3-24-2022

Activated Carbon as Superadsorbent and Sustainable Material for Diverse Applications

Gaurav Sharma
Shenzhen University; Shoolini University; Instituto de Productos Naturales y Agrobiología; Glocal University

Shweta Sharma
Shoolini University

Amit Kumar
Shenzhen University; Shoolini University

Chin Wei Lai
University of Malaya

Mu. Naushad
King Saud University; Yonsei University

See next page for additional authors

Recommended Citation

Sharma, Gaurav; Sharma, Shweta; Kumar, Amit; Lai, Chin Wei; Naushad, Mu.; Shehnaz (Panjab University, Shehnaz (Panjab University; Iqbal, Jibran; and Stadler, Florian J., "Activated Carbon as Superadsorbent and Sustainable Material for Diverse Applications" (2022). *All Works*. 4968.
https://zuscholars.zu.ac.ae/works/4968

Author First name, Last name, Institution
Gaurav Sharma, Shweta Sharma, Amit Kumar, Chin Wei Lai, Mu. Naushad, Shehnaz (Panjab University Shehnaz (Panjab University, Jibran Iqbal, and Florian J. Stadler

Hindawi
Adsorption Science & Technology
Volume 2022, Article ID 4184809, 21 pages
https://doi.org/10.1155/2022/4184809

Review Article

Activated Carbon as Superadsorbent and Sustainable Material for Diverse Applications

Gaurav Sharma,[1,2,3,4] **Shweta Sharma**,[2] **Amit Kumar**,[1,2] **Chin Wei Lai**,[5] **Mu. Naushad**,[6,7] **Shehnaz**,[8] **Jibran Iqbal**,[9] **and Florian J. Stadler**[1]

[1] *College of Materials Science and Engineering, Shenzhen Key Laboratory of Polymer Science and Technology, Guangdong Research Center for Interfacial Engineering of Functional Materials, Nanshan District Key Laboratory for Biopolymers and Safety Evaluation, Shenzhen University, Shenzhen 518060, China*
[2] *International Research Centre of Nanotechnology for Himalayan Sustainability (IRCNHS), Shoolini University, Solan, 173212 Himachal Pradesh, India*
[3] *Instituto de Productos Naturales y Agrobiología, Consejo Superior de Investigaciones Científicas (IPNA-CSIC), Avda. Astrofísico Fco. Sánchez 3, 38206 La Laguna, Tenerife, Spain*
[4] *School of Science and Technology, Glocal University, Saharanpur, India*
[5] *Nanotechnology & Catalysis Research Centre (NANOCAT), Institute for Advanced Studies, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[6] *Department of Chemistry, College of Science, King Saud University, Bldg. #5, Riyadh, Saudi Arabia*
[7] *Yonsei Frontier Lab, Yonsei University, Seoul, South Korea, Republic of Korea*
[8] *Department of Environment Studies, Panjab University, Chandigarh-160014, India*
[9] *College of Natural and Health Sciences, Zayed University, P.O. Box 144534, Abu Dhabi, UAE*

Correspondence should be addressed to Gaurav Sharma; gaurav8777@gmail.com

Received 4 October 2021; Accepted 11 January 2022; Published 24 March 2022

Academic Editor: Chinenye Adaobi Igwegbe

Activated carbon is a carbonaceous material with highly porous structure. Different functionalities can be introduced to its surface by various physical and chemical treatments. Various precursors can be used for the synthesis of activated carbon such as fossil fuels, agricultural wastes, and lignocellulosic wastes, etc. Number of papers have been reported in literature devoted to the synthesis, characterization, and various applications of activated carbon. Herein, in this review, special attention has been paid to the basic properties of activated carbon and its surface chemistry originated due to physical and chemical treatment. In addition, a general introduction to adsorption process, various adsorption isotherms, and adsorption kinetics is also included. A brief description of mechanism of adsorption onto activated carbon is also presented. At last, most probable applications of activated carbon such as adsorption of pollutants (e.g., dyes, heavy metal ions, pesticides, pharmaceutical waste products, and volatile organic organic), as catalyst support, anduse in food and pharmaceutical industries is also presented.

1. Introduction

1.1. Activated Carbon (AC). Activated carbon (AC) refers to the highly carbonaceous materials having high porosity and sorption ability produced from the wood, coconut shells, coal, and cones, etc. AC is one of the frequently used adsorbents utilized in various industries for the removal of numerous pollutants from water and air bodies. Since, AC synthesized from the agricultural and waste products, it has proved to be a great alternative to the traditionally used nonrenewable and expensive sources. For the preparation of AC, two basic processes, carbonization and activation, are used. In the first process, precursors are subjected to high temperatures, between 400 and 850°C, to expel out all the volatile components. High elevated temperature removes all the noncarbon components from the precursor such as hydrogen, oxygen, and nitrogen in the form of gases and tars. This process produces char having high-carbon content but low surface area and porosity. However, the second step involves the activation of previously synthesized char. Pore size enhancement during the activation process can be categorized into three: opening of previously inaccessible pores, new pore development by selective activation, and widening of existing pores.

Usually, two approaches, physical and chemical, are used for activation to get desired surface area and porosity. Physical activation involves the activation of carbonized char using oxidizing gases such as air, carbon dioxide, and steam at high temperatures (between 650 and 900°C). Carbon dioxide is usually preferred because of its pure nature, easy handling, and controllable activation process around 800°C. High pore uniformity can be obtained with carbon dioxide activation in comparison to steam. However, for physical activation, steam is much preferred as compared to carbon dioxide since AC with relatively high surface area can be produced. Due to the smaller molecule size of water, its diffusion within char's structure occurs efficiently. Activation by steam has been found to be around two to three times higher than carbon dioxide with same degree of conversion.

However, chemical approach involves the mixing of precursor with activating agents (NaOH, KOH, and $FeCl_3$, etc.). These activating agents acts as oxidants as well as dehydrating agents. In this approach, carbonization and activation is carried out simultaneously at comparatively lower temperature 300-500°C as compared to the physical approach. As a result, it effects the pyrolytic decomposition and, then, results in expansion of improved porous structure and high carbon yield. Major benefits of chemical over physical approach are the low temperature requirement, high microporosity structures, large surface area, and minimized reaction completion time.

The superiority of chemical activation method can be explained on the basis of a model proposed by Kim and his coworkers [1] according to which various spherical microdomains responsible for the formation of micropores are found in the AC. On the other hand, mesopores are developed in the intermicrodomain regions. Experimentally, they formed activated carbon from phenol-based resin by chemical (using KOH) and physical (using steam) activation (Figure 1). Results showed that AC synthesized by KOH activation possessed high surface area of 2878 m^2/g as compared to 2213 m^2/g by steam activation. In addition, other factors such as pore size, surface area, micropore volume, and average pore width were all found to be better in KOH-activated conditions as compared to steam activated.

Depending upon the particle size and method of preparation, it can be categorized into three types: powered AC, granular AC, and bead AC. Powered AC is formed from fine granules having size 1 mm with average diameter range of 0.15-0.25 mm. Granular AC has comparatively larger size and less external surface area. Granular AC are used for various liquid phase and gaseous phase applications depending upon their dimension ratios. Third class: bead AC is generally synthesized from the petroleum pitch with diameter ranging from 0.35 to 0.8 mm. It is known for its high mechanical strength and low dust content. It is extensively utilized in fluidized bed applications such as water filtration due to its spherical structure.

1.1.1. Surface Chemistry of AC. Surface chemistry of AC is greatly influenced by the type of heteroatom present on its surface such as nitrogen, phosphorus, sulfur, and oxygen. The type of heteroatom present is determined from nature of activation process used. On the basis of type of group present, the surfaces of AC can be categorized into acidic and basic surfaces.

(1) Acidic AC. Groups present on the exterior surface determine the reactivity of AC. Presence of oxygen-containing compounds on the surface of AC contributes to its acidic character. Since the exterior sites constitutes the majority of adsorbent area, the concentration of such reactive groups influences the adsorption capability of AC to a great extent [2–5]. Oxygen-containing acidic groups include carboxylic, quinone, carbonyl, and pyrone, etc. Carboxylic groups can also exist in the form of carboxylic anhydride [6, 7]. Carboxylic acid, lactone, and phenolic hydroxyl groups are categorized as the sources of surface acidity. AC contains oxygen functionalities by the oxidation of gases and aqueous oxidants [7, 8]. For the gas phase treatment, oxygen, air, steam, and carbon dioxide can be used. During such processes, low temperature oxidations results into the development of strong acidic groups. However, high temperature oxidations create weak acid groups [9]. As compared to gas phase, liquid phase oxidation treatments can be used to introduce large amount of oxygen into the carbon moieties. Mixture of nitric acid and carboxylic acid exhibits strong oxidizing properties for introducing momentous oxygenated acidic functionalities such as carboxylic, phenolic hydroxyl, and lactone onto the AC surface [10]. Findings have validated that oxidation of AC in gas phase enhanced mainly due to the concentration of hydroxyl and carbonyl groups present on its surface; however, oxidation in liquid phase can integrate high amount of oxygen in the form of carboxylic and phenolic hydroxyl groups onto the AC surface at comparatively much lower temperatures in comparison to the gas phase oxidation.

(2) Basic AC. Basicity of activated carbon can be related to the resonating electrons of aromatic carbon rings and basic surface functionalities (e.g., nitrogen-containing groups) that are capable of binding with protons. In addition, some oxygen-containing functionalities such as ketone, pyrone, and chromene can also result into basic AC. In basic AC, present electrons act as Lewis bases. Increase in the quantification of nitrogen-containing groups increases the adsorbing ability of AC towards carbon dioxide. Nitrogen-containing functionalities can be hosted into AC either by reaction with nitrogen-containing reagents (such as NH_3, nitric acid, or amines) or activation with nitrogen-containing precursors. Basic AC interacts with acid

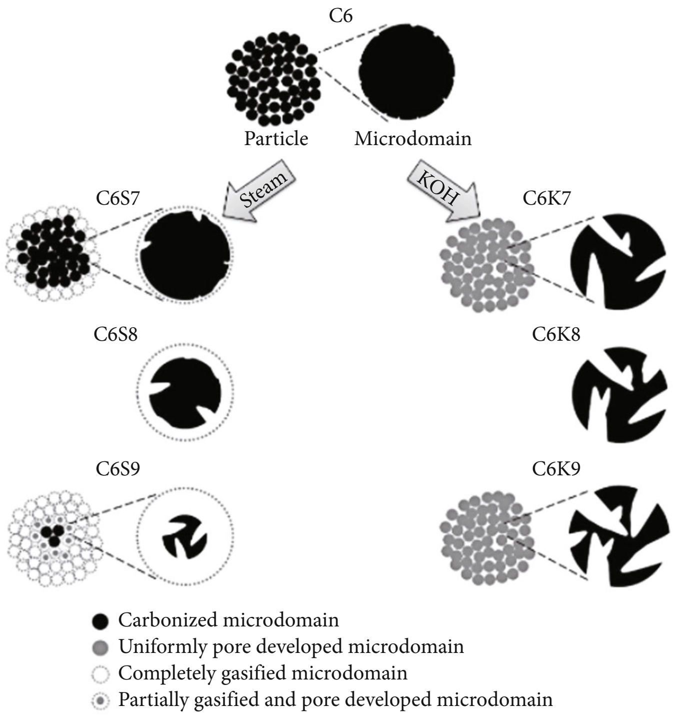


Figure 1: Differences between AC prepared from steam activation (C6S9) and KOH activation (C6K9), respectively, explained in terms of microstructure model [1].

molecules generally through dipole-dipole interactions, covalent bonding, and hydrogen bonding.

2. General Introduction to Adsorption Process

Adsorption is a surface phenomenon involving the adsorption of adsorbate molecules onto adsorbent. Basic principle involving the adsorption process is the variable surface energy. Urge to stabilize the surface energy results into interactions between the adsorbent surface and adsorbate molecules. Adsorption of pollutants onto adsorbent depends upon number of factors such as temperature, solution pH, adsorbate concentration, contact time, coexisting ions, temperature, and surface properties of adsorbent including maximum available surface area, pore size, and pore distribution. Adsorption can be classified into two categories: physical and chemical based on the type of interactions between adsorbate and adsorbent molecules. Chemical adsorption is categorized by the chemical interactions involving exchange of electrons between the two phases, thus forming permanent bonds and resulting in an irreversible process. However, physical adsorption involves the electrostatic, π-π interactions, Vander-Waal's interactions, or H-bonding, resulting into a reversible process [11, 12]. Figure 2 presents the basic terminologies used in adsorption process.

The electrical characteristics of adsorbent surface can easily be determined using two methods; point of zero charge (PZC) and isoelectric point (IEP). PZC determines the solution pH at which the surface charge equals to zero. It can be determined using pH drift method or potentiometric titration, etc. However, IEP occurs when the electrokinetic parameter at shear planes equals to zero. Major difference between the two is that the IEP determines only the external surface charge of adsorbent but PZC determines its internal as well as external surface charge. Difference of the two determines the internal surface charge of adsorbent.

During the adsorption experiments, the efficient performance of adsorbent is determined by its adsorption capacity which can be calculated using equation:

$$q_e = \frac{(C_0 - C_e)}{m} V, \tag{1}$$

where C_0 is the initial concentration of adsorbate in mg/L; C_e is the equilibrium concentration of adsorbate in mg/L; m represents the mass of adsorbent in grams; and V denotes the volume of total reaction solution in liters. m/V is defined to be the solid to liquid ratio. In addition, percent adsorption is also used for denoting the total adsorption occurred during a process which can be calculated using the formula [14]:

$$\%\ \text{Adsorption} = \frac{(C_0 - C_t)}{C_t} \times 100, \tag{2}$$

where C_0 represents the initial concentration of adsorbate in mg/L and C_t is the concentration of adsorbate at time t (minute) in mg/L. To some extent, percent adsorption causes error in the observation, so mostly, q_e is preferred over it.

