

## CHAPTER 1

# *Activated Carbon: Fundamentals, Classification, and Properties*

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## 1.1 Introduction

Activated carbon (AC), also known as activated charcoal, is a rough, imperfectly structured kind of graphite. It has a wide spectrum of pores of varying sizes, from obvious fractures and fissures to molecular dimensions. Because of its significant surface area, AC is frequently utilized for a variety of purposes, including removing impurities from air and water. Small, low-volume pores that are present in AC enhance the surface area that is accessible for chemical reactions such as adsorption (which is different from absorption). Before activation, charcoal has a specific surface area of 2.0 to 5.0 m<sup>2</sup> g<sup>-1</sup>, which increases to 1000 m<sup>2</sup> g<sup>-1</sup> once activated. Gas adsorption analysis suggests that one gram of AC has more than 3000 m<sup>2</sup> surface area because of its high level of microporosity that can deliver a high activation level for practical application. Adsorption of molecules is reinforced on AC

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Activated Carbon: Progress and Applications

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by London dispersion forces (van der Waals forces), gas-phase adsorption and liquid-phase adsorption. Descriptions of the forces that occur between molecules are as follows:

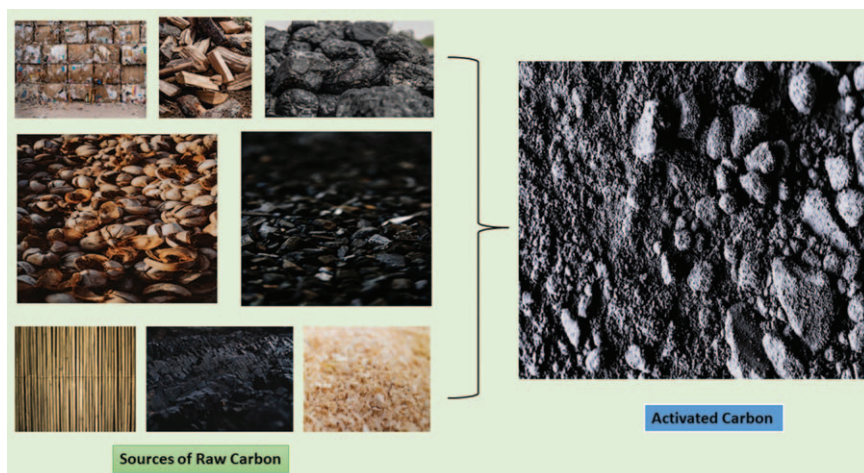
- (a) London dispersion forces: these have an extremely small range and are sensitive to the distance between the adsorbate molecule and the surface of the carbon. Additionally, they are additive, which means that the adsorption force is the sum of all atomic interactions. Due to the short-range and cumulative nature of these forces, AC has the strongest physical adsorption forces among substances known to mankind.
- (b) Gas-phase adsorption: air, natural gas, chemicals, and petrochemicals are typically purified or separated on a large scale using gas-phase adsorption. When gas is exposed to an adsorbent, it draws molecules to its surface where they concentrate and are drawn away from the gas phase. This condensation process causes the bulk-phase molecules to condense in the pores of the AC. The ratio of the compound's partial pressure to vapour pressure controls the adsorption process.
- (c) Liquid-phase adsorption: the adhesion of ions, molecules, or atoms from a liquid to a surface is known as liquid-phase adsorption. An adsorbate layer is formed on the adsorbent's surface as a result of this action. The molecules move from the bulk phase and get adsorbed in the pores in a semi-liquid state. The relationship between a compound's concentration and solubility is what drives adsorption.

On AC, all substances can adsorb to some degree. In actual use, AC is utilized to adsorb mostly organic molecules as well as some inorganic substances with higher molecular weights, such as iodine and mercury. An increase in a compound's adsorbability is typically correlated with its molecular weight, the functional groups attached, like halogens or double bonds, and its polarizability.

Adsorption characteristics are frequently improved by additional chemical treatment. Typically, waste materials like coconut husks,<sup>1-3</sup> paper mill waste,<sup>4-6</sup> coal (bituminous coal, anthracite coal, lignite/brown coal, sub-bituminous coal, *etc.*),<sup>7-10</sup> phenolic resins,<sup>11-13</sup> rayon,<sup>14</sup> wood,<sup>15</sup> acrylonitrile,<sup>16</sup> coal tar pitch,<sup>17</sup> petroleum pitch,<sup>18</sup> sawdust, grass ash (peat),<sup>19</sup> bamboo,<sup>20-23</sup> willow peat,<sup>24</sup> and coir<sup>25</sup> are used to manufacture AC (Figure 1.1). Before being "activated," these raw materials are turned into charcoal. Activated coal is the name given to material that is derived from coal.

### 1.1.1 Structure of AC

The structure of AC has a significant impact on its ability to absorb substances. AC and pure graphite have fundamental chemical structures that are very similar. The layers of fused hexagons that make up the graphite crystal are kept unified by weak van der Waals forces. The structure of AC differs from that of graphite in terms of the distance between layers. The interlayer spacing is 0.34 to 0.35 nm in AC, while it is 0.33 nm in graphite. ACs are divided into

