Adsorption Dynamics

Adsorption Dynamics:

From Technologies to Environmental Solutions

Edited by

Raj Kumar Arya and George D. Verros

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PREFACE

Environmental challenges such as water contamination, air pollution, and resource scarcity have intensified the demand for sustainable and efficient treatment strategies. Among the various approaches, adsorption has stood out as a versatile and powerful technique capable of addressing a wide range of pollutants. Once limited to theoretical and laboratory studies, adsorption has now evolved into a cornerstone of environmental remediation technologies.

This book, Adsorption Dynamics: From Technologies to Environmental Solutions, presents a comprehensive and coherent exploration of adsorption—from its fundamental principles to advanced environmental applications. It integrates the science of adsorption with engineering practices, materials development, and field-level case studies, offering a unified perspective for readers across academia and industry.

The book opens with a foundational overview of adsorption and its environmental significance. It continues with a discussion on traditional adsorbents, followed by detailed insights into the synthesis and characterization of materials. Practical methodologies are covered through in-depth discussions on batch and continuous adsorption techniques, including fixed-bed systems and membrane-based processes.

Further chapters focus on theoretical frameworks, including adsorption kinetics and thermodynamics, which are essential for designing and optimizing processes. The applications section highlights adsorption in water purification—covering removal of heavy metals, organic pollutants, and emerging contaminants—supported by real-world case studies. The scope then extends to air purification, exploring topics such as volatile organic compound (VOC) and odor control, indoor air quality management, and industrial air treatment.

We are deeply grateful to all the contributors for their outstanding chapters and for sharing their research and insights with dedication and professionalism. Our sincere thanks go to Alison Duffy, Commissioning Editor at Cambridge Scholars Publishing, UK, whose unwavering support and timely guidance were instrumental in bringing this book to completion. Finally, we extend our heartfelt appreciation to our families, whose patience, encouragement, and understanding made this endeavor possible.

Editors
Raj Kumar Arya
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CHAPTER 1

INTRODUCTION TO ADSORPTION: FUNDAMENTALS AND ENVIRONMENTAL APPLICATIONS

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Abstract

The adsorption phenomena has been recognized by humans for an extensive period of time. It is progressively employed for the aim of purification or separation. The adsorption process is often a surface phenomenon that involves a porous solid medium. In this process, a combination of multicomponent fluid (liquid or gas) is attracted to the solid surface through chemical or physical bonding. The aim of this chapter is to provide a comprehensive overview of the adsorption. At first the adsorption history is briefly reviewed. Then the fundamental laws of adsorption are summarized.

In recent years, research has focused on the production of new groundbreaking materials using nanotechnology, as well as the utilization of adsorbents derived from industrial or agricultural waste. The purpose of this chapter is also to present a comprehensive summary of the latest progress in the field of adsorbents. Finally, conclusions are drawn.

Keywords: Adsorption, history of, classification of, isotherm, models, environment, applications, nanotechnology, industrial waste, agricultural waste.

1.1 Adsorption History

Adsorption is a relatively unknown and often overlooked natural occurrence. It is intriguing since our overall existence tends to be shallow, and we frequently encounter and experience sorption effects in various situations. Sorption science is a relatively new field, although its origins may be traced back to ancient times when adsorption was already being used, but without a fundamental understanding of its effects.

Initially, there was complete absorption. Kayser coined the term “adsorption” in 1881, based on a suggestion from physiologist Du Bois-Reymond, to distinguish the process of molecules adhering to the outer and inner surfaces from the process of molecules being absorbed into the bulk. The term “sorption” was introduced by McBain in 1909.

Clay has been utilized since ancient times as a desiccant and whitening agent, a binder for paintings, and for many medicinal applications. Sand was utilized for the purpose of water desalination. Charcoal was suggested as a remedy. After Lowitz discovered the decolorizing action in 1785, charcoal was initially employed for the purification of sugar. Ostrejko’s patents in 1900 paved the way for its industrial implementation. The Bible already contains a description of an experiment involving adsorption.

The initial instruments used for measuring adsorption were hygrometers, as documented by Nicholas of Cues in 1450, Alberti, and Leonardo da Vinci. These hygrometers consisted of balances that were equipped with textile fibers. The German cardinal Nicolaus Cusanus (1401-1463) was the first to describe an apparatus based on gravimetry. The objective of the initial gravimetric adsorption measurements was to predict weather conditions using a specific method. In 1833, Talabot constructed a conditioning device to verify the quality of raw silk imported from China. Thermogravimetry originated with Talabot in 1833 when he set up a laboratory in Lyon with 39 thermobalances to measure the water content of Chinese raw silk.