Number of techniques has been put forward for environmental remediation purposes such as osmosis, photocatalysis, membrane filtration, and adsorption; out of all, adsorption has been found to be quite effective due to the low cost production of adsorbents, high efficiency, simple

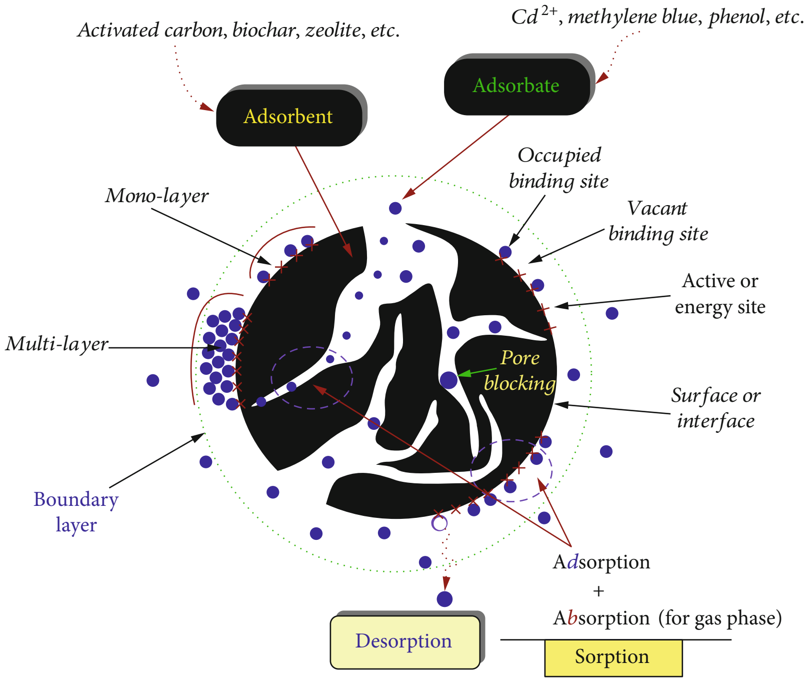


Figure 2: Basic terminologies used in adsorption process [13].

designing, and insensitivity to toxic pollutants, etc. This method not even produce toxic side products at the end of reaction. Number of toxic pollutants such as pesticides, organic dyes, metal ions, gases, and PPCPs can be removed using this technique. Table 1 presents the different carbon precursors and their surface area being used for adsorption of various pollutants.

2.1. Adsorption Isotherm. Adsorption isotherms help in evaluating the mechanism of adsorption of adsorbate molecules onto the adsorbent. In addition, models aids in determining the maximum adsorption capacity of adsorbent. Adsorption can be mono-layered or multilayered depending upon the type of interactions between adsorbate and adsorbent that can be easily determined from the Langmuir and Freundlich isotherm models, respectively. In addition to these two, some other isotherm models commonly used are Temkin, Redlich-Peterson, and Dubinin-Radushkevich isotherm model. Table 2 shows the linear equations and significance of various adsorption isotherm and kinetic models.

2.1.1. Langmuir Isotherm Model. Langmuir isotherm model assumes the adsorption of adsorbate molecules onto energetically homogeneous sites. It also generalizes that the interaction occurs by monolayer adsorption onto the adsorbent surface [28, 29]. Equations explaining this model have the linear as well as nonlinear forms and these are:

$$\begin{aligned} q_e &= \frac{q_m K_a C_e}{1 + K_a C_e} \quad \text{[Non-linear form]}, \\ \frac{C_e}{q_e} &= \frac{C_e}{q_m} + \frac{1}{K_a q_m} \quad \text{[Linear form]}, \end{aligned} \tag{3}$$

where q_e is the adsorption capacity of adsorbent at equilibrium in mg/g; q_m represents the maximum adsorption capacity in mg/g; K_a is the Langmuir constant in L/mg; and C_e is the equilibrium concentration of adsorbate in mg/L.

2.1.2. Freundlich Isotherm Model. Compared to Langmuir isotherm, Freundlich isotherm model assumes the adsorption of adsorbate molecules onto energetically heterogeneous sites. This model explains the multilayered adsorption of adsorbate. This model can be represented by the nonlinear equation as:

$$q_e = K_f C_e^{1/n}. \tag{4}$$

The linearized form of Freundlich isotherm model is

$$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e, \tag{5}$$

where q_e is the amount of metal ion adsorbed at equilibrium time (mg/g), C_e is the equilibrium concentration of dye in solution (mg/L), K_f is the capacity of the adsorbent, and n is the intensity of adsorption constant for Freundlich. The plot of ln q_e versus ln C_e is employed to determine the K_f and n from intercept and slope, respectively.

2.2. Adsorption Kinetics. Number of governing mechanisms such as mass transfer coefficient, chemical reaction, or diffusion control generalize the adsorption kinetic models. Kinetic studies help in determining the best reaction conditions for undertaking the adsorption experiment for full-

Table 1: Activated carbon precursors utilized for adsorption of various adsorbates.

Precursor	Surface area (m^2/g)	Adsorbate	Maximum adsorption capacity (mg/g)	Reference
Banana peel	<1038	Malachite green	22.5	[15]
Coconut shell	951.84	Phenol	23.745	[16]
Coal-derived carbon	936	NO	—	[17]
Macadamia nut shell	1524	Tetracycline	455.33	[18]
Char and by-products from woody biomass gasification	776.46	Rhodamine B	189.83	[19]
Grape bagasse	1455	Cu(II)	43.47	[20]
Cocoa shell	619	Diclofenac	63.47	[21]
Sucrose	1534	Methylene blue	704.20	[22]
Grape processing industry waste	1455	Metanil yellow	386	[23]
Longan seed	1511.80	Cr(VI)	169.49	[24]
Walnut wood	42.770	Pb(II)	58.823	[25]
Date seeds	798.38	CO_2	141.14	[26]
Pistachio wood waste	1448	Hg(II)	202	[27]

Table 2: Linear equation and significance of various isotherm and kinetic models.

Model	Equation	Significance	Plots
Langmuir	$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{K_a q_m}$	Signifies monolayer adsorption of adsorbate molecules onto adsorbent	C_e vs. C_e/q_e
Freundlich	$\ln q_e = \ln K_f + \frac{1}{n} \ln C_e$	Surface heterogeneity and exponential distribution of active sites and their energies	Log C_e vs. log q_e
Pseudofirst-order	$\log (q_e - q_t) = \log q_e - \frac{k_1}{2.303} t$	Adsorption at the solid-liquid interface	Time vs. log $(q_e - q_t)$
Pseudosecond-order	$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_t}$	Rate-limiting step in adsorption is controlled by chemical interactions	Time vs. t/q_t
Intraparticle diffusion	$q_t = k_{id} t^{0.5}$	Rate-limiting step includes the transference of solute from solution into adsorbent pores	q_t vs. $t^{0.5}$

scale batch process. Adsorption kinetics demonstrates the rate of solute uptake and the mechanism of how this rate govern the residence time of adsorbate at the interface of solution. Number of models can be utilized for analyzing the kinetic data such as seudo-first-order, pseudo-second-order, intraparticle diffusion model, and Elovich model.

2.2.1. Pseudo-first-Order Kinetics. Pseudo-first-order kinetic model explains the adsorption at the solid-liquid interface. The linearized form of pseudo-first-order kinetic model can be formulated as [30]:

$$\log (q_e - q_t) = \log q_e - \frac{k_1}{2.303} t, \tag{6}$$

where q_e and q_t represents the adsorption capacity of adsorbent at equilibrium and time t in mg/g, respectively, k_1 is the pseudofirst-order rate constant, and t is the contact time (minute). Linear plot of log (q_e-q_t) versus t gives the value of k_1 and q_e which can be calculated from its slope and intercept, respectively.

2.2.2. Pseudo-second-Order Kinetics. Pseudo- second-order kinetic model assumes that the rate-limiting step in adsorption is controlled by chemical interactions between adsorbate and adsorbent molecules. Differential form of this model can be explained by the following equation [31, 32]:

$$\frac{dq_t}{dt} = k_2 (q_e - q_t)^2, \tag{7}$$

where k_2 represents the pseudo-second-order rate constant (g (mg min)$^{-1}$). The linearized form of this model is [33]:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t. \tag{8}$$

Linear plot of t/q_t versus t gives the value of q_e and k_2 which can be calculated from its slope and intercept, respectively.

2.2.3. Intraparticle Diffusion Method. The intraparticle diffusion model specifies that rate-limiting step involves the transference of solute from the solution into the adsorbent pores through an intraparticle process. Weber and Morris formulated that for most of the adsorption processes, amount of adsorption varies proportional with $t^{1/2}$ inspite with the contact time, and this can be expressed as [34].

$$q_t = k_{id} t^{0.5}, \quad (9)$$

where q_t is the adsorption capacity at time t, $t^{0.5}$ is the half-life time in second, and k_{id} (mg/g $\min^{0.5}$) is the rate constant of intraparticle diffusion. To find out the rate constants, plot q_t versus $t^{0.5}$ gives a linear relationship, and k_{id} can be determined from the slope of the plot.

2.3. Thermodynamic Studies. Thermodynamic studies help in determining (a) type of adsorption; either physical or chemical (b) randomness; (c) exothermic or endothermic nature; and (d) spontaneity of the adsorption reaction taking place. All these factors can be determined from the following presented equations [33, 35]:

$$\begin{aligned} \Delta G^0 &= -RT \ln K_C, \\ \Delta G^0 &= \Delta H^0 - T\Delta S^0, \\ \ln K_C &= -\frac{\Delta H^0}{R} \times \frac{1}{T} + \frac{\Delta S^0}{R}, \end{aligned} \quad (10)$$

where R is the universal gas constant 8.3144 J/(mol × K) and T is the operational temperature in kelvin. Value of ΔG^0 (Gibbs free energy change) can be calculated directly from Equation (8); however, ΔS^0 (Change in entropy) and ΔH^0 (change in enthalpy) are determined from the intercept and slope of the thermodynamic graph plotted between ln K_C and $1/T$. In addition, K_c is determined from the adsorption-isotherm constants. ΔG^0 is expressed in J/mol and temperature in K.

3. Mechanism of Adsorption onto AC

Mechanism of adsorption of various pollutants onto AC is very important to be elaborated. Mainly four processes are involved; (a) bulk transfer, (b) film diffusion, (c) pore diffusion, and (d) intraparticle diffusion. Bulk transfer involves the transport of adsorbate molecules in the solution phase and occurs instantaneously. In the film diffusion form, the adsorbate molecules are transferred to the external surface of adsorbent molecule by hydrodynamic boundary. Pore diffusion involve the transference of adsorbate molecules into the pores of adsorbent, thus decreasing the overall adsorption rate. Lastly, intraparticle diffusion involves the diffusion of adsorbate molecules from exterior of adsorbent into the pores of adsorbent and also along the pore-wall surfaces [36]. Figure 3 presents the probable adsorption mechanism.

Various interactions play an important role in their adsorption such as bonding, electrostatic, and π-π and n-π interactions [37]. π-π interactions, also known as π-π electron donor-acceptor interactions, exist between π-electrons of AC and adsorbate molecules. Presence of electron withdrawing groups at the edges and surface of AC results into appreciable drop in the π electron density. Removal of metal cations by AC is generally favored by Cπ-cation interactions that exists between the π-electron cloud of AC and metal cations. For example, in 2015, Tran et al. synthesized biochar having properties similar to that of AC from orange peels by pyrolysis. Adsorption of cadmium ions onto biochar surface followed the Cπ-cation interactions with maximum adsorption capacity of 114.69 mg/g [38]. The adsorption of metal cations has been found to be strongly dependent upon the solution pH as observed by Bui and Choi [39].

In addition to the above-reported interactions, hydrogen bonding also plays an important role in the adsorption of organic aromatic compounds onto AC. These interactions exist between the functional groups such as N-H in atrazine and O-H in paracetamol of the adsorbent and AC. Considering particular mechanism, O-H groups present on the surface of AC form hydrogen bond with the functional groups present in the organic adsorbates. Net intensity of the interactions regulates the magnitude of adsorption. In this mechanism, some complexes between solvent molecules and surface oxides are formed, which could block the migration of the solute molecules from the outside to the micropore structure of AC [40]. These interactions are highly temperature dependent as they vanish with the increase in temperature due to rise in kinetic energy of the adsorbed molecules.

4. Adsorption of Various Pollutants onto Activated Carbon-Based Materials

4.1. Heavy Metals. Metals having atomic weight between 63.5 and 200.6 g/mol are categorized into heavy metals [41]. Fertilizer, paper, pesticide, tannery, and battery industries are the major contributor for the addition of heavy metals into the environment directly or indirectly. Heavy metals are non-biodegradable in nature and accumulate in living organisms and most of heavy metal ions are known to be toxic or carcinogenic in nature such as mercury, cobalt, cadmium, and lead [42–44].