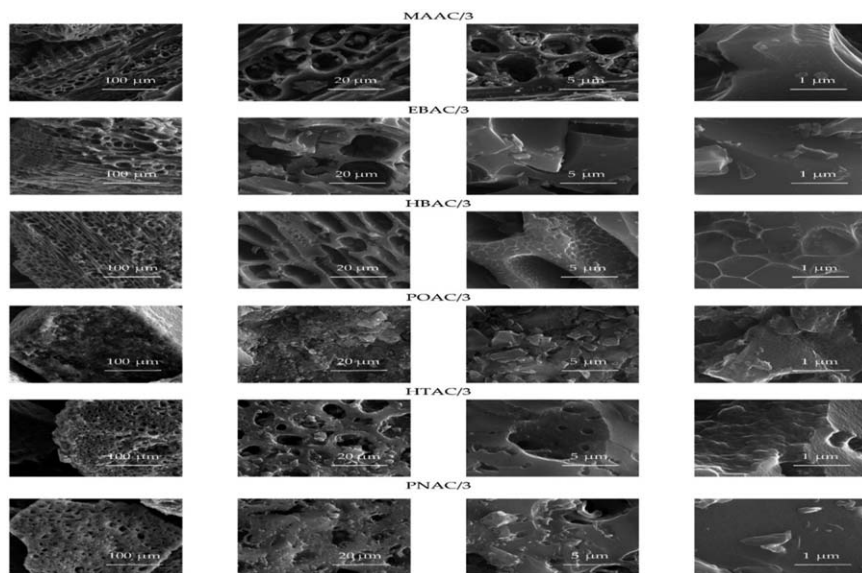


**Figure 1.1** Raw sources of AC.

graphitizing and non-graphitizing varieties based on their ability to form graphite. There are several graphene layers in the graphitizing carbon that are positioned parallel to one another. Because of the weak cross-linking between the nearby microcrystallites and the underdeveloped porous structure, the carbon produced is sensitive. The strong cross-linking between crystallites makes the non-graphitizing carbons tough, and they exhibit a well-developed microporous structure.<sup>26,27</sup> When linked oxygen is present or when the amount of hydrogen in the initial raw material is insufficient, non-graphitizing structures with strong crosslinks can form more readily. Carbon-carbon bonds hold the layers together. The AC's ultimate features, which include its pore structure, are largely influenced by the raw material and manufacturing process. It has long been controversial to identify the structure of AC. Harry Marsh and Francisco Rodriguez-Reinoso examined more than 15 models for the structure which is mentioned in their book released in 2006, but they were unable to determine which was the most accurate.<sup>28,29</sup> The structure of ACs consists of heptagonal and pentagonal rings which are quite similar to the fullerene structure, according to recent research utilizing aberration-corrected transmission electron microscopy.<sup>29</sup>

The raw material's structure also affects the porous structure and useful properties of carbonaceous adsorbents. As a result, selecting an appropriate material is just as crucial as choosing an appropriate production technology and figuring out the ideal processing conditions. As a result, efforts have been made to find novel raw resources that could be used in the creation of carbonaceous adsorbents. In particular, biomass waste from wood, food, and other sources as well as agriculture has attracted attention in this respect.

The manufacturing of biomass waste-derived ACs could boost economic returns and lower pollution because wood processing, carpentry, and other



**Figure 1.2** SEM micrographs of the AC samples that were obtained from various biomass materials.<sup>30</sup> Reproduced from ref. 30, <https://doi.org/10.3390/ma14154121>, under the terms of the CC BY 4.0 license <https://creativecommons.org/licenses/by/4.0/>.

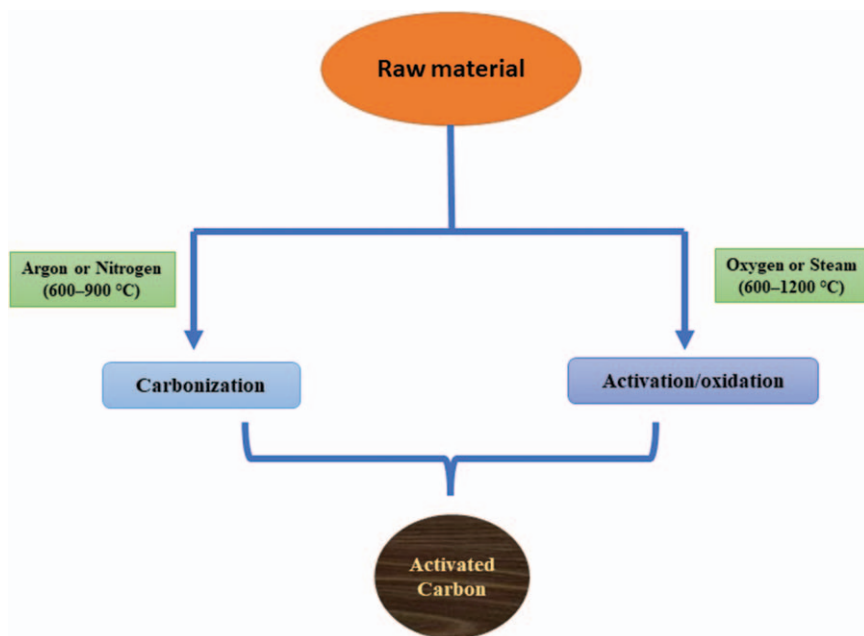
associated industries have huge raw material supply potential. Kwiatkowski *et al.* investigated the production of ACs from numerous biomass-derived resources by activation with KOH. They also carried out a thorough computer analysis of the porous structure and adsorption characteristics of the carbons based on benzene ( $C_6H_6$ ) adsorption isotherms. SEM imaging results showed that the topological structures of the ACs made from ebony (EBAC/3), mahogany (MAAC/3), and hornbeam wood (HBAC/3) were strikingly comparable (Figure 1.2). The examination of the ACs' porous structure, therefore, revealed the substantial potential for producing ACs from waste biomass with a very high adsorption capacity and significant specific surface area by activation with KOH.<sup>30</sup>

## 1.1.2 Activation Reaction or Activation of Carbon

Raw carbon is transformed into a porous substance by activation, increasing its surface area. Chemical and physical activation are the two methods of activation, described in the following sections:

### 1.1.2.1 Physical Activation

Hot gases are used to generate AC from source materials.<sup>31,32</sup> The gases are subsequently burned out with the help of air, resulting in a filtered, polished, and brushed form of AC (Figure 1.3). One or more of the following



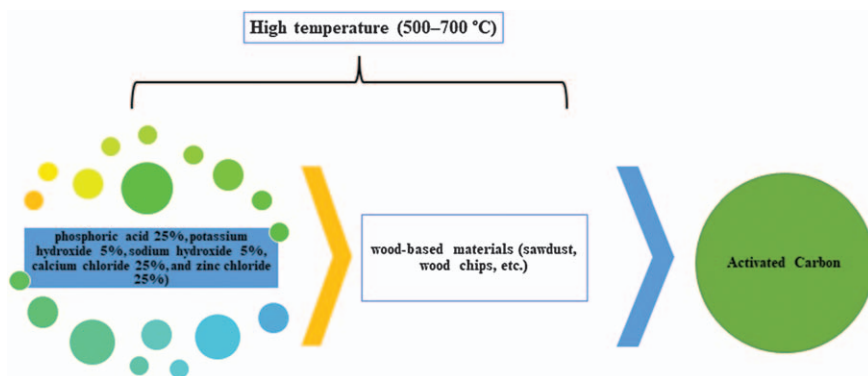
**Figure 1.3** Illustration of the physical activation process of carbon.

procedures described in the following list are typically used to accomplish this:

- (i) **Carbonization:** in the presence of gases like nitrogen and argon (inert environment) and at temperatures ranging between 600 and 900 °C, material containing carbon is pyrolyzed.
- (ii) **Activation/oxidation:** at temperatures ranging between 600 and 1200 °C, raw material is exposed to an oxidizing atmosphere (steam or oxygen). The sample is heated for 1 hour at 450 °C in an air-filled muffle furnace to activate it.

