–2446. https://doi.org/10.1021/ac051524q

Zheng, Y., Chu, F., Zhang, B., Yan, J., & Chen, Y. (2018). Ultrahigh adsorption capacities of carbon tetrachloride on MIL-101 and MIL-101/graphene oxide composites. *Microporous and Mesoporous Materials, 263*(6), 71–76. https://doi.org/10.1016/j.micromeso.2017.12.007

Zheng, C., Kang, K., Xe, Y., Yang, X., Lan, L., Song, H., & Bai, S. (2023). Competitive adsorption and selectivity of water vapor/R134a on activated carbon for indoor air purification. *Separation and Purification Technology, 317*(7), 123741. https://doi.org/10.1016/j.seppur.2023.123741

Zhou, X., Huang, W., Shi, J., Zhao, Z., Xia, Q., Li, Y., Wang, H., & Li, Z. (2014). A novel MOF/ graphene oxide composite GrO@MIL-101 with high adsorption capacity for acetone. *Journal of Materials Chemistry A, 2*(13), 4722–4730. https://doi.org/10.1039/C3TA15086K

Zhu, H., Xu, C., Wu, D., Wei, B., Vajtai, R., & Ajayan, P. (2002). Direct synthesis of long single-walled carbon nanotube strands. *Science, 296*(5569), 884–886. https://doi.org/10.1126/science.1066996

Zhu, L., Tian, S., & Shi, Y. (2005). Adsorption of volatile organic compounds onto porous clay heterostructures based on spent organo-bentonites. *Clays and Clay Minerals, 53*(2), 123–136. https://doi.org/10.1346/CCMN.2005.0530202

Zhu, J. X., Zhang, P., Wang, Y. B., & Wen, K. (2017a). Effect of acid activation of palygorskite on their toluene adsorption behaviors. *Applied Clay Science, 159*(6), 60–67. https://doi.org/10.1016/j.clay.2017.07.019

Zhu, M., Hu, P., Tong, Z., Zhao, Z., & Zhao, Z. (2017b). Enhanced hydrophobic MIL(Cr) metal-organic framework with high capacity and selectivity for benzene VOCs capture from high humid air. *Chemical Engineering Journal, 313*(4), 1122–1131. https://doi.org/10.1016/j.cej.2016.11.008

Zhu, L., Shen, D., & Luo, K. H. (2020). A critical review on VOCs adsorption by different porous materials: Species, mechanisms and modification methods. *Journal of Hazardous Materials, 389*(5), 122102. https://doi.org/10.1016/j.jhazmat.2020.122102

Zhu, H., Gong, L., Jiang, L., Liu, X., Hu, L., Wu, W., Lin, D., & Yang, K. (2024). Green synthesis of a superhydrophobic porous organic polymer for the removal of volatile organic compounds at high humidity. *Science of the Total Environment, 946*(10), 174073. https://doi.org/10.1016/j.scitotenv.2024.174073