Zinc is a transition metal with atomic number 30 which is quite essential for human health. Intake of zinc in excess amount causes serious issues such as skin irritations, stomach cramps, nausea, vomiting, and anemia. Another one is mercury which is neurotoxin that causes damage to the central nervous system. High concentrations of mercury cause impairment of pulmonary and kidney function, chest pain, and dyspnea, etc. One most common disease caused by the presence of mercury is Minamata Bay [45]. In addition to mercury, lead can also cause central nervous system damage. It can also affect the kidney, liver, and reproductive system and malfunctions the brain activities. The toxic side effects are anemia, headache, dizziness, insomnia, weakness of muscles, and renal damages [46]. Chromium occurs in environment in mainly two states: Cr(III) and Cr(VI), out of which is Cr(VI) which is highly toxic [47]. It affects human physiology, gathers in the food chain, and causes many health issues ranging from simple skin irritation to lung carcinoma [48]. Table 3 summarizes the adsorption of heavy metal ions onto activated carbon derived from various

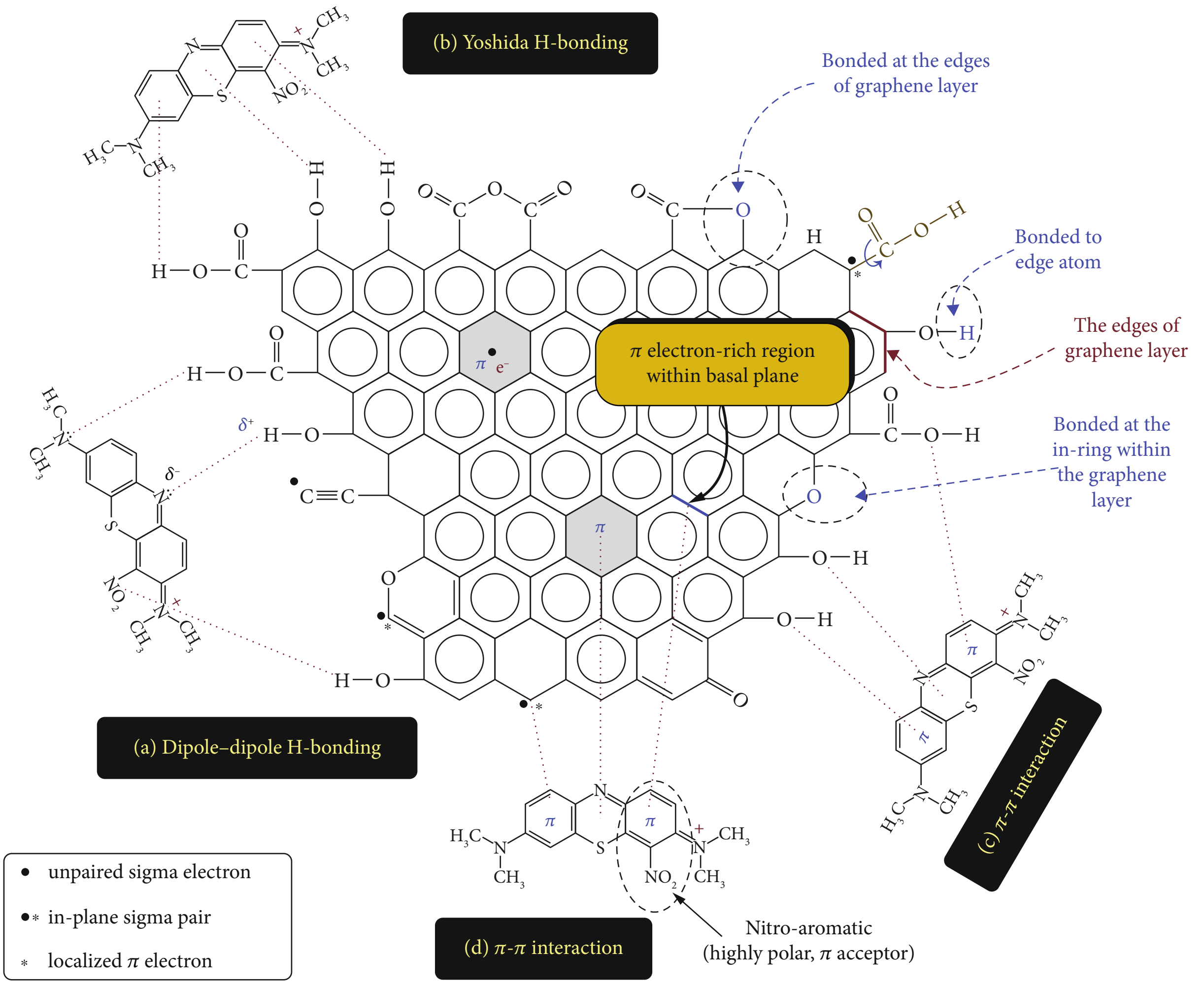


Figure 3: Possible interactions between various pollutants and activated carbon.

sources with their maximum adsorption capacity and reaction conditions.

Metal ions interact with AC through Cπ-cation interactions and thus get adsorbed onto its surface and into the pores. A number of papers have been reported in the literature that mark the utilization of Cπ-cation interactions for the adsorption of heavy metal ions onto AC. Production of AC from rapeseed was used for the removal of lead ions from aqueous effluents. For providing an evidence for the involvement of Cπ-Pb(II) interactions, FTIR analysis was carried out. Disappearance of characteristic peak of C=O at 1710 cm^{-1} after adsorption of Pb(II) ions showed the complexation with Cπ-cation interactions [49].

In another study, AC synthesized from coconut shell was utilized for the adsorption of Pb(II) ions from aqueous solution. Adsorption was reported to be strongly dependent upon solution pH, and maximum was observed at pH 4.5 with maximum adsorption capacity of 26.50 mg/g. Reaction was found to be endothermic as generalized by thermodynamic analysis [50]. AC synthesized from coirpith was chemically activated and utilized for the adsorption of Ni(II) ions from aqueous solution. The concentration ratio of carbon/nickel ions affected the adsorption rate to a great extent. pH studies revealed the maximum adsorption of Ni(II) ions in the basic medium and consequently showed desorption ability in acidic environment of HCl. Maximum adsorption capacity of coirpith-designed activated carbon was 62.5 mg/g [51].

Adsorption of Pb(II) and Cd(II) ions onto AC preactivated by physical (steam) and chemical treatment (H_3PO_4 and KOH) was studied by El-Hendawy. Out of the three activation treatment processes, H_3PO_4 chemical treatment activation was found to be the most effective with maximum adsorption capacity of 139 mg/g for Pb(II) and 129 mg/g for Cd(II). Pb(II) ions were removed or adsorbed in preference to Cd(II) ions due to their lower solubility and lower pH requirement for complexation [52]. Another group of researchers, Ameh synthesized activated carbon by chemical treatment with NaOH and utilized it for the adsorption of Cu(II) and Cd(II) ions. Maximum adsorption capacity calculated from Langmuir isotherm for Cu(II) and Cd(II) ions was 118.06 and 88.42 mg/g, respectively. Adsorption capability was found to be strongly dependent upon the adsorbent dosage [53].

Table 3: Adsorption of heavy metal ions onto activated carbon derived from various sources with their maximum adsorption capacity and reaction conditions.

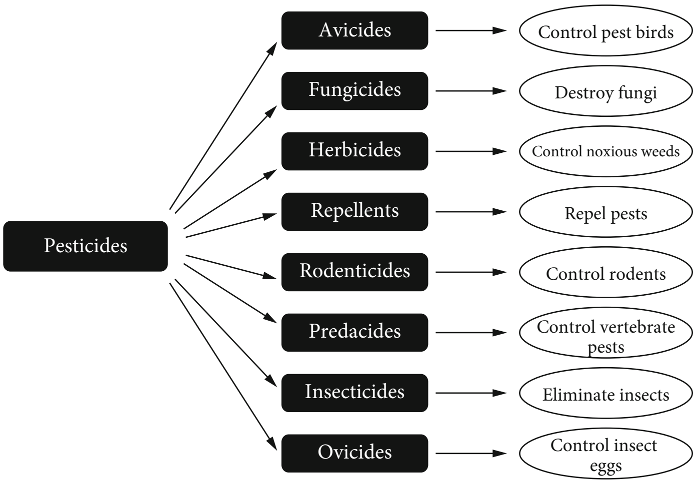
Activated carbon derived from	Adsorbate	Maximum adsorption capacity (mg/g)	Reaction conditions	Reference
Coconut	Cd(II)	10.716	Concentration = 500 mg/dm^3 Temperature = 303 K Mass = 20 g/dm^3	[54]
Coconut coirpith	Cd(II)	93.4	Temperature = 303 K pH = 5.0	[55]
Apricot stone	Cr(VI)	34.70	pH = 1 Temperature = 298.15 Mass = 0.1 g	[56]
Fertilizer waste	Pb(II)	1110.6	pH = 4 Concentration = 5×10^{-2} M	[57]
Bagasse (agricultural waste)	Zn(II)	31.11	Temperature = 298.15 K pH = 4.5	[58]
Potato peels	Pb(II)	171	—	[59]

4.2. Pesticides. Pesticides are defined as the group of chemical or biological compounds having antimicrobial and disinfectant properties applied intentionally against various microbes and pests comprising insects, weeds, birds, mammals, and nematodes, etc. It help in increasing the productivity, processing, storage, and transport of diverse variety of food [60]. Specifically, pesticide is characterized by its exceptional chemical structure established to mimic and substitute specific molecules to the targeted pests, which offer a lethal disruption to the anticipated biological reactions [61]. Pesticides actually helps in diminishing the effect of unwanted microbes or other agents and helps in fulfilling the ever increasing food demands due to increasing world population. These can be applied to the agricultural field in the form of herbicides, insecticides, ovicides, rodenticides, fungicides, avicides, nematicides, and bactericides, etc [62, 63]. Pesticides can be classified in accordance to their physicochemical properties and targeted implications as presented in Figure 4.

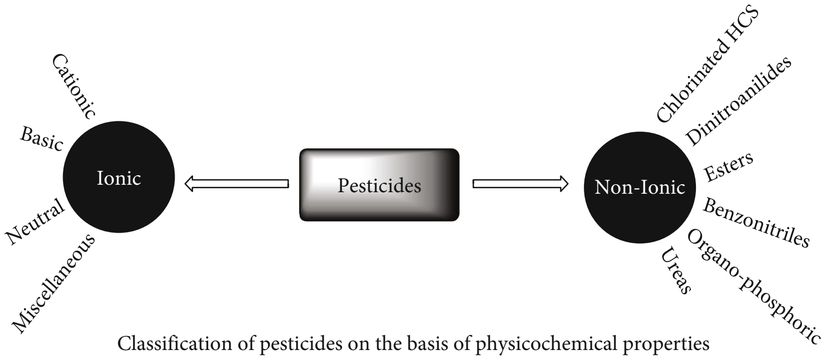
Recent decades have marked the advent of pesticide practice as an agricultural repellant, fumigant, defoliant, or sterilant and has inferred as the most challenging tasks, due to which gained high momentum and popularity across the world [64]. Diverse purification or treatment techniques such as precipitation, flotation, sedimentation, membrane processes, filtration, coagulation–flocculation, biological process, adsorption, electrochemical techniques, chemical reactions, and ion exchange with variable level of success have augmented a dramatic progress in the scientific community [65–68]. Among them, adsorption process is documented as the most effective and auspicious approach in the wastewater treatment processes. Table 4 shows various forms of AC used for removal of pesticides with their maximum adsorption capacity.

2,4-Dichlorophenoxyacetic acid (2,4-D) is an herbicide that is used for the careful control of broadleaf weeds. Hameed et al. studied its removal from aqueous solution by employing AC treated with KOH/CO_2 for physiochemical activation. Various adsorption isotherms were employed, and results showed that Langmuir data fitted best. Maximum adsorption capacity calculated was 238.10 mg/g. Herbicide initial concentration was of greater influence as compared to solution pH and other factors [69]. In 2006, Chingombe et al. [70] described the heat treatment via annealing the AC in a reactor that enhanced the micropore content, thus increasing the surface area from 790 to 960 m^2/g due to the reduction in oxygen-containing functional groups. Such enhancement in surface area increased the uptake of 2,4-dichlorophenoxyacetic acid and benzolin onto its heat-treated AC. Adam et al. investigated the adsorption of a fungicide, propiconazole under two different activation treatments, one by basic treatment (NaOH) and other by acidic treatment (HNO_3 and H_2O_2). Results presented that acidic treatment of AC decreased its adsorption abilities. Actually, acidic groups increased the oxygen-containing functionalities onto the surface that showed negative effect on adsorption of propiconazole as a result of which the adsorption capacity decreased [71]. Yoo et al. stated that nitric acid-treated AC increased the concentration of carboxylic groups onto its surface for the treatment. However, this treatment did not mark any strong effect on the adsorption rate of oligosaccharides (carbohydrate compounds) from aqueous solutions [72].

4.3. Pharmaceutical and Personal Care Products (PPCPs). Number of possible routes has been put forward for designating the sources responsible for the enhancement of pharmaceutical pollution which includes incomplete metabolized and excreted drugs in the urine and feces, which enter into the water system. Other feasible source is the spare, or expired drugs, that may be dumped into toilets. Few drugs are not easily degradable and thus persist in the water system. Adverse effects of PPCPs include aquatic toxicity, genotoxicity, and endocrine disruption. Additionally, presence of trace amount of PPCPs in drinking water is also a public health concern, as little is known about probable chronic health issues related to long-term ingestion of mixtures of such compounds through drinking water. Table 5 presents the adsorption of various pharmaceutical and personal care products onto AC.



Classification of pesticides on basis of targeted implication



Classification of pesticides on the basis of physicochemical properties

FIGURE 4: Classification of pesticides on the basis of targeted implication and physicochemical properties.

Salman with his coworkers studied the removal of bentazon and carbofuran pesticides from aqueous solution. For this, they synthesized date seed-based AC with potassium hydroxide and carbon dioxide used as the activating agents [84]. Freundlich model for both pesticides fitted better to the adsorption equilibrium data as compared to Langmuir model. Maximum adsorption capacities as calculated from Langmuir isotherms were 86.26 and 137.04 mg/g for bentazon and carbofuran, respectively. Due to smaller size of carbofuran as compared to bentazon, it easily penetrated into the pores of AC thus offering high removal efficiency. Pesticide initial concentration was found to be the more influential factor as compared the solution pH.

4.4. Dyes. Dyes are the colorful compounds designed intentionally to give hue to fabrics and paper. These have the tendency of attaching to any responsive material. These have been utilized since the past many centuries. In the initial times, these were derived from the natural sources such as plants, insects, or microbes, but one major problem with these dyes was their short-term application part. Under the influence of sunlight and temperatures, these dyes faded away which led to the need for the emergence of synthetic dyes. Synthetic dyes are the laboratory-synthesized dyes first invented by WH Perkins in 1856 that solved the issue of persistency of dye color. Such synthetically produced dyes were structurally stable and difficult to degrade [94–96]. With their emergence, industries started utilizing them as their major product constituent and disposed them off into water system after use without any treatment process that raised serious environmental and health issues. Relative proportion of dye effluents added by various industries to the environment has been presented in Figure 5. Although it seems that resuming the usage of natural dyes are a better alternative, it was found to be more bad as employing synthetic dyes alone because in order to increase the bonding capability with the fabrics, a mordant is required. Mordants are basically binding agents that help in the attachment of natural dye to materials. These are much more toxic and dangerous than that of synthetic dyes.

Dyes can be classified into numerous classes based on various categories such as structure, color, application, and chemical composition [34]. Dyes classified on the basis of chemical structure are presented in Figure 6 [34]. In addition, these can also be categorized on the basis of particle charge acquired upon dissolution in aqueous medium [97–99], for example, cationic, anionic, and nonionic.