### 1.1.2.2 Chemical Activation

Various compounds are infused into the carbon material. Typically, the substance infused is one of the following: phosphoric acid (25%), potassium hydroxide (5%), sodium hydroxide (5%), calcium chloride (25%), and zinc chloride (25%). After blocking the air, carbon is heated to high temperatures (500–700 °C) to prevent the generation of tar and AC (Figure 1.4). The carbon is thought to be activated at this point by the temperature, which causes the substance to crack open and develop more small pores. Because of the lower temperatures, improved uniformity in quality, and smaller activation times required for the material, chemical activation is favoured over physical activation. To prevent the production of tar, wood-based products (such as sawdust and wood chips) are heated to a high temperature. Chemical agents that



**Figure 1.4** Illustration of the chemical activation process of carbon.

degrade the fibres of wood-based materials are applied and are allowed to enter, such as zinc chloride and phosphoric acid.  $K_2CO_3$ ,  $KOH$ ,  $ZnCl_2$ , and  $H_3PO_4$  are the chemical activators that are most frequently utilized.<sup>33–35</sup> Complex processes like condensation, dewatering, carbonization, polymerization, and oxidation are all part of this reaction.

## 1.2 Categorization of ACs

ACs are intricate products that are categorized based on their behaviour, surface properties, and other essential properties. Some generic classification based on their processing techniques, size, and industrial applications is described in the following sections.<sup>36</sup>

### 1.2.1 Powdered AC (PAC)

PAC or pulverized AC is the term used by the ASTM, formerly known as the American Society for Testing and Materials, to describe particles that pass through an 80-mesh sieve (0.180 mm). PAC has small AC particles made by milling or pulverizing AC, with an average size that is typically  $<0.075$  mm and a mean particle diameter (MPD) of  $<0.045$  mm. It has a low diffusion distance and a high surface area-to-volume ratio. 95–100% of the carbon particles that make up PAC will pass through a specific mesh sieve after being crushed or powdered. PAC is typically applied to other processing components directly like fast mix basins, raw water intakes, gravity filters, and clarifiers. PAC is used in various processes, including the purification of hydrolyzed vegetable protein, and the control of taste and odour in drinking water.

### 1.2.2 Granular AC (GAC)

The external surface of GAC is smaller than that of PAC because of its bigger particle size. The size range of the irregularly shaped particles that make up

GAC is 0.2 to 5 mm. The basic material is either activated directly or after being agglomerated to create GACs. Therefore, the adsorbate's diffusion is a significant factor. These carbons are appropriate for gas and vapour adsorption owing to the rapid diffusion of gaseous substances. GACs are utilized for water and air purification, substance segregation, and generalized deodorization in rapid mix basins and flow systems. Coconut shells, coal, peat, and other basic organic materials high in carbon are used to make GAC. As water passes through a filter made of GAC, heat is used to activate the carbon's surface area, eliminating some compounds that have been dissolved in water. Because of its porous characteristics, GAC absorbs the chemical compounds. On the inside surface of the AC, the adsorption takes place. Adsorption is the process of removing substances from liquids or gases by diffusing them to the surface of the adsorbent through the porous structure of AC. Attractive forces then retain the substances on the surface of the adsorbent.

### **1.2.3 Extruded AC (EAC)**

Pulverized anthracite or charcoal and an appropriate binder are combined to create extruded ACs (pressed pellets), which are then extruded at high pressure into cylindrical forms with diameters ranging from 0.8 to 130 mm. To achieve a particular pore shape, activation catalysts like potassium hydroxide are occasionally used before extrusion. Because of their excellent mechanical strength, minimal dust content, and low-pressure loss, these are mostly employed for gas-phase applications.

### **1.2.4 Bead AC (BAC)**

BAC comes in diameters ranging from around 0.35 to 0.80 mm and is manufactured from petroleum pitch. Similar to EAC, although with lower grain size, it is likewise renowned for its low pollution concentration, high mechanical strength, and very little pressure drop. It is favoured for water filtration due to its spherical shape.

### **1.2.5 Impregnated AC**

When chemicals and metal particles are evenly distributed on the inner surfaces of AC's pores, surface impregnation chemically alters the material. The synergism between the chemicals and the carbon significantly increases the adsorptive ability of the carbon. Additionally, it offers a practical means of removing contaminants from gas streams that would not otherwise be possible. Iodine and silver are only two examples of the several inorganic component types found in porous carbons. Aluminium, manganese, zinc, iron, lithium, and calcium are only a few of the cations that have been used for specific applications in the reduction of air pollution, particularly in both exhibitions and museums. AC with silver is utilized as an adsorbent for the

filtration of household water because of its antibacterial and antiseptic properties. Natural water can be converted into drinkable water by treating it with a solution of AC and the flocculant  $\text{Al}(\text{OH})_3$ . Hydrogen sulphide ( $\text{H}_2\text{S}$ ) and thiols can also be adsorbed on impregnated carbons. There have been reports of  $\text{H}_2\text{S}$  adsorption rates up to 50% by weight. Silver-infused carbon is a powerful adsorbent for purification in earth-based homes and other water systems due to its antimicrobial/antiseptic properties. Flue gases in coal-fired power plants and other air pollution regulator applications are treated using impregnated AC. Aldehydes, radioactive iodine and mercury, and inorganic gases like arsine and phosphine can all be removed using AC by selectively impregnating it with these substances. Inorganic gases such as  $\text{HCN}$ ,  $\text{H}_2\text{S}$ , phosphine, and arsine are the targets of metal-oxide-impregnated carbon.

### 1.2.6 Polymer-coated Carbon

To create a smooth, permeable covering without clogging the pores, a biocompatible polymer can be applied to a porous carbon using this method. Hemoperfusion can benefit from the resultant carbon. Hemoperfusion is a medical procedure that removes hazardous compounds from the blood by passing a patient's blood over an adsorbent material.

### 1.2.7 Woven Carbon

It's feasible to produce AC cloth for carbon filtration using technical rayon fibres. According to the BET theory, activated cloth has an increased capability for absorption than activated charcoal (surface area:  $500\text{--}1500\text{ m}^2\text{ g}^{-1}$ , pore volume:  $0.3\text{--}0.8\text{ cm}^3\text{ g}^{-1}$ ).

## 1.3 Properties of AC

Physically activated carbon uses van der Waals forces or London dispersion forces to bond materials. Alcohols, diols, strong bases and acids, metals, and the majority of inorganic substances, like sodium, lithium, lead, iron, fluorine, arsenic, and boric acid, do not bond well to AC. Iodine is particularly well adsorbed by AC.

AC is not very effective at adsorbing carbon monoxide. The fact that the material is used in respiratory filters, fume hoods, or other gas regulator equipment should be of particular concern to those who use them because the gas is hazardous to metabolism and the nervous system and is imperceptible to the human senses. To increase the adsorptive ability for some inorganic (and hazardous organic) molecules like ammonia ( $\text{NH}_3$ ),  $\text{H}_2\text{S}$ , mercury ( $\text{Hg}$ ), formaldehyde ( $\text{HCOH}$ ), and radioactive iodine-131 ( $\text{I-131}$ ), AC can be employed as a medium for the adsorption of diverse chemicals. In the following sections the various characteristics of ACs are described.