Dye-utilizing industries purge dye effluents into the water sources without any treatment process. Water pollution due to dyes is objectionable to environmentalists due

Table 4: Adsorption of various pesticides onto AC with reaction conditions.

Adsorbent	Adsorbate	Maximum adsorption capacity (mg/g)	Reference
Activated carbon derived from date stones (DSAC)	2,4-Dichlorophenoxyacetic acid (2,4-D)	238.10	[69]
Banana stalk-activated carbon	Bentazon	115.07	[73]
Activated carbon fibers	Atrazine	238.10	[74]
Activated carbon prepared from waste rubber tire	Methoxychlor	112.00	[75]
Activated carbon fibers	Simazine	370.4	[74]
Activated carbon prepared from waste rubber tire	Methyl parathion	88.90	[75]
Banana stalk-activated carbon	2,4-D	196.33	[73]
CARBOPAL-activated carbon	Bentazon	185.07	[76]
CAT-activated carbon	Bentazon	391.65	[76]
Spectracarb 2225 (commercial-activated carbon cloth)	Ametryn	354.61	[64]
Filtrasorb 400 (commercial GAC)	Lindane	181.00	[77]
Activated carbon fiber (commercial)	Simazine	370.40	[74]
NFEN 12915 (commercial GAC)	Metribuzin	210.00	[78]
The absorbent is used tires derived AC	Paraquat dichloride	75.8	[79]
Activated carbon (commercial)	Methidathion	0.456	[80]
Filtrasorb 400 (commercial GAC)	Chlorophenoxyacetic acid	2.77 mol/kg	[81]
Darco G-60 (commercial AC)	Bromoxynil	500.00	[82]
Charcoal-based PAC (commercial)	4-(4-Chloro-o-tolyloxy)butyric acid		[83]
Date stone-activated carbon	Carbofuran	137.04	[84]

to their toxic and hazardous nature [100, 101]. Addition of concentrated dye effluents to water bodies with acidic characteristics and high temperature disturbs the oxygen transfer mechanism and the self-purification ability of environmental water bodies. Mixing of water bodies with dye effluents also results into turbidity that forms a visible foam layer above the water surface due to which it blocks the penetration of sunlight into water system, thus limiting the requirement of sunlight by aquatic species for photosynthesis and respiration. Presence of dye effluents in the water bodies becomes a breeding ground for various microbes such as bacteria and fungi, and their presence in water makes it unsuitable for consumption. Recently, a law governing the level of presence of these effluents has been established by the International Dye Industry Wastewater Discharge Quality Standards according to which industries have to ensure the wastewater released into the water bodies [102–104]. Table 6 summarizes the removal of dyes by various AC-based absorbents.

Adsorption of dyes onto AC is mainly influenced by the surface properties. It is an amphoteric material having ability to exhibit cationic as well as acidic characters. Its interaction with the dye molecules is mainly influenced by the solution pH that makes the surface to behave differently in different solution pH. In 2007, activated carbon prepared from groundnut shell by chemical treatment with $ZnCl_2$ was utilized for the adsorptive removal of malachite green from aqueous solution [125]. High surface area of 1200 m^2/g favored the adsorption of malachite green onto it. Maximum adsorption capacity of 114 mg/g was calculated. In another work, cotton fiber was used as the carbon precursor, and $ZnCl_2$ was employed as the activating agent. As designed cotton fiber-activated carbon (CFAC) was utilized for the removal of methylene blue from aqueous solution, BET surface analysis determined the high surface area, 2060 m^2/g of CFAC with maximum adsorption capacity of 597 mg/g. Adsorption data fitted best to the Langmuir isotherms. Study showed that acidic pH favored the adsorption process. Chemical interactions favored the adsorption of methylene blue onto CFAC as generalized by pseudosecond kinetic model [126].

In addition to agricultural products, microorganisms such as *E. prolifera* were also used for the preparation of carbon. It was treated with $NaAlO_2$ for chemical activation to add functionalities onto its surface and make it reactive. Activation by $NaAlO_2$ endorsed it with high surface area of 1374 m^2/g. It was successfully employed for the adsorptive elimination of brilliant scarlet from aqueous solution. High adsorption capacity of 1000 mg/g was obtained as calculated by Langmuir isotherm [127].

A number of activated carbon precursors have been reported in the literature designed particularly for the removal of methylene blue such as *Albizia lebbeck* [128], hazelnut husk [129], macadamia nut endocarp [130], oil palm wood [131], olive stone [132], acacia fumosa seed [133], vetiver roots [134], waste tea [135], and date stones [136].

4.5. Volatile Organic Compounds. Volatile organic compounds (VOCs) are the chemical compounds documented as the major cause of air pollution. VOCs such as phenol, benzene, formaldehyde, ketone, butane, xylene, toluene, and chlorinated compounds are quite dangerous since these are carcinogenic, mutagenic, and toxic. Increase in industrialization has led to the increase in VOC emission into the

Table 5: Adsorption of various pharmaceutical and personal care products onto AC.

Activated carbon precursor	Adsorbate	Reaction conditions	Maximum adsorption capacity (mg/g)	Reference
Rice husk	Tetracycline	Adsorbent dosage = 2.4 g/L Temperature = 30°C Time = 72 h	44.8	[85]
Grape pulps	Tetracycline	Adsorbent dosage = 0.2 g/L Time = 8 h Temperature = 25°C	204-313	[86]
Lotus stalk	Norfloxacin	Adsorbent dosage = 0.1 g/L Time = 24 h Temperature = 21°C pH = 5.5	933.70 μmol/g	[87]
Pomegranate wood	Amoxicillin	Adsorbent dosage = 0.8 g/L Time = 40 min Temperature = 25°C pH = 6	262	[88]
Vine wood	Penicillin G	Adsorbent dosage = 0.4 g/L Time = 8 h Temperature = 25°C pH = 2	8.41	[89]
Olive stones	Amoxicillin	Adsorbent dosage = 0.3 g/L Time = 24 h Temperature = 25°C pH = 4.3	0.38 mmol/g	[90]
Cotton linters	Oxytetracycline	Adsorbent dosage = 1 g/L Time = 28 h Temperature = 25°C pH = 3.1 − 3.4	516-746	[91]
Petroleum coke	Tetracycline	Adsorbent dosage = 0.1 g/L Time = 35 h Temperature = 30°C pH = 4	923.2	[92]
Tyre char	Tetracycline	Adsorbent dosage = 0.5 g/L Time = 48 h Temperature = 25°C pH = 7	312.41	[93]

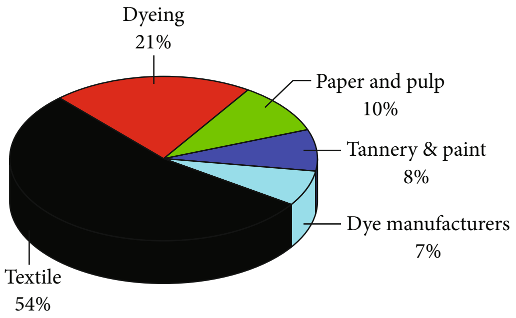


Figure 5: Relative proportion of dye effluents added by various industries to the environment.

environment. Other sources of VOCs in environment include transportation, construction, and natural emissions. Usually, these are present in higher concentration near petrochemical plants as compared to the suburban areas. Presence of VOCs in the environment leads to global warming, ozone depletion, acid rain, and photochemical smog. In human beings, they cause skin irritation, liver damage, liver malfunctioning, and asthma. There has been a rapid increase in concentration of VOCs in the environment, such as, in China, the total amount of VOCs has increased from 1.15 in 1980 to 13.35 Tg in 2010 [137].

Number of techniques has been suggested in literature for VOC removal such as catalytic oxidation, photocatalytic oxidation, reverse osmosis, ion exchange condensation, thermal oxidation, biological treatments, and adsorption. Out of all, adsorption process is the simplest, efficient, and economical alternative to this since it offers high degree of operation stability, no toxic by-product formation, no additional treatment requirement, and cost effectiveness. A number of articles have been published in literature for VOC removal by activated carbon. AC prepared from avocado kernels and activated by carbon dioxide possesses surface area of 206 m^2/g. It was utilized for the removal of phenol. Results presented that slightly acidic pH favored the adsorption, and maximum adsorption capacity obtained was 90 mg/g [138]. Chemical interactions favored the adsorption of

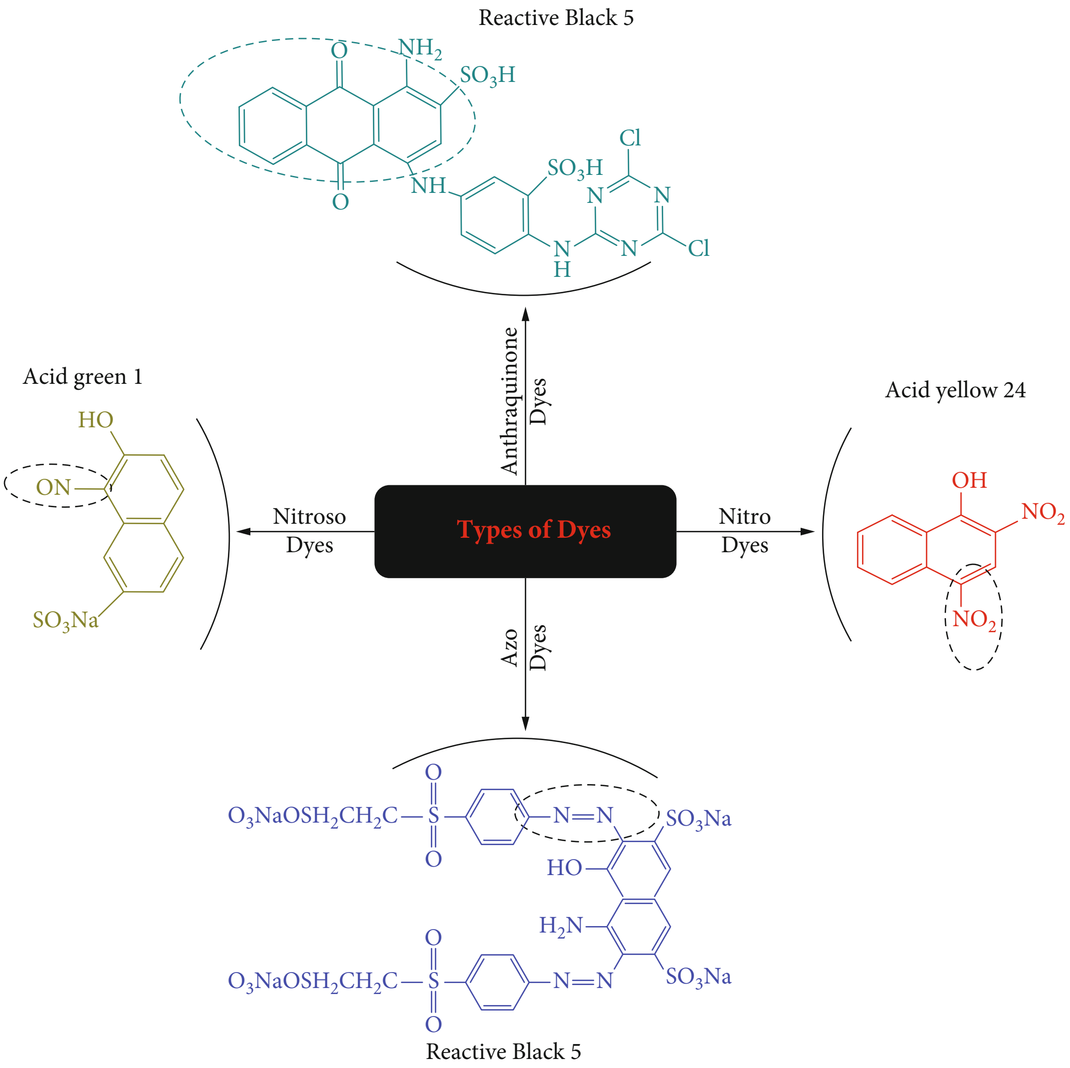


Figure 6: Classification of dyes based on the chemical structure.

phenol onto AC as generalized by kinetic studies. Durian shell-derived activated carbon was also reported in literature, activated by H_3PO_4 which possessed high surface area of 1404 m^2/g. It was used for adsorptive removal of toluene with maximum adsorption capacity of 874 mg/g. Isotherm studies showed that Freundlich isotherm explained the adsorption process better in comparison to Langmuir isotherm [139]. Kenaf rapeseeds were also utilized as the carbon precursors. It was then activated by carbon dioxide which endorsed it high surface area of 1112 m^2/g. It was used for the removal of phenol, and maximum adsorption capacity as recorded by Langmuir isotherm was 84.1 mg/g. Results showed that adsorption was strongly dependent upon solution pH, and maximum adsorption was observed at pH 10 [140].

5. Activated Carbon as a Catalyst Support

Overall activity and reactivity of any catalyst depends upon the chemical composition, surface area, and physical properties. Any active material or phase can be imprinted onto a suitable support to provide it high surface area and improve its mechanical strength. In addition, extremely dispersed active phase can be stabilized by depositing it into the micropores of support. A synergistic relation exists between the active phase and support that enhances its catalytic activity. It helps in preventing the agglomeration rate. Most important parameter during catalyst designing is the proper dispersion of active phase onto the support that is described as the ratio of number of surface atoms of active phase to the total number of atoms present.

Number of materials can act as a support, and one among them is the AC that is extensively utilized due to nontoxic, cheap availability and easy synthetic routes. It acts as a sink for the produced electron-hole pairs and thus helps in lowering the recombination of e^--h^+ pairs. However, their activity gets highly influenced by the presence of impurities, also called catalyst poison such as copper, zinc, and iron. Major advantage of AC as a catalyst support is the fact that its pore structure and internal surface both can be widely varied. It consists of small area of disordered graphitic structure elements. Their catalytic activity is determined by

Table 6: Removal of dyes by various AC-based absorbents.