### 1.3.1 Iodine Number

A method used to assess the adsorption potential of ACs is the iodine number. The quantity of iodine absorbed by 1 g of carbon at the mg level is the iodine number, which measures the porosity of the AC.<sup>37</sup> The usable surface area in  $\text{m}^2 \text{g}^{-1}$  of virgin carbon is indicated by the iodine number (or “iodine value”) (ASTM D4607). The iodine number, which is associated with the “activity” of AC and is frequently used as a quality control (QC) parameter in the production and reactivation of AC, does not always offer a measure of the carbon’s capacity to adsorb other chemicals. The iodine number is typically 50 to  $100 \text{ mg g}^{-1}$  lower than the BET surface area. It is widely known that the carbon surface oxygen complexes, pH, and ash components all have an impact on the iodine adsorption from aqueous solutions. A virgin AC’s iodine number will decrease by 20 to 50 points after being moistened with water and dried because the surface oxygen complex has changed. In an AC filter, QC samples should be collected dry rather than wet. Many carbons adsorb small compounds selectively. The most essential factor used to describe the performance of AC is the iodine number. It is a measurement of the level of activity (a greater number indicates a higher degree of activation) and is frequently expressed in  $\text{mg g}^{-1}$  (usual range: 500–1200  $\text{mg g}^{-1}$ ). By iodine adsorption from solution, the micropore content of AC (0–20, or up to 2 nm) is measured. It corresponds to a carbon surface area of 900–1100  $\text{m}^2 \text{g}^{-1}$ . It serves as the benchmark in liquid-phase applications. The iodine values for carbons used in water treatment typically range from 600 to 1100. This metric is frequently used to assess how much carbon is used up. Chemical interactions between the adsorbent and iodine may change the adsorption of iodine if this method is employed carelessly and produce inaccurate results. In light of this, it is only advised to use the iodine number as a gauge of a carbon bed’s level of exhaustion if the bed has been demonstrated to be free of chemical interactions with adsorbates and if an experimental association between the iodine number and the degree of exhaustion has been established for the specified application.

### 1.3.2 Molasses Number

Certain carbons are better at adsorbing heavy compounds. By adsorbing molasses from solution, AC’s mesopore content ( $>2 \text{ nm}$ ) is measured as the molasses number or molasses efficiency.<sup>38</sup> Increased adsorption of large molecules is indicated by a high molasses number (range 95–600). The decolorizing performance of caramel is comparable to that of molasses. The molasses efficiency is in the range of 40% to 185%, and it corresponds to the molasses number (600 = 185%, 425 = 85%). The decolorization capability of AC is measured using the molasses number (DSTM 16), which also serves as an indicator of the macropore and transport pore structure of the material. A quantity of powdered carbon is combined with a standard

molasses solution and heated for a predetermined period. The molasses number describes how much more colour is removed by AC as compared to regular carbon. So, the better the product, the higher the molasses number. The relationship between the European and North American molasses numbers (525–110) is inverse. A standard diluted molasses solution standardized against AC is given a molasses number, which represents the degree of decolourization. The molasses number shows the possible pore capacity that might be accessible for bigger adsorbing entities due to the size of colour bodies.

### 1.3.3 Apparent Density

A fixed volume of AC's weight is calculated using an apparent density. The solid or skeletal density of ACs normally ranges between 2.0 and 2.1  $\text{g cm}^{-3}$  (125–130 lbs per  $\text{ft}^3$ ) (*i.e.*, if all pore gaps were removed). Nevertheless, as there is a significant amount of void space between the particles in an AC sample, the actual operational (apparent) density is often lower, ranging from 0.4 to 0.5  $\text{g cm}^{-3}$  (25–31 lbs per  $\text{ft}^3$ ). When comparing the same source material, greater volume activity and better-activated carbon are typically indicated by higher apparent density. It may also suggest various starting materials (such as bituminous coal *vs.* lignite coal *vs.* wood). ACs typically have a solid or skeletal density of 2000–2100  $\text{kg m}^{-3}$  (125–130 lbs per cubic foot). The actual or apparent density of an AC sample will be lower, approximately 400 to 500  $\text{kg m}^{-3}$  (25–31 lbs per cubic foot), because a significant portion of the sample will be made up of air space between the particles. Greater volume activity and better-quality AC is typically associated with higher density. The apparent density of AC is calculated using ASTM D 2854-09 (2014).

### 1.3.4 Hardness/Abrasion Number

The mechanical strength of AC is one of its fundamental mechanical characteristics. It can be described as a material's resistance to wear and tear while it is being used. There are numerous tests available to assess the mechanical toughness of GAC. These tests measure the number of fines produced or the change in particle size distribution. To quantify the distinct characteristics of strengths, various mechanical strength test methods cannot be mathematically related to one another. The hardness number is the most popular test method, followed by the abrasion number. The hardness number (DSTM 20) gauges how well AC's external integrity holds up to wear along the edges and breaking of small points. After shaking granules under specific circumstances, it is stated as a percentage of loss on a specific sieve. The AWWA B604 abrasion number gauges the structural durability of GAC. It assesses a particle's resistance to shear pressures brought on by particles rubbing against one another or against surfaces like supporting screens or

column walls.<sup>39</sup> It is assessed as a percentage decrease in mean particle diameter (MPD) by agitating granules with steel balls in a container under specific conditions. The AC's resistance to attrition is gauged with this parameter. The ability of AC to preserve its physical integrity and withstand frictional forces is a crucial indicator. The raw material and activity levels have a significant impact on the hardness of ACs.

### 1.3.5 Ash Content

Total ash measures the weight-based mineral oxide concentration of AC. At 800 °C, the mineral components are transformed into their corresponding oxides to determine the value. The amount of ash, which is primarily made up of silica and aluminium, depends on the primary raw material utilized to create the finished product. The typical values for ACs based on wood, coconut shells, and coal are 2–3% w/w, 5% w/w, and 8–15% w/w, respectively. Ash decreases both the total activity of AC and the effectiveness of reactivation; the amount is solely based on the base raw material used to make the AC (*e.g.*, coconut, wood, coal). Discolouration can come from the metal oxides ( $\text{Fe}_2\text{O}_3$ ) leaching out of AC. The ash content that is acid/water soluble is more important than the total ash content. For aquarists, the amount of soluble ash can be crucial since ferric oxide can encourage the formation of algae. For marine fish, freshwater fish, and reef tanks, a carbon with a low soluble ash concentration should be used to prevent heavy metal toxicity and excessive plant/algal growth. The ash content of AC is ascertained using the ASTM (D2866 Standard Test Method).

### 1.3.6 Carbon Tetrachloride Activity

The level of AC activation can be determined using this test procedure. When AC is saturated with carbon tetrachloride ( $\text{CCl}_4$ ) under the circumstances specified in this test method, carbon tetrachloride activity is defined as the weight of  $\text{CCl}_4$  absorbed by the AC sample divided by the sample weight (in %).

### 1.3.7 Particle Size Distribution

An AC's access to surface area and the rate of adsorption kinetics are both improved and accelerated by finer particle size.<sup>40</sup> This must be weighed against pressure drop, which will affect energy costs in systems with vapour phases. Particle size distribution should be carefully taken into account for considerable operational benefits. Nevertheless, the particle size should fall between 3.35 and 1.4 millimetres when utilizing AC for the adsorption of minerals like gold (0.132–0.055 in). It would not be appropriate to elute AC with particles smaller than 1 mm.<sup>41</sup>

## 1.4 Modification of the Properties and Reactivity of AC

AC is a popular choice for contaminant removal media due to its adaptability and broad variety of uses. The latest studies have concentrated on improving the efficiency of AC by changing its unique features to make it more apt to attract certain pollutants.<sup>42,43</sup> The makeup of the surface functional groups has a significant impact on the properties of acid–base, oxidation–reduction, and particular adsorption processes. Conventional AC has a reactive surface that can be oxidized by ozone, carbon dioxide, and ambient oxygen as well as oxygen plasma steam. Several different chemicals might produce oxidation in the liquid phase ( $\text{HNO}_3$ ,  $\text{H}_2\text{O}_2$ ,  $\text{KMnO}_4$ ).<sup>44</sup> The surface of oxidized carbon can acquire several basic and acidic groups, which can alter the material's sorption and other characteristics dramatically from its unaltered state.

Natural compounds, polymers, or the use of nitrogenating reagents during the processing of carbon can nitrogenate AC.<sup>45</sup> Fluorine, chlorine, and bromine can all interact with AC.<sup>46,47</sup> Like other carbon materials, the surface of AC can be fluoralkylated *via* a CVD process or treatment with (per)-fluoropolyether peroxide in a liquid phase. Such materials can be employed as electrode materials for supercapacitors because they have excellent electrical and thermal conductivity, high hydrophobicity, and chemical stability.<sup>48</sup> It is believed that the development of ACs from halogenated precursors results in a catalyst that is more efficient because the stability of the remaining halogens is improved. AC with chemically grafted superacid sites is also known in the literature. The presence of the surface-active carbon double bond has been related to a number of the chemical features of AC. AC can get saturated and lose its absorption ability during use. Compared to routinely replacing AC to obtain the desired effect, which wastes resources, AC regeneration has more economic and environmental advantages. Adsorption is a process in which AC, adsorbate, and solvent achieve adsorption equilibrium. To allow AC to desorb and regain its activity, the initial equilibrium conditions must be disrupted on the following grounds:

- (i) External heating to raise the temperature to alter the equilibrium conditions, because the amount of adsorbed mass decreases as the temperature increases, resulting in the desorption of the adsorbed mass.
- (ii) Modifying the adsorbate's chemical characteristics.
- (iii) Adsorbate extraction using a solvent having a strong affinity for the adsorbate.
- (iv) Substitution of the adsorbate with a compound that has a high affinity for the AC, followed by desorption of the replacement material and regeneration of the AC.
- (v) Desorbing an adsorbate involves decreasing the concentration (or pressure) of the solute in the solvent.
- (vi) Decomposing or oxidizing the adsorbed material (organic materials) to remove it.

### 1.4.1 Regeneration of AC

AC regeneration (*i.e.*, reactivation) is the process of removing adsorbed material from AC by physical or chemical means without altering its original structure, and restoring its adsorption efficiency for reuse. Before selecting the AC regeneration technique, it is essential to have a thorough understanding of the treated object and the extent of the treatment. The largest reactivation facility in the world is located in Feluy, Belgium. There is a reactivation centre for AC also in Roeselare, Belgium. Reactivation or regeneration of ACs entails desorbing impurities from the AC surface to restore the adsorptive ability of saturated AC. There are numerous regeneration methods for AC, including thermal regeneration, biological regeneration, wet oxidation regeneration, electrochemical regeneration, solvent regeneration, and catalytic wet oxidation, as mentioned in the following sections.

#### 1.4.1.1 Thermal Regeneration Method

One of the oldest and most established AC regeneration techniques is thermal regeneration. After treating organic wastewater, AC is typically regenerated in three stages: drying, high-temperature carbonization, and activation depending on how organic matter changes at various temperatures. The volatile elements on the AC are mostly eliminated during the drying process. While some of the organic matter adsorbed on the AC boils, vaporizes, and desorbs in the high-temperature carbonization stage, another organic matter decomposes to produce small molecule hydrocarbons and desorbs, with the remaining organic matter remaining in the pores of the AC to be converted to fixed carbon. The temperature will increase to 800–900 °C at this point. The procedure is typically carried out in a vacuum or an inert environment to prevent oxidation of the AC. The following step of activation involves adding CO<sub>2</sub>, CO, H<sub>2</sub>, or water vapour to the reactor to purge the AC's micropores and restore its adsorption capacity, which is essential to the whole regeneration process. Despite the broad use and high regeneration effectiveness of the thermal regeneration technique, it needs extra energy for heating during the regeneration process, which raises the cost of both the initial investment and ongoing operations.

#### 1.4.1.2 Biological Regeneration Method

To remove the organic matter that has become adsorbed on AC and further digest and degrade it into H<sub>2</sub>O and CO<sub>2</sub>, the biological regeneration process uses domesticated bacteria. There are also aerobic and anaerobic approaches, and the biological regeneration method is comparable to the biological wastewater treatment method. It is generally accepted that cell autolysis occurs during the regeneration process, in which case cell enzymes flow to the extracellular space, and AC has an adsorption effect on enzymes, forming an enzymatic centre on the surface of carbon, thereby promoting

the decomposition of pollutants and achieving the goal of regeneration. The pore size of AC itself is very small, some only a few nanometers, so microorganisms cannot enter such pores. The biological process takes a long time and is strongly impacted by water quality and temperature, yet it is straightforward and can be quickly executed with cheap start-up and running expenses.

#### 1.4.1.3 *Wet Oxidation Regeneration Method*

Under high temperature and pressure conditions, oxygen or air is utilized to oxidize and break down the organic material adsorbed on the AC into tiny molecules. This process is known as wet oxidation regeneration. The following are the ideal regeneration conditions for AC: 230 °C regeneration temperature, 1 h regeneration period, 20.6 MPa oxygenation, 15 g carbon, and 300 mL water. After 5 rounds of regeneration, the regeneration efficiency drops only by 3% from its peak of  $45 \pm 5\%$ . The primary factor causing the decline in regeneration efficiency is the partial oxidation of AC surface micropores.