Adsorbent	Adsorbent	Maximum adsorption capacity (mg/g)	Reference
Coirpith-activated carbon	Congo red	6.7	[105]
Oil palm fibre-activated carbon	Methylene blue	277.78	[106]
Rattan sawdust-based activated carbon	Methylene blue	294.14	[107]
Apricot stone-activated carbon	Methylene blue	36.68	[108]
Pine sawdust	Acid yellow 132	398.80	[109]
Wood sawdust	Xylenol orange	140.00	[110]
Persian mesquite grain	Methyl orange	66.80	[111]
Cashew nut shell	Methylene blue	476.00	[112]
Banana trunk-derived activated carbon	Methylene blue	166.51	[113]
Aluminium-modified activated carbon	Methylene blue	181.82	[114]
Matured tea leaf-activated carbon modified sulfonic acid (MTLAC-SA)	Rhodamine B	757.60	[115]
Activated carbon produced from steam-activated bituminous coal	Methylene blue	580.00	[116]
Activated carbon produced from tea (*Camellia sinensis* L.) seed shells	Methylene blue	324.7	[117]
Activated carbon derived from periwinkle shells	Methylene blue	500.00	[118]
Sulphuric acid-treated activated carbon	Methylene blue	149.30	[119]
Granular-activated carbon	Methyl violet	95.00	[120]
Acid modified activated carbon	Methyl violet	90.10	[121]
Coconut shell-based activated carbon	Malachite green	214.63	[122]
Attapulgite/rice hull-based activated carbon nanocomposite	Yellow X-GL	213.00	[123]
Walnut shell-activated carbon	Methylene blue	315.00	[124]

electron transfer from the edges of carbon sheets. Therefore, the presence and distribution of these active sites are important. The catalytic activity of the graphite structure can be changed by the presence of heteroatoms such as sulphur and nitrogen in the lattice. Its activity also got influenced by the presence of acid or base surface oxide complexes. Key features of AC as the support material include (a) high resistance to acidic or basic mediums; (b) designed pore size distribution for particular reactions; (c) minimized cost as compared to silica and alumina supports; and (d) stability at high temperatures.

Activated carbon and its composites can be utilized as a catalyst or catalyst support for various chemical reactions such as hydrolysis, hydrogenation, esterification, and hydrogenation. The carbon catalyst having amorphous morphology and highly reactive groups such as -COOH, -OH, and -SO_3H acts as an efficient catalyst for the hydrolysis of pure cellulose to glucose which was not possible with conventionally used catalysts such as Amberlyst-15, Nafion, and H-mordenite. The carbon catalyst enhanced the hydrolysis rate due to its low activation energy requirement. High catalyst performance is accredited to its tendency to adsorb 1,4-glucan [141]. Figure 7 shows the conversion of cellulose to glucose by hydrolysis.

Hydrodeoxygenation reactions is another branch where carbon acts as a catalyst or as its support. Such reactions involve the conversion of carbohydrates to unsaturated compounds by catalyst favoring the cleavage of C-O in comparison to C-C with minimized amount of H_2 utilization. MXenes such as Mo_2C supported on activated carbon helps in the conversion of vegetable oil such as rapeseed, olive, and soya bean to diesel-range hydrocarbons [143].

Hydrogenation reactions involves the treatment of compounds with molecular hydrogen. Hydrogenation being carried out at industrial scale involves the reduction of nitro groups in nitroaromatic compounds to reduce the chances of production of other compounds such as aniline. Hydrogenation of nitrobenzene was studied by Pt catalyst supported on AC in 1977 [144]. Results presented show that catalytic activity of Pt got enhanced by its impregnation onto AC. Catalytic activity was found to be highly dependent upon the dispersion of Pt onto AC, pore structure of AC, chemical composition of AC surface, and temperature also. Linear relationship between activity and Pt dispersion (calculated at equivalent reduction temperature) has been found.

AC also acts as support material in case of oxidation of phenol. Shukla and his coworkers designed a catalyst synthesized by impregnation of Co(II) ions onto AC and utilized it for the activation of peroxymonosulphate that carried out the oxidation of phenol. Co(II) ions were uniformly distributed onto AC surface. Results indicated that Co/AC demonstrated high activity in oxidation of phenol with sulphate radicals and 100% decomposition and 80% TOC removal could be achieved in 60 minutes [145].

6. Activated Carbon in Food and Pharmaceutical Industries

Activated carbon and its various derivatives have found to be used in food and pharmaceutical industries. AC utilized as

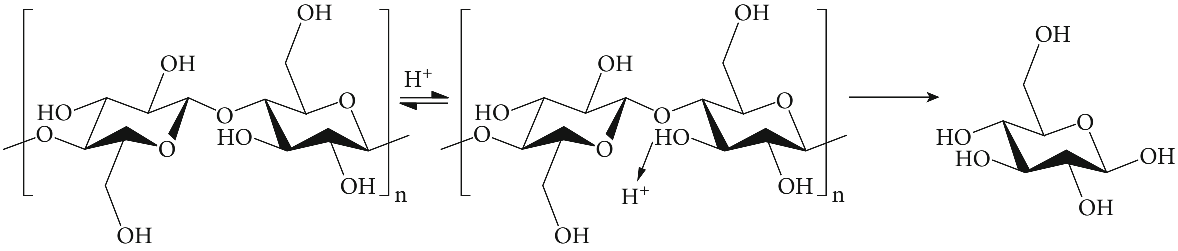


Figure 7: Hydrolysis of cellulose to glucose [142].

Table 7: Activated carbon as a storage material for various gases.

Precursor	Activating agent	Surface area	Gas	Total capacity	Reference
Lignin	KOH	1946	H_2	1.89 wt%	[153]
Rice husks	KOH	2682	H_2	2.85 wt%	[154]
Olive stones	H_3PO_4	1014	CH_4	4.69 mmol/g	[155]
Sugarcane molasses	KOH	2202	CH_4	197.23 mg/g	[156]
Gelatin and starch	KOH	1957	CO_2	7.49 mmol/g	[157]
Tobacco		1104	CO_2	3.56 mmol/g	[158]
Coffee residues	CO_2 and KOH	590	CO_2	2.4 mmol/g	[159]

acidulants found a prominent use in food and pharmaceutical industries as a pH regulator, chelating agents, and antioxidant synergist. AC as acidulants helps in decolorizing maleic acid and adipic acid prior to their conversion and crystallization. Sodium benzoate and sodium sorbate are used as preservatives in food, beverage, and pharmaceutical industries. Granular AC helps in decolorizing and deodorizing them even in less than 1% dosage during manufacturing [146].

Due to high purity and performance, AC has also been found to be a proficient adsorbent during pharmaceutical processing applications that entail highly efficient filtration system. This safeguards soluble minerals with low acid content that lessens the adulteration of the final product with negligible impact on solution pH. Due to exclusive adsorptive properties and bio-origin endorse AC with antitoxin properties also, it quickly enables to lessen the effects of poisons or overconsumption of stimulants, through aid with digestion and sensitive alimentary conditions. In veterinary medicine field, AC is extensively employed as a feed additive. It functions as a curative agent the same way as in human medicine by adsorbing undesirable or potentially harmful substances from animal's gastrointestinal tract, making it an effective treatment for poisoning and diarrhea.

7. Activated Carbon as Storage System for Gases

Increase in industrialization has led to the enhancement in the presence of gases (above their permissible limit) such as carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen (H_2), and methane (CH_4) in the environment.

Carbon dioxide (CO_2) is the major reason for temperature increase of earth, and it also contributes to the ozone layer depletion. Major sources of CO_2 in the atmosphere are the industrial practices, fuel burning, and deforestation. Researchers have suggested the adsorption and sequestration of CO_2 from the point of its origin. A number of techniques have been put forward for CO_2 capturing such as membrane separation, cryogenic techniques, liquid solvent absorption, temperature adsorption, solid sorbents, and pressure adsorption [6, 147]. Adsorption is categorized as the most effective one due to its ease of operation, cost effectiveness, and economic processing. CO_2 adsorption onto AC requires the presence of basic functionalities such as the nitrogen-containing functional groups on its surface that favor the maximum CO_2 capturing [148]. When the carbon materials are treated with ammonia at ambient temperatures, ammonia decomposes to form free radicals (-NH_2, -NH, and atomic hydrogen and nitrogen). These generated free radicals attack the carbon surface to form nitrogen-containing functional groups [149]. CO_2 capturing can be successfully determined using various techniques such as Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), and temperature programmed desorption (TPD).

Methane has established significant consideration as a future clean energy source due to its natural profusion, relative safety (compared to other fuels), cost effectiveness, and low carbon emission. For convenient storage solicitations in future transportation technologies, intended materials must offer extraordinary storage aptitude, high storage, and release kinetics and long cycle effectiveness under modest thermodynamic conditions [150]. It has been found that CH_4 storage using AC synthesized from polymers, hardwood, and coconut shell is equivalent to the compressed natural gas at 250 bar, with high methane uptake of approximately 200 *v*/*v* at 27°C and pressure between 34 and 48 bar [151].

In addition to methane, hydrogen is also a supreme fuel for future generations. Hydrogen infrastructure play an essential role in the commercialization of fuel cells. The

U.S. Department of Energy (DOE) has fixed the necessity of 5.5 wt% H_2 for gravimetric and 40 g H_2/L for volumetric systems [152]. For acquiring convenient hydrogen storage systems to function fuel cells using H_2, storage containers having high volumetric and gravimetric density are required. Now-a-days, conventional technologies for H_2 storage/transport are compression, cryogenic and cryo-compressed storage, metal hydrides, and activated carbon. Table 7 avails the summary of storage conditions of various gases onto AC.

8. Regeneration of AC

Regeneration is very important as it helps in increasing the productive life of the adsorbent and enhances its practical utility. Considering the regeneration of AC, it can be done by various methods, and some of them are explained below.

8.1. Thermal Regeneration. This method involves the temperature treatment which is accomplished using fixed bed furnaces, fluidized bed furnaces, and rotary kilns. Under this, adsorbed gases such as carbon dioxide, partially oxidized contaminants, and particulate matter can be removed from the adsorbent surface. It includes gasification of organism pollutants, drying at 105°C, and pyrolysis under inert atmosphere. However, due to the high-temperature conditions, the adsorption efficiency of adsorbent gets drastically affected. Although thermal regeneration is quite a simple regeneration method, it is an energy- and time-consuming way and also leads to significant amount of C loss. In addition, numerous hazardous by-products can also be produced during the implication of this method [160].

8.2. Chemical Regeneration. In this method, certain chemicals are used for the regeneration of adsorbent by desorbing the adsorbed molecules from the adsorbent surface. The proficiency of this method depends strongly on the type of contaminant present on or in the spent of AC. This method typically leads to zero carbon-attrition and helps in maintaining the actual adsorption capacities of AC. The affinity of adsorbed molecules with that of the acidic or alkaline reagents used determines the extent of regeneration. The efficiency of this type of regeneration therefore depends on the solubility and the reactivity of the adsorbents with the chemical reagents [161].

8.3. Electrochemical Regeneration. This technique is quite efficient as it involves the use of moderate temperature and requires no addition of chemicals. In this method, organic contaminants adsorbed on the surface of AC get cracked in situ while the structural integrity and characteristics of the carbon are not altered. The major mechanisms include electrooxidation, electroreduction, and electrosorption [162].

8.4. Bioregeneration. It makes the use of microbial agents for regenerating the adsorption capacity and surface activity of AC. Bioregeneration occurs when the organic contaminant species can be easily desorbed. The concentration gradient of the organic contaminants between the adsorbent and the bulk liquid aids the bioregeneration. This two-step process of desorption and biological removal of the adsorbed organics has been verified in a closed-loop recirculating batch system [163]. It has been found that biodegradation occurs due to the presence of concentration gradient of the pollutant as one moves from the carbon surface to the bulk solvent. There are many factors that crucially affects the biogeneration of AC such as carbon activation method used, porosity of AC, concentration gradient and carbon saturation, type of microorganism used, and concentration of biomass. Major target compounds for the adsorption bioregeneration are synthetic organic compounds, explosive-contaminated ground water, industrial wastewater, and residual disinfectants [164].

9. Conclusions

An overall review has been presented on the activated carbon. Chemical and physical approach treatments have been discussed in detail. These treatments influence the overall activity of activated carbon towards various pollutants. Data presented emphasize the need for the presence of basic functionalities on activated carbon surface for the adsorption and storage of carbon dioxide. Adsorption capacities of activated carbon depends upon the surface area, pore size and volume, surface functionalities, and mineral matter content. Different precursors can be used for the activated carbon synthesis such as fossil fuels, agricultural wastes, and lignocellulosic. Precursors of biobased origin offer economical and easy availability that serves as a potent alternative to activated carbon derived from fossil fuels. Due to its attractive properties, it serves as a potential applicant for the adsorption of heavy metals, dyes, pesticides, and pharmaceutical effluents. Activated carbon also helps in the storage of various gases such as carbon dioxide, methane, and hydrogen. Despite such high application fields, we think its applications can still further be explored in various other fields such as antimicrobial, photocatalysis, and hydrogen production.

Abbreviations

AC:	Activated carbon
PZC:	Point of zero charge
q_e:	Adsorption amount at equilibrium
C_o:	Initial concentration
C_e:	Equilibrium concentration
%:	Percent
C:	Celsius
g:	Gram
m:	Meter
PPCPs:	Pharmaceutical and personal care products
VOCs:	Volatile organic compounds
TPD:	Temperature-programmed desorption
XPS:	X-ray photoelectron spectroscopy
FTIR:	Fourier-transform infrared
DSAC:	Activated carbon derived from date stones
2,4-D:	2,4-Dichlorophenoxyacetic acid
V:	Volume
q_m:	Maximum adsorption capacity
CFAC:	Cotton fiber-activated carbon
K_L:	Langmuir constant

K_F: Freundlich constant
DOE: Department of Energy
IEC: Isoelectric point
T: Temperature
ΔH: Enthalpy change
ΔG: Gibbs free energy change
ΔS: Entropy change.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] D.-W. Kim, H.-S. Kil, K. Nakabayashi, S.-H. Yoon, and J. Miyawaki, "Structural elucidation of physical and chemical activation mechanisms based on the microdomain structure model," *Carbon*, vol. 114, pp. 98–105, 2017.