#### 1.4.1.4 *Solvent Regeneration Method*

The solvent regeneration methodology incorporates the phase equilibrium between the AC, solvent, and adsorbed material to disrupt the adsorption equilibrium by adjusting the temperature, solvent pH value, and other variables to desorb the adsorbed material from the AC. For such reversible adsorptions, including the adsorption of organic wastes with high concentrations and low boiling points, the solvent regeneration approach is more suited. It is more focused since a solvent often has a limited range of contaminants that it can desorb, while the water treatment process may deal with a large variety of pollutants.

#### 1.4.1.5 *Electrochemical Regeneration Method*

A brand-new approach to AC regeneration is electrochemical regeneration. In this procedure, a DC electric field is applied to the electrolyte while AC is sandwiched between the two primary electrodes. A micro-electrolytic cell is created when the electric field causes the AC to become polarized, with one end acting as the anode and the other as the cathode. This technique is simple to use, very effective and uses little energy, and its treatment object is subject to fewer restrictions. If the treatment procedure is flawless, secondary contamination may be prevented.

#### 1.4.1.6 *Catalytic Wet Oxidation Method*

Regeneration using the conventional wet oxidation approach uses a lot of energy but is only moderately effective. The primary determinant of

regeneration efficiency is regeneration temperature, although raising the temperature can also accelerate the surface oxidation of AC, lowering the regeneration efficiency. As a result, it is thought that using a high-efficiency catalyst will allow for the regeneration of AC.

## 1.5 Applications of AC

The filtration of drinking water, treatment of groundwater and municipal water supplies, reduction of landfill and power plant gas emissions, and recovery of precious metals are just a few of the many industrial and domestic uses for AC. In Figure 1.5, the uses of AC are shown.

In addition to these uses, AC is employed in the production of methane and hydrogen chloride, hydrogen storage, decaffeination, air purification, capacitive deionization, gold extraction, solvent recovery, supercapacitive swing adsorption, water purification, medicine, metal extraction, and sewage treatment.<sup>49</sup> The applications of AC are described in detail in the following sections:<sup>50</sup>

### 1.5.1 Industrial Applications

Utilizing AC in metal polishing to clean electroplating solutions is a significant industrial use. For instance, it is the primary method for purifying bright nickel-plating solution to eliminate organic contaminants. To improve the deposit attributes of plating solutions and to enhance features like brightness, smoothness, and ductility, a range of organic compounds are added. Organic additives produce undesired breakdown products in solution as a result of the flow of direct current and the electrolytic processes of anodic oxidation and cathodic reduction. They may hurt the physical characteristics of the deposited metal and the plating quality. Such contaminants are eliminated by AC treatment, which also restores the plating performance to the required degree.



Figure 1.5 Applications of AC.

## 1.5.2 Medications

AC is listed as one of the essential medicines by the World Health Organization. Poisonings and overdoses caused by oral consumption of drugs are treated with AC, but it is not effective in cyanide, lithium, alcohol, and iron poisoning, and AC needs to be administered only in a health care facility. Many nations utilize tablets or capsules of AC to alleviate diarrhoea, indigestion, and gas. Nevertheless, AC has no impact on intestinal gas and diarrhoea and is typically therapeutically worthless when poisoning is caused by ingesting corrosive substances like petroleum products and boric acid. It is also mainly futile when poisoning is caused by strong bases and acids like iron, cyanide, arsenic, lithium, methanol, and ethanol. AC is also used in teeth whitening and oral health. AC can cause side effects such as black stools, black tongue, vomiting, constipation, and gastrointestinal blockage (in severe cases).

## 1.5.3 Analytical Chemistry

AC can be used in the chromatographic separation of carbohydrates (stationary phase = AC 50% w/w combination with celite, and mobile phase = ethanol solution). Direct oral anticoagulants (DOACs) like apixaban, dabigatran, edoxaban, and rivaroxaban can be removed from blood plasma samples using AC. AC has been manufactured into “minitablets” for this use, with each having 5 mg of AC to treat 1 ml of DOAC samples. Since heparin, most other anticoagulants, and blood clotting factors are unaffected by this AC, a plasma sample may be examined for anomalies that the DOACs would normally influence.

## 1.5.4 Water Purification

The removal of contaminants in the field of wastewater treatment has been greatly aided by the use of AC made from agricultural waste and products. The price of this adsorbent, however, is highly dependent on the sources of its basic materials. As a result of the financial benefits and environmental benefits, the method of manufacturing AC from agricultural waste is highly recommended. Water filtration systems often employ AC. Numerous field and industrial processes, including groundwater remediation, air purification, spill clean-up, filtration of drinking water, and the capture of volatile organic compounds from dry cleaning, painting, and gasoline dispensing, among others, use carbon adsorption to remove pollutants from air or water streams.

EPA officials created a regulation that advocated mandating the use of GAC in drinking water treatment facilities during the early stages of the Safe Drinking Water Act's adoption in the United States in 1974. The water supply sector, notably the biggest water utilities in California, strongly opposed the so-called GAC regulation because of its high cost throughout the nation. As a result, the agency disregarded the regulation. Due to its versatility, AC filtration is a successful way to purify water. Depending on the pollutants



present, distinct kinds of AC filtering techniques and apparatus are recommended.

#### 1.5.4.1 Tannin Removal

Tannins, mixtures of small and big molecules, are a class of naturally occurring organic compounds that are water soluble and created by the metabolism of trees and plants. They are a component of the fulvic acid materials that are formed during the breakdown of vegetation and are resistant to degradation. The tannin adsorption capacity of carbon is measured in parts per million (200–362 ppm). Tannins, which may give water a yellowish to a brown hue, are made of minute, high-molecular-weight colloidal particles that have a very little negative charge. Tannins may be found in practically every water body where there has been a significant breakdown of flora. This often happens in areas with peaty soils, deep woods, or marshlands. Tannins are more prevalent in the Northeast, Southeast, Northwest, and Great Lakes regions of the United States. Typically, only tannins with very high molecular weights may be adsorbed by AC. As a result, it is the choice of treatment that can be used least widely. However, it has the advantage of generally reduced maintenance costs and overall system expenses (as compared to ion exchange).<sup>51</sup>

#### 1.5.4.2 Methylene Blue Adsorption

Dye pollution occurs in wastewater from the textile, cosmetic, printing, dyeing, food processing, and paper sectors. Because of their harmful and cancer-causing effects on living things, the discharge of coloured effluents poses a significant environmental challenge for developing nations. For the elimination of pigments, dyes, and other inorganic and organic pollutants, AC sorption is very successful.<sup>52</sup>

#### 1.5.4.3 Dechlorination

Dechlorination is a very swift process in which AC takes part, and free chlorine is changed to chloride. In the top 10 cm of the filter bed, the reaction happens quickly. The dechlorination half-life length, which gauges how well-activated carbon removes chlorine, is used to assess certain carbons. The amount of carbon needed to remove chlorine by 50% is known as the dechlorination half-value length. A shorter half-value length indicates higher efficiency.<sup>53</sup>

### 1.5.5 Agricultural Applications

Organic farmers are permitted to utilize AC (charcoal) in the production of both wine and animals. It serves as a pesticide, an animal feed additive, processing agent, a non-agricultural chemical, and a disinfectant in the

production of animals. Utilizing AC as a chemical intermediate to remove brown colour pigments from white grape extracts is permitted in the production of organic wine.