[2] T. Karanfil and J. E. Kilduff, "Role of granular activated carbon surface chemistry on the adsorption of organic compounds. 1. Priority pollutants," *Environmental Science & Technology*, vol. 33, no. 18, pp. 3217–3224, 1999.

[3] G. S. Szymański, Z. Karpiński, S. Biniak, and A. Świątkowski, "The effect of the gradual thermal decomposition of surface oxygen species on the chemical and catalytic properties of oxidized activated carbon," *Carbon*, vol. 40, pp. 2627–2639, 2002.

[4] T. Karanfil, M. Kitis, J. E. Kilduff, and A. Wigton, "Role of granular activated carbon surface chemistry on the adsorption of organic compounds. 2. Natural organic matter," *Environmental Science & Technology*, vol. 33, pp. 3225–3233, 1999.

[5] J. A. Menéndez, J. Phillips, B. Xia, and L. R. Radovic, "On the modification and characterization of chemical surface properties of activated carbon: in the search of carbons with stable basic properties," *Langmuir*, vol. 12, pp. 4404–4410, 1996.

[6] M. S. Shafeeyan, W. M. A. W. Daud, A. Houshmand, and A. Shamiri, "A review on surface modification of activated carbon for carbon dioxide adsorption," *Journal of Analytical and Applied Pyrolysis*, vol. 89, pp. 143–151, 2010.

[7] H. Boehm, "Some aspects of the surface chemistry of carbon blacks and other carbons," *Carbon*, vol. 32, pp. 759–769, 1994.

[8] M. J. McGuire and I. H. Suffet, "Aqueous chlorine/activated carbon interactions," *Journal of Environmental Engineering*, vol. 110, pp. 629–645, 1984.

[9] C. L. Mangun, K. R. Benak, M. A. Daley, and J. Economy, "Oxidation of activated carbon fibers: effect on pore size, surface chemistry, and adsorption properties," *Chemistry of Materials*, vol. 11, pp. 3476–3483, 1999.

[10] Y. Otake and R. G. Jenkins, "Characterization of oxygen-containing surface complexes created on a microporous carbon by air and nitric acid treatment," *Carbon*, vol. 31, no. 1, pp. 109–121, 1993.

[11] G. Sharma, B. Thakur, A. Kumar, S. Sharma, M. Naushad, and F. J. Stadler, "Gum acacia-*cl*-poly(acrylamide)@carbon nitride nanocomposite hydrogel for adsorption of ciprofloxacin and its sustained release in artificial ocular solution," *Macromolecular Materials and Engineering*, vol. 305, p. 2000274, 2020.

[12] Z. Fallah, E. N. Zare, M. Ghomi et al., "Toxicity and remediation of pharmaceuticals and pesticides using metal oxides and carbon nanomaterials," *Chemosphere*, vol. 275, p. 130055, 2021.

[13] H. N. Tran, S.-J. You, A. Hosseini-Bandegharaei, and H.-P. Chao, "Mistakes and inconsistencies regarding adsorption of contaminants from aqueous solutions: a critical review," *Water Research*, vol. 120, pp. 88–116, 2017.

[14] G. Sharma, B. Thakur, A. Kumar, S. Sharma, M. Naushad, and F. J. Stadler, "Atrazine removal using chitin-cl-poly(-acrylamide-co-itaconic acid) nanohydrogel: isotherms and pH responsive nature," *Carbohydrate Polymers*, vol. 241, p. 116258, 2020.

[15] R. K. Liew, E. Azwar, P. N. Y. Yek et al., "Microwave pyrolysis with KOH/NaOH mixture activation: a new approach to produce micro-mesoporous activated carbon for textile dye adsorption," *Bioresource Technology*, vol. 266, pp. 1–10, 2018.

[16] Z. Hao, C. Wang, Z. Yan, H. Jiang, and H. Xu, "Magnetic particles modification of coconut shell-derived activated carbon and biochar for effective removal of phenol from water," *Chemosphere*, vol. 211, pp. 962–969, 2018.

[17] Y. Wang, Z. Liu, L. Zhan, Z. Huang, Q. Liu, and J. Ma, "Performance of an activated carbon honeycomb supported V_2O_5 catalyst in simultaneous SO_2 and NO removal," *Chemical Engineering Science*, vol. 59, pp. 5283–5290, 2004.

[18] A. C. Martins, O. Pezoti, A. L. Cazetta et al., "Removal of tetracycline by NaOH-activated carbon produced from macadamia nut shells: kinetic and equilibrium studies," *Chemical Engineering Journal*, vol. 260, pp. 291–299, 2015.

[19] T. Maneerung, J. Liew, Y. Dai, S. Kawi, C. Chong, and C.-H. Wang, "Activated carbon derived from carbon residue from biomass gasification and its application for dye adsorption: kinetics, isotherms and thermodynamic studies," *Bioresource Technology*, vol. 200, pp. 350–359, 2016.

[20] H. Demiral and C. Güngör, "Adsorption of copper (II) from aqueous solutions on activated carbon prepared from grape bagasse," *Journal of Cleaner Production*, vol. 124, pp. 103–113, 2016.

[21] C. Saucier, M. A. Adebayo, E. C. Lima et al., "Microwave-assisted activated carbon from cocoa shell as adsorbent for removal of sodium diclofenac and nimesulide from aqueous effluents," *Journal of Hazardous Materials*, vol. 289, pp. 18–27, 2015.

[22] K. C. Bedin, A. C. Martins, A. L. Cazetta, O. Pezoti, and V. C. Almeida, "KOH-activated carbon prepared from sucrose spherical carbon: adsorption equilibrium, kinetic and thermodynamic studies for methylene blue removal," *Chemical Engineering Journal*, vol. 286, pp. 476–484, 2016.

[23] H. Sayğılı, F. Güzel, and Y. Önal, "Conversion of grape industrial processing waste to activated carbon sorbent and its performance in cationic and anionic dyes adsorption," *Journal of Cleaner Production*, vol. 93, pp. 84–93, 2015.

[24] J. Yang, M. Yu, and W. Chen, "Adsorption of hexavalent chromium from aqueous solution by activated carbon prepared from longan seed: kinetics, equilibrium and thermodynamics," *Journal of Industrial and Engineering Chemistry*, vol. 21, pp. 414–422, 2015.

[25] M. Ghaedi, H. Mazaheri, S. Khodadoust, S. Hajati, and M. Purkait, "Application of central composite design for

simultaneous removal of methylene blue and Pb^{2+} ions by walnut wood activated carbon," *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 135, pp. 479–490, 2015.

[26] A. E. Ogungbenro, D. V. Quang, K. A. Al-Ali, L. F. Vega, and M. R. Abu-Zahra, "Physical synthesis and characterization of activated carbon from date seeds for CO_2 capture," *Journal of Environmental Chemical Engineering*, vol. 6, no. 4, pp. 4245–4252, 2018.

[27] S.-A. Sajjadi, A. Mohammadzadeh, H. N. Tran et al., "Efficient mercury removal from wastewater by pistachio wood wastes-derived activated carbon prepared by chemical activation using a novel activating agent," *Journal of Environmental Management*, vol. 223, pp. 1001–1009, 2018.

[28] G. G. V. Kumar, R. S. Kannan, T. C.-K. Yang, J. Rajesh, and G. Sivaraman, "An efficient "Ratiometric" fluorescent chemosensor for the selective detection of Hg^{2+} ions based on phosphonates: its live cell imaging and molecular keypad lock applications," *Analytical Methods*, vol. 11, pp. 901–916, 2019.

[29] G. Sharma, A. Kumar, A. A. Ghfar, A. García-Peñas, M. Naushad, and F. J. Stadler, "Fabrication and characterization of xanthan gum-cl-poly(acrylamide-co-alginic acid) hydrogel for adsorption of cadmium ions from aqueous medium," *Gels*, vol. 8, 2022.

[30] M. D. G. de Luna, E. D. Flores, D. A. D. Genuino, C. M. Futalan, and M.-W. Wan, "Adsorption of Eriochrome Black T (EBT) dye using activated carbon prepared from waste rice hulls–optimization, isotherm and kinetic studies," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 44, no. 4, pp. 646–653, 2013.

[31] Y.-S. Ho and G. McKay, "Pseudo-second order model for sorption processes," *Process Biochemistry*, vol. 34, pp. 451–465, 1999.

[32] G. Sharma, M. Naushad, A. Kumar et al., "Efficient removal of coomassie brilliant blue R-250 dye using starch/poly (alginic acid-cl-acrylamide) nanohydrogel," *Process Safety and Environmental Protection*, vol. 109, pp. 301–310, 2017.

[33] G. Sharma, A. Kumar, C. Chauhan et al., "Pectin-c _rosslinked_ -guar gum/SPION nanocomposite hydrogel for adsorption of m-cresol and o-chlorophenol," *Sustainable Chemistry and Pharmacy*, vol. 6, pp. 96–106, 2017.

[34] M. T. Yagub, T. K. Sen, S. Afroze, and H. M. Ang, "Dye and its removal from aqueous solution by adsorption: a review," *Advances in Colloid and Interface Science*, vol. 209, pp. 172–184, 2014.

[35] O. Moradi and G. Sharma, "Emerging novel polymeric adsorbents for removing dyes from wastewater: a comprehensive review and comparison with other adsorbents," *Environmental Research*, vol. 201, p. 111534, 2021.

[36] W. J. Weber and E. H. Smith, "Simulation and design models for adsorption processes," *Environmental Science & Technology*, vol. 21, pp. 1040–1050, 1987.

[37] R. W. Coughlin and F. S. Ezra, "Role of surface acidity in the adsorption of organic pollutants on the surface of carbon," *Environmental Science & Technology*, vol. 2, pp. 291–297, 1968.

[38] H. N. Tran, S.-J. You, and H.-P. Chao, "Effect of pyrolysis temperatures and times on the adsorption of cadmium onto orange peel derived biochar," *Waste Management & Research*, vol. 34, pp. 129–138, 2016.

[39] T. X. Bui and H. Choi, "Comment on "Adsorption and desorption of oxytetracycline and carbamazepine by multiwalled carbon nanotubes"," *Environmental Science & Technology*, vol. 44, pp. 4828–4828, 2010.

[40] Z. Jeirani, C. H. Niu, and J. Soltan, "Adsorption of emerging pollutants on activated carbon," *Reviews in Chemical Engineering*, vol. 33, pp. 491–522, 2017.

[41] N. Srivastava and C. Majumder, "Novel biofiltration methods for the treatment of heavy metals from industrial wastewater," *Journal of Hazardous Materials*, vol. 151, pp. 1–8, 2008.

[42] M. Naushad, S. Vasudevan, G. Sharma, A. Kumar, and Z. A. Alothman, "ALOthman, Adsorption kinetics, isotherms, and thermodynamic studies for Hg2+ adsorption from aqueous medium using alizarin red-S-loaded amberlite IRA-400 resin," *Desalination and Water Treatment*, vol. 57, pp. 18551–18559, 2016.

[43] M. Naushad, Z. A. ALOthman, and G. Sharma, "Kinetics, isotherm and thermodynamic investigations for the adsorption of Co (II) ion onto crystal violet modified amberlite IR-120 resin," *Ionics*, vol. 21, pp. 1453–1459, 2015.

[44] G. Sharma, D. Pathania, M. Naushad, and N. Kothiyal, "Fabrication, characterization and antimicrobial activity of polyaniline Th (IV) tungstomolybdophosphate nanocomposite material: efficient removal of toxic metal ions from water," *Chemical Engineering Journal*, vol. 251, pp. 413–421, 2014.

[45] C. Namasivayam and K. Kadirvelu, "Uptake of mercury (II) from wastewater by activated carbon from an unwanted agricultural solid by-product: coirpith," *Carbon*, vol. 37, no. 1, pp. 79–84, 1999.

[46] R. Naseem and S. Tahir, "Removal of Pb (II) from aqueous/acidic solutions by using bentonite as an adsorbent," *Water Research*, vol. 35, pp. 3982–3986, 2001.

[47] G. Sharma, M. Naushad, H. Ala'a et al., "Fabrication and characterization of chitosan- _crosslinked_ -poly(alginic acid) nanohydrogel for adsorptive removal of Cr(VI) metal ion from aqueous medium," *International Journal of Biological Macromolecules*, vol. 95, pp. 484–493, 2017.

[48] L. Khezami and R. Capart, "Removal of chromium (VI) from aqueous solution by activated carbons: kinetic and equilibrium studies," *Journal of Hazardous Materials*, vol. 123, pp. 223–231, 2005.

[49] I. Morosanu, C. Teodosiu, C. Paduraru, D. Ibanescu, and L. Tofan, "Biosorption of lead ions from aqueous effluents by rapeseed biomass," *New Biotechnology*, vol. 39, pp. 110–124, 2017.

[50] M. Sekar, V. Sakthi, and S. Rengaraj, "Kinetics and equilibrium adsorption study of lead (II) onto activated carbon prepared from coconut shell," *Journal of Colloid and Interface Science*, vol. 279, pp. 307–313, 2004.

[51] K. Kadirvelu, K. Thamaraiselvi, and C. Namasivayam, "Adsorption of nickel (II) from aqueous solution onto activated carbon prepared from coirpith," *Separation and Purification Technology*, vol. 24, pp. 497–505, 2001.

[52] A.-N. A. El-Hendawy, "The role of surface chemistry and solution pH on the removal of Pb^{2+} and Cd^{2+} ions via effective adsorbents from low-cost biomass," *Journal of Hazardous Materials*, vol. 167, pp. 260–267, 2009.

[53] P. O. Ameh, "Modeling of the adsorption of Cu (II) and Cd (II) from aqueous solution by Iraqi palm-date activated carbon (IPDAC)," *International Journal of Modern Chemistry*, vol. 5, pp. 136–144, 2013.

[54] V. C. Srivastava, I. D. Mall, and I. M. Mishra, "Adsorption of toxic metal ions onto activated carbon: study of sorption behaviour through characterization and kinetics," *Chemical Engineering and Processing: Process Intensification*, vol. 47, pp. 1269–1280, 2008.

[55] K. Kadirvelu and C. Namasivayam, "Activated carbon from coconut coirpith as metal adsorbent: adsorption of Cd(II) from aqueous solution," *Advances in Environmental Research*, vol. 7, no. 2, pp. 471–478, 2003.