### 1.5.6 Distilled Alcoholic Beverage Purification

Vodka and whiskey may be cleaned using AC filters to remove organic contaminants that can alter their flavour, colour, and aroma. Vodka with a much higher level of organic purity, as determined by odour and flavour, may be obtained by passing an organically contaminated vodka through an AC filter at the right flow rate.

### 1.5.7 Fuel Storage

A variety of pore shapes and surface chemistry are available in ACs for the adsorption of gases. The capacity of different ACs to adsorb hydrogen and natural gas is being researched. The porous substance works as a sponge for various gases. van der Waals forces cause the gas to be drawn to the carbon substance. The bonding energies of certain carbons have been seen to range between 5 and 10 kJ mol<sup>-1</sup>. When exposed to higher temperatures, the gas may then be desorbed and either burned to generate power or used in a hydrogen fuel cell. Compared to pressure tanks, fuel storage in an air conditioner is easier due to the low-mass, low-volume, and low-pressure requirements that may be fulfilled. In the domain of studying and creating nanoporous carbon materials, the US Department of Energy has set out several objectives to be met. Although many organizations, like the ALL-CRAFT programme, are still working in this area, not all of the objectives have yet been met.

### 1.5.8 Gas Purification

For gas purification GAC is often used. Siloxanes, hydrogen sulphide, carbon dioxide, biomethane, sewage gas, hydrogen gas, landfill gas, and other gases are often removed from the air using filters containing AC in compressed air and gas purification. In the majority of designs, AC is included in the filter medium and there is either a single step of filtration or two stages of filtration. Radioactive gases are kept confined in the air sucked from a nuclear reactor condenser using AC filters. These gases are absorbed and held in place by the massive charcoal beds as they quickly decompose into non-radioactive solid substances. While the air is being filtered, the solids are being held in the charcoal particles.

### 1.5.9 Chemical Purification

ACs of certain grades are designed to work in acidic chemical processes. To utilize the ACs in acidic settings, some of them are acid washed to eliminate acid soluble ash. Acids like phosphoric acid, HCl, and sulphuric acid are

often treated. In the laboratory, AC is often used to clean solutions of organic molecules that include undesirable coloured organic contaminants. AC can be used to treat organic acids such as acetic acid, oxalic acid, lactic acid, malic acid, benzoic acid, and formic acid.

### 1.5.10 Mercury Scrubbing

AC is very effective in the removal of mercury from flue gas (coal-fired power plants, cement manufacture, industrial boilers, waste incinerators, *etc.*) as well as liquid natural gas. AC is costly to utilize while being effective. The problem with disposing of mercury-filled AC is that it is often not recycled. Federal rules in the United States permit the stabilization of AC (*e.g.*, encasing it in concrete) for landfilling if the mercury content is less than 260 ppm. However, garbage with a mercury content of more than 260 ppm is classified as high-mercury waste and cannot be dumped in landfills (Land-Ban Rule). A 100-ton-per-year accumulation of this material is now occurring in deep abandoned mines and warehouses. The problem of disposing of AC that contains mercury is not exclusive to the United States. In the Netherlands, the AC is disposed of *via* total combustion, producing carbon dioxide (CO<sub>2</sub>), and the mercury is mainly recovered.

### 1.5.11 Food Additive

To give some foods, such as pizza bases, black ice cream, and hotdogs, a smoky flavour, activated charcoal is employed as a food ingredient. Foods and drinks with activated charcoal should be avoided when taking drugs, such as birth control pills and antidepressants, since they lessen the effectiveness of the medication. Activated charcoal may slow down the pace at which the body absorbs hazardous compounds, according to research, but there isn't enough concrete proof to back up its detoxifying abilities.

### 1.5.12 Skin Care

Activated charcoal is a common ingredient in a variety of skin care treatments because of its absorbent properties. The cleaning power of soap is combined with the absorption power of activated charcoal in products like activated charcoal soaps, face masks, and scrubs.

## 1.6 Largest Producers of AC in the World

The biggest manufacturer of AC in the world is Norit NV of the Netherlands, a subsidiary of Cabot Corporation. The world's leading providers of AC are as follows:

- (i) Shinkwang Chem. Ind. Co., Ltd., South Korea
- (ii) Indo German Carbons Limited, Oman

- (iii) Haycarb, Indonesia, Sri Lanka, and Thailand
- (iv) Japan. Kuraray Co., Ltd, Kuraray Europe
- (v) Oxbow Coal SARL, Belgium

## 1.7 Conclusion

The categorization, characteristics, and uses of AC are briefly discussed in this chapter. A broad variety of carbonized materials with high surface area and porosity are included in AC. In many regions of the globe, it has a variety of uses in the purification of water, analytical chemistry, pharmaceuticals, skin care, fuel storage, industrial wastewater treatment, gas purification, and odour elimination due to its special properties. The production of AC currently involves using a variety of industrial wastes. A combination of physical and chemical processes is used to activate AC. Chemical activation is more cost-effective than physical activation because it has a lower activation temperature, a faster processing time, and higher carbon efficiency.

## References

1. I. Tan, A. Ahmad and B. Hameed, *Chem. Eng. J.*, 2008, **137**, 462–470.
2. I. Tan, A. Ahmad and D. B. Hameed, *J. Hazard. Mater.*, 2008, **153**, 709–717.
3. I. Tan, A. Ahmad and B. Hameed, *J. Hazard. Mater.*, 2008, **154**, 337–346.
4. M. Begum, A. Rahman, M. Molla and M. Rahman, *Int. J. Environ. Sci. Technol.*, 2022, 1–14.
5. V. Gupta, N. Bhardwaj and R. Rawal, *Int. J. Environ. Sci. Technol.*, 2022, **19**, 2641–2658.
6. N. R. Khalili, M. Campbell, G. Sandi and J. Golaś, *Carbon*, 2000, **38**, 1905–1915.
7. H. Teng, T.-S. Yeh and L.-Y. Hsu, *Carbon*, 1998, **36**, 1387–1395.
8. H. Teng and H. C. Lin, *AIChE J.*, 1998, **44**, 1170–1177.
9. B.-L. Xing, H. Guo, L.-J. Chen, Z.-F. Chen, C.-X. Zhang, G.-X. Huang, W. Xie and J.-L. Yu, *Fuel Process. Technol.*, 2015, **138**, 734–742.
10. F. Zhou, J. Cheng, J. Liu, Z. Wang, J. Zhou and K. Cen, *Fuel*, 2016, **170**, 39–48.
11. C. Lei, N. Amini, F. Markoulidis, P. Wilson, S. Tennison and C. Lekakou, *J. Mater. Chem. A*, 2013, **1**, 6037–6042.
12. M. Kubota, A. Hata and H. Matsuda, *Carbon*, 2009, **47**, 2805–2811.
13. H. An, B. Feng and S. Su, *Carbon*, 2009, **47**, 2396–2405.
14. A. Pastor, F. Rodriguez-Reinoso, H. Marsh and M. Martinez, *Carbon*, 1999, **37**, 1275–1283.
15. T. Wang, S. Tan and C. Liang, *Carbon*, 2009, **47**, 1880–1883.
16. A. Kumar, B. Prasad and I. Mishra, *J. Hazard. Mater.*, 2008, **152**, 589–600.
17. J. Maciá-Agulló, B. Moore, D. Cazorla-Amorós and A. Linares-Solano, *Carbon*, 2004, **42**, 1367–1370.