[56] M. Kobya, E. Demirbas, E. Senturk, and M. Ince, "Adsorption of heavy metal ions from aqueous solutions by activated carbon prepared from apricot stone," *Bioresource Technology*, vol. 96, pp. 1518–1521, 2005.

[57] V. Gupta, S. Srivastava, D. Mohan, and S. Sharma, "Design parameters for fixed bed reactors of activated carbon developed from fertilizer waste for the removal of some heavy metal ions," *Waste Management*, vol. 17, no. 8, pp. 517–522, 1998.

[58] D. Mohan and K. P. Singh, "Single-and multi-component adsorption of cadmium and zinc using activated carbon derived from bagasse—an agricultural waste," *Water Research*, vol. 36, pp. 2304–2318, 2002.

[59] G. Z. Kyzas, G. Bomis, R. I. Kosheleva et al., "Nanobubbles effect on heavy metal ions adsorption by activated carbon," *Chemical Engineering Journal*, vol. 356, pp. 91–97, 2019.

[60] J. Dich, S. H. Zahm, A. Hanberg, and H.-O. Adami, "Pesticides and cancer," *Cancer Causes & Control*, vol. 8, pp. 420–443, 1997.

[61] M. Gavrilescu, "Fate of pesticides in the environment and its bioremediation," *Engineering in Life Sciences*, vol. 5, pp. 497–526, 2005.

[62] G. Sharma, A. Kumar, K. Devi et al., "Guar gum-crosslinked-soya lecithin nanohydrogel sheets as effective adsorbent for the removal of thiophanate methyl fungicide," *International Journal of Biological Macromolecules*, vol. 114, pp. 295–305, 2018.

[63] A. Hossain, K. Sakthipandi, A. A. Ullah, and S. Roy, "Recent progress and approaches on carbon-free energy from water splitting," *Nano-Micro Letters*, vol. 11, pp. 1–26, 2019.

[64] E. Ayranci and N. Hoda, "Adsorption kinetics and isotherms of pesticides onto activated carbon-cloth," *Chemosphere*, vol. 60, pp. 1600–1607, 2005.

[65] A. L. Ahmad, L. Tan, and S. A. Shukor, "Dimethoate and atrazine retention from aqueous solution by nanofiltration membranes," *Journal of Hazardous Materials*, vol. 151, pp. 71–77, 2008.

[66] F. K. Yuen and B. Hameed, "Recent developments in the preparation and regeneration of activated carbons by microwaves," *Advances in Colloid and Interface Science*, vol. 149, pp. 19–27, 2009.

[67] C.-F. Chang, C.-Y. Chang, K.-E. Hsu, S.-C. Lee, and W. Höll, "Adsorptive removal of the pesticide methomyl using hypercrosslinked polymers," *Journal of Hazardous Materials*, vol. 155, no. 1-2, pp. 295–304, 2008.

[68] W. K. Lafi and Z. Al-Qodah, "Combined advanced oxidation and biological treatment processes for the removal of pesticides from aqueous solutions," *Journal of Hazardous Materials*, vol. 137, pp. 489–497, 2006.

[69] B. Hameed, J. Salman, and A. Ahmad, "Adsorption isotherm and kinetic modeling of 2,4-D pesticide on activated carbon derived from date stones," *Journal of Hazardous Materials*, vol. 163, no. 1, pp. 121–126, 2009.

[70] P. Chingombe, B. Saha, and R. Wakeman, "Effect of surface modification of an engineered activated carbon on the sorption of 2, 4-dichlorophenoxy acetic acid and benazolin from water," *Journal of Colloid and Interface Science*, vol. 297, pp. 434–442, 2006.

[71] O. Adam, M. Bitschené, G. Torri, F. De Giorgi, P.-M. Badot, and G. Crini, "Studies on adsorption of propiconazole on modified carbons," *Separation and Purification Technology*, vol. 46, pp. 11–18, 2005.

[72] J.-W. Yoo, T.-Y. Kim, S.-Y. Cho, S.-G. Rho, and S.-J. Kim, "Adsorption and desorption characteristics of maltooligosaccharide for the surface treated activated carbons," *Adsorption*, vol. 11, pp. 719–723, 2005.

[73] J. Salman, V. Njoku, and B. Hameed, "Adsorption of pesticides from aqueous solution onto banana stalk activated carbon," *Chemical Engineering Journal*, vol. 174, no. 1, pp. 41–48, 2011.

[74] C. Faur, H. MEtivier-Pignon, and P. Le Cloirec, "Multicomponent adsorption of pesticides onto activated carbon fibers," *Adsorption*, vol. 11, pp. 479–490, 2005.

[75] V. Gupta, B. Gupta, A. Rastogi, S. Agarwal, and A. Nayak, "Pesticides removal from waste water by activated carbon prepared from waste rubber tire," *Water Research*, vol. 45, no. 13, pp. 4047–4055, 2011.

[76] A. Spaltro, S. Simonetti, S. A. Torrellas et al., "Adsorption of bentazon on CAT and CARBOPAL activated carbon: experimental and computational study," *Applied Surface Science*, vol. 433, pp. 487–501, 2018.

[77] J. Sotelo, G. Ovejero, J. Delgado, and I. Martınez, "Adsorption of lindane from water onto GAC: effect of carbon loading on kinetic behavior," *Chemical Engineering Journal*, vol. 87, pp. 111–120, 2002.

[78] O. Kitous, A. Cheikh, H. Lounici, H. Grib, A. Pauss, and N. Mameri, "Application of the electrosorption technique to remove Metribuzin pesticide," *Journal of Hazardous Materials*, vol. 161, no. 2-3, pp. 1035–1039, 2009.

[79] N. K. Hamadi, S. Swaminathan, and X. D. Chen, "Adsorption of paraquat dichloride from aqueous solution by activated carbon derived from used tires," *Journal of Hazardous Materials*, vol. 112, pp. 133–141, 2004.

[80] A. H. El-Sheikh, J. A. Sweileh, Y. S. Al-Degs, A. A. Insisi, and N. Al-Rabady, "Critical evaluation and comparison of enrichment efficiency of multi-walled carbon nanotubes, C18 silica and activated carbon towards some pesticides from environmental waters," *Talanta*, vol. 74, pp. 1675–1680, 2008.

[81] T.-Y. Kim, S.-S. Park, S.-J. Kim, and S.-Y. Cho, "Separation characteristics of some phenoxy herbicides from aqueous solution," *Adsorption*, vol. 14, p. 611, 2008.

[82] Y. Yang, Y. Chun, G. Sheng, and M. Huang, "pH-dependence of pesticide adsorption by wheat-residue-derived black carbon," *Langmuir*, vol. 20, pp. 6736–6741, 2004.

[83] J.-Y. Hu, T. Aizawa, Y. Ookubo, T. Morita, and Y. Magara, "Adsorptive characteristics of ionogenic aromatic pesticides in water on powdered activated carbon," *Water Research*, vol. 32, pp. 2593–2600, 1998.

[84] J. Salman, V. Njoku, and B. Hameed, "Bentazon and carbofuran adsorption onto date seed activated carbon: kinetics and equilibrium," *Chemical Engineering Journal*, vol. 173, no. 2, pp. 361–368, 2011.

[85] S. Álvarez-Torrellas, A. Rodríguez, G. Ovejero, and J. García, "Comparative adsorption performance of ibuprofen and

tetracycline from aqueous solution by carbonaceous materials," *Chemical Engineering Journal*, vol. 283, pp. 936–947, 2016.

[86] F. Güzel and H. Sayğılı, "Adsorptive efficacy analysis of novel carbonaceous sorbent derived from grape industrial processing wastes towards tetracycline in aqueous solution," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 60, pp. 236–240, 2016.

[87] W. Liu, J. Zhang, C. Zhang, and L. Ren, "Sorption of norfloxacin by lotus stalk-based activated carbon and iron-doped activated alumina: mechanisms, isotherms and kinetics," *Chemical Engineering Journal*, vol. 171, pp. 431–438, 2011.

[88] G. Moussavi, A. Alahabadi, K. Yaghmaeian, and M. Eskandari, "Preparation, characterization and adsorption potential of the NH_4Cl-induced activated carbon for the removal of amoxicillin antibiotic from water," *Chemical Engineering Journal*, vol. 217, pp. 119–128, 2013.

[89] H. Pouretedal and N. Sadegh, "Effective removal of amoxicillin, cephalexin, tetracycline and penicillin G from aqueous solutions using activated carbon nanoparticles prepared from vine wood," *Journal of Water Process Engineering*, vol. 1, pp. 64–73, 2014.

[90] H. Mansouri, R. J. Carmona, A. Gomis-Berenguer, S. Souissi-Najar, A. Ouederni, and C. O. Ania, "Competitive adsorption of ibuprofen and amoxicillin mixtures from aqueous solution on activated carbons," *Journal of Colloid and Interface Science*, vol. 449, pp. 252–260, 2015.

[91] Y. Sun, Q. Yue, B. Gao et al., "Preparation of activated carbon derived from cotton linter fibers by fused NaOH activation and its application for oxytetracycline (OTC) adsorption," *Journal of Colloid and Interface Science*, vol. 368, pp. 521–527, 2012.

[92] D. Zhang, J. Yin, J. Zhao, H. Zhu, and C. Wang, "Adsorption and removal of tetracycline from water by petroleum coke-derived highly porous activated carbon," *Journal of Environmental Chemical Engineering*, vol. 3, pp. 1504–1512, 2015.

[93] R. Acosta, V. Fierro, A. M. de Yuso, D. Nabarlatz, and A. Celzard, "Tetracycline adsorption onto activated carbons produced by KOH activation of tyre pyrolysis char," *Chemosphere*, vol. 149, pp. 168–176, 2016.

[94] A. Ahmad, S. H. Mohd-Setapar, C. S. Chuong et al., "Recent advances in new generation dye removal technologies: novel search for approaches to reprocess wastewater," *RSC Advances*, vol. 5, no. 39, pp. 30801–30818, 2015.

[95] J. Abdi, M. Vossoughi, N. M. Mahmoodi, and I. Alemzadeh, "Synthesis of metal-organic framework hybrid nanocomposites based on GO and CNT with high adsorption capacity for dye removal," *Chemical Engineering Journal*, vol. 326, pp. 1145–1158, 2017.

[96] G. Sharma, A. Kumar, M. Naushad et al., "Fabrication and characterization of gum arabic-cl-poly (acrylamide) nanohydrogel for effective adsorption of crystal violet dye," *Carbohydrate Polymers*, vol. 202, pp. 444–453, 2018.

[97] G. Sharma, A. Khosla, A. Kumar et al., "A comprehensive review on the removal of noxious pollutants using carrageenan based advanced adsorbents," *Chemosphere*, vol. 289, p. 133100, 2022.

[98] M. Purkait, S. DasGupta, and S. De, "Adsorption of eosin dye on activated carbon and its surfactant based desorption," *Journal of Environmental Management*, vol. 76, pp. 135–142, 2005.

[99] A. Sharma, G. Sharma, M. Naushad, A. A. Ghfar, and D. Pathania, "Remediation of anionic dye from aqueous system using bio-adsorbent prepared by microwave activation," *Environmental Technology*, vol. 39, pp. 917–930, 2018.

[100] G. Sharma, A. Kumar, M. Naushad et al., "Adsorptional-photocatalytic removal of fast sulphon black dye by using chitin-cl-poly(itaconic acid-co-acrylamide)/zirconium tungstate nanocomposite hydrogel," *Journal of Hazardous Materials*, vol. 416, p. 125714, 2021.

[101] G. Sharma, B. Thakur, M. Naushad et al., "Applications of nanocomposite hydrogels for biomedical engineering and environmental protection," *Environmental Chemistry Letters*, vol. 16, pp. 113–146, 2018.

[102] S. A. Ganiyu, O. O. Ajumobi, S. A. Lateef et al., "Boron-doped activated carbon as efficient and selective adsorbent for ultra-deep desulfurization of 4, 6-dimethyldibenzothiophene," *Chemical Engineering Journal*, vol. 321, pp. 651–661, 2017.

[103] L. Liu, J. Zhang, Y. Tan et al., "Rapid decolorization of anthraquinone and triphenylmethane dye using chloroperoxidase: catalytic mechanism, analysis of products and degradation route," *Chemical Engineering Journal*, vol. 244, pp. 9–18, 2014.

[104] G. Sharma, M. Naushad, D. Pathania, A. Mittal, and G. El-Desoky, "Modification of Hibiscus cannabinus fiber by graft copolymerization: application for dye removal," *Desalination and Water Treatment*, vol. 54, no. 11, pp. 3114–3121, 2015.

[105] C. Namasivayam and D. Kavitha, "Removal of Congo Red from water by adsorption onto activated carbon prepared from coir pith, an agricultural solid waste," *Dyes and Pigments*, vol. 54, pp. 47–58, 2002.

[106] I. Tan, B. Hameed, and A. Ahmad, "Equilibrium and kinetic studies on basic dye adsorption by oil palm fibre activated carbon," *Chemical Engineering Journal*, vol. 127, pp. 111–119, 2007.

[107] B. Hameed, A. Ahmad, and K. Latiff, "Adsorption of basic dye (methylene blue) onto activated carbon prepared from rattan sawdust," *Dyes and Pigments*, vol. 75, pp. 143–149, 2007.

[108] C. Djilani, R. Zaghdoudi, F. Djazi et al., "Adsorption of dyes on activated carbon prepared from apricot stones and commercial activated carbon," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 53, pp. 112–121, 2015.

[109] M. Özacar and İ. A. Şengil, "Adsorption of metal complex dyes from aqueous solutions by pine sawdust," *Bioresource Technology*, vol. 96, pp. 791–795, 2005.

[110] W. Liu, X. Wang, and M. Zhang, "Preparation of highly mesoporous wood-derived activated carbon fiber and the mechanism of its porosity development," *Holzforschung*, vol. 71, pp. 363–371, 2017.

[111] E. Ghasemian Lemraski, S. Sharafinia, and M. Alimohammadi, "New activated carbon from Persian mesquite grain as an excellent adsorbent," *Physical Chemistry Research*, vol. 5, pp. 81–98, 2017.