18. E. Raymundo-Pinero, D. Cazorla-Amorós, A. Linares-Solano, J. Find, U. Wild and R. Schlögl, *Carbon*, 2002, **40**, 597–608.
19. C. Srinivasakannan and M. Z. A. Bakar, *Biomass Bioenergy*, 2004, **27**, 89–96.
20. X. Ma, H. Yang, L. Yu, Y. Chen and Y. Li, *Materials*, 2014, **7**, 4431–4441.
21. Q.-S. Liu, T. Zheng, P. Wang and L. Guo, *Ind. Crops Prod.*, 2010, **31**, 233–238.
22. A. Ahmad and B. Hameed, *J. Hazard. Mater.*, 2010, **173**, 487–493.
23. S. Mahanim, I. W. Asma, J. Rafidah, E. Puad and H. Shaharuddin, *J. Trop. For. Sci.*, 2011, 417–424.
24. V. Siipola, T. Tamminen, A. Källi, R. Lahti, H. Romar, K. Rasa, R. Keskinen, J. Hyväluoma, M. Hannula and H. Wikberg, *BioResources*, 2018, **13**, 5976–6002.
25. C. Namasivayam and D. Kavitha, *Dyes Pigment.*, 2002, **54**, 47–58.
26. R. E. Franklin, *Acta Crystallogr.*, 1951, **4**, 253–261.
27. G. M. Jenkins and K. Kawamura, *Polymeric carbons: carbon fibre, glass and char*, Cambridge University Press, 1976.
28. H. Marsh and F. R. Reinoso, *Activated carbon*, Elsevier, 2006.
29. C. S. Allen, F. Ghamouss, O. Boujibar and P. J. Harris, *Proc. R. Soc. A*, 2022, **478**, 20210580.
30. M. Kwiatkowski and E. Broniek, *Materials*, 2021, **14**, 4121.
31. A. Ould-Idriss, M. Stitou, E. Cuerda-Correa, C. Fernández-González, A. Macías-García, M. Alexandre-Franco and V. Gómez-Serrano, *Fuel Process. Technol.*, 2011, **92**, 261–265.
32. B. P. Kumar, K. Shivakamy, L. R. Miranda and M. Velan, *J. Hazard. Mater.*, 2006, **136**, 922–929.
33. G. Stavropoulos and A. Zabaniotou, *Microporous Mesoporous Mater.*, 2005, **82**, 79–85.
34. J. Acharya, J. Sahu, C. Mohanty and B. Meikap, *Chem. Eng. J.*, 2009, **149**, 249–262.
35. H. Deng, G. Li, H. Yang, J. Tang and J. Tang, *Chem. Eng. J.*, 2010, **163**, 373–381.
36. J. Oubagaranadin and Z. V. P. Murthy, *Activated Carbon: Classifications, Properties and Applications*, 2011, pp. 239–266.
37. S. Mopoung, P. Moonsri, W. Palas and S. Khumpai, *Sci. World J.*, 2015, **2015**, 415961.
38. O. Kazak, Y. Ramazan Eker, H. Bingol and A. Tor, *Bioresour. Technol.*, 2017, **241**, 1077–1083.
39. F. Benstoem, D. Mousel and J. Pinnekamp, *Abrasion of granular activated carbon used for elimination of micropollutants in municipal waste water treatment*, 2015.
40. P. Satya Sai and K. Krishnaiah, *Ind. Eng. Chem. Res.*, 2005, **44**, 51–60.
41. C. Hu, S. Sedghi, S. H. Madani, A. Silvestre-Albero, H. Sakamoto, P. Kwong, P. Pendleton, R. J. Smernik, F. Rodríguez-Reinoso and K. Kaneko, *Carbon*, 2014, **78**, 113–120.

42. L. Fan, J. Wang, L. Zhao, N. Hou, T. Gan, X. Yao, P. Li, Y. Zhao and Y. Li, *Electrochim. Acta*, 2018, **284**, 630–638.
43. A. B. García, A. Martínez-Alonso, C. A. L. Y Leon and J. M. Tascón, *Fuel*, 1998, **77**, 613–624.
44. M. Belhachemi, R. V. Rios, F. Addoun, J. Silvestre-Albero, A. Sepulveda-Escribano and F. Rodriguez-Reinoso, *J. Anal. Appl. Pyrolysis*, 2009, **86**, 168–172.
45. A. Yaumi, M. A. Bakar and B. Hameed, *Energy*, 2018, **155**, 46–55.
46. A. Daifullah, S. Yakout and S. Elreefy, *J. Hazard. Mater.*, 2007, **147**, 633–643.
47. C. Pongener, P. C. Bhomick, A. Supong, M. Baruah, U. B. Sinha and D. Sinha, *J. Environ. Chem. Eng.*, 2018, **6**, 2382–2389.
48. J. R. Kastner, J. Miller, D. P. Geller, J. Locklin, L. H. Keith and T. Johnson, *Catal. Today*, 2012, **190**, 122–132.
49. S. Wong, N. Ngadi, I. M. Inuwa and O. Hassan, *J. Cleaner Prod.*, 2018, **175**, 361–375.
50. K. Koehlert, *Chem. Eng.*, 2017, **124**, 32–40.
51. G. Jordan, M. Predotova, M. Ingold, S. Goenster, H. Dietz, R. G. Joergensen and A. Buerkert, *J. Plant Nutr. Soil Sci.*, 2015, **178**, 218–228.
52. Ü. Geçgel, G. Özcan and G. Ç. Gürpınar, *J. Chem.*, 2013, **2013**, 614083.
53. G. L. Seegert and A. S. Brooks, *J. Fish. Res. Board Can.*, 1978, **35**, 88–92.