[112] A. A. Spagnoli, D. A. Giannakoudakis, and S. Bashkova, "Adsorption of methylene blue on cashew nut shell based carbons activated with zinc chloride: the role of surface and structural parameters," *Journal of Molecular Liquids*, vol. 229, pp. 465–471, 2017.

[113] M. Danish, T. Ahmad, S. Majeed et al., "Use of banana trunk waste as activated carbon in scavenging methylene blue dye:

kinetic, thermodynamic, and isotherm studies," *Bioresource Technology Reports*, vol. 3, pp. 127–137, 2018.

[114] T. S. Kazeem, S. A. Lateef, S. A. Ganiyu et al., "Aluminium-modified activated carbon as efficient adsorbent for cleaning of cationic dye in wastewater," *Journal of Cleaner Production*, vol. 205, pp. 303–312, 2018.

[115] M. Goswami and P. Phukan, "Enhanced adsorption of cationic dyes using sulfonic acid modified activated carbon," *Journal of Environmental Chemical Engineering*, vol. 5, pp. 3508–3517, 2017.

[116] E. N. El Qada, S. J. Allen, and G. M. Walker, "Adsorption of methylene blue onto activated carbon produced from steam activated bituminous coal: a study of equilibrium adsorption isotherm," *Chemical Engineering Journal*, vol. 124, no. 1-3, pp. 103–110, 2006.

[117] J.-J. Gao, Y.-B. Qin, T. Zhou et al., "Adsorption of methylene blue onto activated carbon produced from tea (Camellia sinensis L.) seed shells: kinetics, equilibrium, and thermodynamics studies," *Journal of Zhejiang University Science B*, vol. 14, no. 7, pp. 650–658, 2013.

[118] O. S. Bello, I. A. Adeogun, J. C. Ajaelu, and E. O. Fehintola, "Adsorption of methylene blue onto activated carbon derived from periwinkle shells: kinetics and equilibrium studies," *Chemistry and Ecology*, vol. 24, pp. 285–295, 2008.

[119] A. H. Jawad, R. A. Rashid, M. A. M. Ishak, and L. D. Wilson, "Adsorption of methylene blue onto activated carbon developed from biomass waste by H_2SO_4 activation: kinetic, equilibrium and thermodynamic studies," *Desalination and Water Treatment*, vol. 57, pp. 25194–25206, 2016.

[120] S. Azizian, M. Haerifar, and H. Bashiri, "Adsorption of methyl violet onto granular activated carbon: equilibrium, kinetics and modeling," *Chemical Engineering Journal*, vol. 146, pp. 36–41, 2009.

[121] A. M. Din, C. Foo, B. Hameed, and A. Ahmad, "Adsorption of methyl violet dye onto acid modified activated carbon: isotherms and thermodynamic analyses," in *12th APCChE Congress*, vol. 5-133, Dalian, China, 2008.

[122] O. S. Bello and M. A. Ahmad, "Coconut (Cocos nucifera) shell based activated carbon for the removal of malachite green dye from aqueous solutions," *Separation Science and Technology*, vol. 47, pp. 903–912, 2012.

[123] W. Liu, C. Yao, M. Wang, J. Ji, L. Ying, and C. Fu, "Kinetics and thermodynamics characteristics of cationic yellow X-GL adsorption on attapulgite/rice hull-based activated carbon nanocomposites," *Environmental Progress & Sustainable Energy*, vol. 32, no. 3, pp. 655–662, 2013.

[124] J. Yang and K. Qiu, "Preparation of activated carbons from walnut shells via vacuum chemical activation and their application for methylene blue removal," *Chemical Engineering Journal*, vol. 165, pp. 209–217, 2010.

[125] R. Malik, D. Ramteke, and S. Wate, "Adsorption of malachite green on groundnut shell waste based powdered activated carbon," *Waste Management*, vol. 27, pp. 1129–1138, 2007.

[126] K.-L. Chiu and D. H. Ng, "Synthesis and characterization of cotton-made activated carbon fiber and its adsorption of methylene blue in water treatment," *Biomass and Bioenergy*, vol. 46, pp. 102–110, 2012.

[127] Y. Gao, W. Zhang, Q. Yue et al., "Simple synthesis of hierarchical porous carbon from Enteromorpha prolifera by a self-template method for supercapacitor electrodes," *Journal of Power Sources*, vol. 270, pp. 403–410, 2014.

[128] M. J. Ahmed and S. K. Theydan, "Optimization of microwave preparation conditions for activated carbon from _Albizia lebbeck_ seed pods for methylene blue dye adsorption," *Journal of Analytical and Applied Pyrolysis*, vol. 105, pp. 199–208, 2014.

[129] G. Karaçetin, S. Sivrikaya, and M. Imamoğlu, "Adsorption of methylene blue from aqueous solutions by activated carbon prepared from hazelnut husk using zinc chloride," *Journal of Analytical and Applied Pyrolysis*, vol. 110, pp. 270–276, 2014.

[130] O. P. Junior, A. L. Cazetta, R. C. Gomes et al., "Synthesis of $ZnCl_2$-activated carbon from macadamia nut endocarp (Macadamia integrifolia) by microwave-assisted pyrolysis: optimization using RSM and methylene blue adsorption," *Journal of Analytical and Applied Pyrolysis*, vol. 105, pp. 166–176, 2014.

[131] A. Ahmad, M. Loh, and J. Aziz, "Preparation and characterization of activated carbon from oil palm wood and its evaluation on methylene blue adsorption," *Dyes and Pigments*, vol. 75, no. 2, pp. 263–272, 2007.

[132] M. Berrios, M. Á. Martín, and A. Martín, "Treatment of pollutants in wastewater: adsorption of methylene blue onto olive-based activated carbon," *Journal of Industrial and Engineering Chemistry*, vol. 18, pp. 780–784, 2012.

[133] M. Kumar and R. Tamilarasan, "Modeling studies for the removal of methylene blue from aqueous solution using Acacia fumosa seed shell activated carbon," *Journal of Environmental Chemical Engineering*, vol. 1, pp. 1108–1116, 2013.

[134] S. Altenor, B. Carene, E. Emmanuel, J. Lambert, J.-J. Ehrhardt, and S. Gaspard, "Adsorption studies of methylene blue and phenol onto vetiver roots activated carbon prepared by chemical activation," *Journal of Hazardous Materials*, vol. 165, pp. 1029–1039, 2009.

[135] Y. Gokce and Z. Aktas, "Nitric acid modification of activated carbon produced from waste tea and adsorption of methylene blue and phenol," *Applied Surface Science*, vol. 313, pp. 352–359, 2014.

[136] M. J. Ahmed and S. K. Dhedan, "Equilibrium isotherms and kinetics modeling of methylene blue adsorption on agricultural wastes-based activated carbons," *Fluid Phase Equilibria*, vol. 317, pp. 9–14, 2012.

[137] X. Zhang, B. Gao, A. E. Creamer, C. Cao, and Y. Li, "Adsorption of VOCs onto engineered carbon materials: a review," *Journal of Hazardous Materials*, vol. 338, pp. 102–123, 2017.

[138] L. A. Rodrigues, M. L. C. P. da Silva, M. O. Alvarez-Mendes, A. dos Reis Coutinho, and G. P. Thim, "Phenol removal from aqueous solution by activated carbon produced from avocado kernel seeds," *Chemical Engineering Journal*, vol. 174, no. 1, pp. 49–57, 2011.

[139] Y. Tham, P. A. Latif, A. Abdullah, A. Shamala-Devi, and Y. Taufiq-Yap, "Performances of toluene removal by activated carbon derived from durian shell," *Bioresource Technology*, vol. 102, pp. 724–728, 2011.

[140] J. V. Nabais, J. Gomes, P. Carrott, C. Laginhas, and S. Roman, "Phenol removal onto novel activated carbons made from lignocellulosic precursors: influence of surface properties," *Journal of Hazardous Materials*, vol. 167, pp. 904–910, 2009.

[141] S. Suganuma, K. Nakajima, M. Kitano et al., "Hydrolysis of cellulose by amorphous carbon bearing SO_3H, COOH, and OH groups," *Journal of the American Chemical Society*, vol. 130, no. 38, pp. 12787–12793, 2008.

[142] E. Lam and J. H. Luong, “Carbon materials as catalyst supports and catalysts in the transformation of biomass to fuels and chemicals,” *ACS Catalysis*, vol. 4, pp. 3393–3410, 2014.

[143] J. Han, J. Duan, P. Chen, H. Lou, and X. Zheng, “Molybdenum carbide-catalyzed conversion of renewable oils into diesel-like hydrocarbons,” *Advanced Synthesis & Catalysis*, vol. 353, pp. 2577–2583, 2011.

[144] M. M. Perez, C. S. M. de Lecea, and A. L. Solano, “Platinum supported on activated carbon cloths as catalyst for nitrobenzene hydrogenation,” *Applied Catalysis A: General*, vol. 151, pp. 461–475, 1997.

[145] P. R. Shukla, S. Wang, H. Sun, H. M. Ang, and M. Tadé, “Activated carbon supported cobalt catalysts for advanced oxidation of organic contaminants in aqueous solution,” *Applied Catalysis B: Environmental*, vol. 100, no. 3-4, pp. 529–534, 2010.

[146] A. Silem, A. Boualia, R. Kada, and A. Mellah, “Adsorption of organic matter from a wet phosphoric acid using activated carbon: batch-contact time study and linear driving force models,” *Canadian Journal of Chemical Engineering*, vol. 70, pp. 491–498, 1992.

[147] F. Dong, H. Lou, A. Kodama, M. Goto, and T. Hirose, “The Petlyuk PSA process for the separation of ternary gas mixtures: exemplification by separating a mixture of CO_2–CH_4–N_2,” *Separation and Purification Technology*, vol. 16, pp. 159–166, 1999.

[148] A. L. Chaffee, G. P. Knowles, Z. Liang, J. Zhang, P. Xiao, and P. A. Webley, “CO_2 capture by adsorption: materials and process development,” *International Journal of Greenhouse Gas Control*, vol. 1, pp. 11–18, 2007.

[149] B. Stöhr, H. Boehm, and R. Schlögl, “Enhancement of the catalytic activity of activated carbons in oxidation reactions by thermal treatment with ammonia or hydrogen cyanide and observation of a superoxide species as a possible intermediate,” *Carbon*, vol. 29, pp. 707–720, 1991.

[150] M. Sabo, A. Henschel, H. Fröde, E. Klemm, and S. Kaskel, “Solution infiltration of palladium into MOF-5: synthesis, physisorption and catalytic properties,” *Journal of Materials Chemistry*, vol. 17, pp. 3827–3832, 2007.

[151] S.-H. Yeon, S. Osswald, Y. Gogotsi et al., “Enhanced methane storage of chemically and physically activated carbide-derived carbon,” *Journal of Power Sources*, vol. 191, no. 2, pp. 560–567, 2009.

[152] H. T. Hwang and A. Varma, “Hydrogen storage for fuel cell vehicles,” *Current Opinion in Chemical Engineering*, vol. 5, pp. 42–48, 2014.

[153] K. Babeł and K. Jurewicz, “KOH activated lignin based nanostructured carbon exhibiting high hydrogen electrosorption,” *Carbon*, vol. 46, pp. 1948–1956, 2008.

[154] Y.-J. Heo and S.-J. Park, “Synthesis of activated carbon derived from rice husks for improving hydrogen storage capacity,” *Journal of Industrial and Engineering Chemistry*, vol. 31, pp. 330–334, 2015.

[155] W. Djeridi, N. B. Mansour, A. Ouederni, P. Llewellyn, and L. El Mir, “Influence of the raw material and nickel oxide on the CH_4 capture capacity behaviors of microporous carbon,” *International Journal of Hydrogen Energy*, vol. 40, pp. 13690–13701, 2015.

[156] J. Sreńscek-Nazzal, W. Kamińska, B. Michalkiewicz, and Z. C. Koren, “Production, characterization and methane storage potential of KOH-activated carbon from sugarcane molasses,” *Industrial Crops and Products*, vol. 47, pp. 153–159, 2013.

[157] A. Alabadi, S. Razzaque, Y. Yang, S. Chen, and B. Tan, “Highly porous activated carbon materials from carbonized biomass with high CO_2 capturing capacity,” *Chemical Engineering Journal*, vol. 281, pp. 606–612, 2015.

[158] Y. Sha, J. Lou, S. Bai, D. Wu, B. Liu, and Y. Ling, “Facile preparation of nitrogen-doped porous carbon from waste tobacco by a simple pre-treatment process and their application in electrochemical capacitor and CO_2 capture,” *Materials Research Bulletin*, vol. 64, pp. 327–332, 2015.

[159] M. Plaza, A. González, C. Pevida, J. Pis, and F. Rubiera, “Valorisation of spent coffee grounds as CO_2 adsorbents for post-combustion capture applications,” *Applied Energy*, vol. 99, pp. 272–279, 2012.

[160] G. San Miguel, S. Lambert, and N. Graham, “The regeneration of field-spent granular-activated carbons,” *Water Research*, vol. 35, pp. 2740–2748, 2001.

[161] Q. Li, Y. Qi, and C. Gao, “Chemical regeneration of spent powdered activated carbon used in decolorization of sodium salicylate for the pharmaceutical industry,” *Journal of Cleaner Production*, vol. 86, pp. 424–431, 2015.

[162] Y. Han, X. Quan, S. Chen, H. Zhao, C. Cui, and Y. Zhao, “Electrochemically enhanced adsorption of aniline on activated carbon fibers,” *Separation and Purification Technology*, vol. 50, pp. 365–372, 2006.

[163] Ö. Aktaş and F. Çeçen, “Adsorption, desorption and bioregeneration in the treatment of 2-chlorophenol with activated carbon,” *Journal of Hazardous Materials*, vol. 141, pp. 769–777, 2007.

[164] M. El Gamal, H. A. Mousa, M. H. El-Naas, R. Zacharia, S. J. S. Judd, and P. Technology, “Bio-regeneration of activated carbon: a comprehensive review,” *Separation and Purification Technology*, vol. 197, pp. 345–359, 2018.