The systematic investigation commenced in 1773 when Scheele noticed the adsorption of air by charcoal using a volumetric device. Both Priestley in England and the Abbe Fontana in Italy conducted nearly contemporaneous experiments in which they introduced flaming charcoal into an inverted glass cylinder filled with mercury. Mitscherlich, during the mid-19th century, determined that the average pore diameter of active carbon is 10 picometers and the thickness of a carbon dioxide adsorbed layer is 5 picometers. Forrester and Giles (1971) state that Chappuis and Kayser were the first to measure and plot adsorption isotherms in the 19th century. Since 1912, Emich pioneered the development of electrical microbalances, which are highly sensitive instruments used to study adsorption. However, disruptions caused by adsorbed layers hindered precise measurements.

Ostwald is credited with introducing the term “adsorption isotherm“ in 1885. Mitscherlich, Chappuis, and Kayser conducted measurements of isotherms during the late 19th century. The volumetric method proved to be highly effective, and the apparatus developed by Brunauer, Emmett, and Teller served as the model for several instruments designed to measure surface area and porosity. In 1916, Langmuir derived the isotherm equation, which is currently named after him, by using the concepts of the kinetic theory of gases, albeit in an empirical manner. This equation is applicable for chemisorption and micropore-filling alone, assuming that each adsorption site may bind only one molecule.

The theoretical method is founded on the research conducted by London in the 1930s, where he computed the attraction forces between molecules. Additionally, Born and Mayer calculated the repulsive forces. The combination yields the familiar picture of the molecule’s potential energy as it approaches a surface.

In the late 1930s, Brunauer, Emmett, and Teller expanded on Lanymuir’s idea by incorporating the concept of several layers of adsorption.

This led to the development of the BET equation, which is now widely used to determine the specific surface area. Brunauer, Deming, and Teller developed the BDDT classification for isotherms, which has subsequently been replaced by the IUPAC classification.

The origins of the condensation effect in pores can be attributed to the research conducted by Laplace in 1806 and Young in 1855. In 1871, Thomson (Lord Kelvin) published an equation that describes the relationship between the pressure and curvature of liquids in capillaries. Despite several advancements and novel methodologies, the BET and Kelvin equations remain the fundamental basis for all computations in this discipline. The interested reader for a detailed overview in history of adsorption has to resort to Robens (1994)

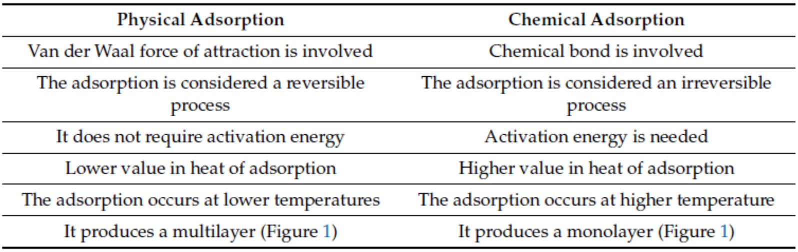
1.2 Definitions and Classifications

Adsorption is a surface process where a chemical species (adsorbate) from its vapor phase or solution is concentrated onto or near the surfaces or pores of a solid (adsorbent). This phenomenon of surface excess arises when the attraction energy between a substance and a solid surface, known as adhesive work, is greater than the cohesive energy of the substance itself (Chiou, 2002). The adsorptive absorption is enhanced when the solid substance possesses a large surface area.

Sorption is the term used to describe the connection of chemicals with a solid phase. The distinction between absorption and adsorption lies in the mechanism by which molecules interact with a matrix. In absorption, molecules permeate a three-dimensional matrix, whereas in adsorption, molecules adhere to a two-dimensional matrix. Adsorption is typically classified as either chemisorption or physical sorption, depending on the intensity of the interaction between the adsorbate and the substrate. Physical sorption is a result of weak electrostatic interactions, such as London forces, dipole-dipole forces, and Van der Waals contacts. These connections are easily disrupted, leading to the breaking of the bands. Chemisorption occurs when a covalent link is formed between the adsorbate and the substrate by the sharing or transferring of electrons. Chemisorption has a significantly higher level of interaction strength compared to physisorption, with a difference of two orders of magnitude. Chemisorption involves the production of a single layer of adsorbate on the adsorbent, whereas physisorption occurs when many layers of adsorbate form on the adsorbent. Physisorption is characterized by a low enthalpy and takes place at temperatures below the boiling point of the adsorbate. Additionally, it is a reversible process (see to Table 1.1). Nevertheless, the differentiation between physical adsorption and chemisorption is not consistently clear-cut. For instance, the process of polar vapors being attracted and sticking to polar solids can be categorized differently based on the strength of the attraction, known as adsorption energy.

During the process of adsorption, the solute will adhere to the surface of the adsorbent as a result of the attractive interactions between them. Based on the experimental results, it can eventually form either a monolayer or a multilayer, as shown in Figure 1.1

Table 1.1 Physical versus Chemical Adsorption (Adopted from Ho (2022), open access)



Physical Adsorption	Chemical Adsorption
Van der Waal force of attraction is involved	Chemical bond is involved
The adsorption is considered a reversible process	The adsorption is considered an irreversible process
It does not require activation energy	Activation energy is needed
Lower value in heat of adsorption	Higher value in heat of adsorption
The adsorption occurs at lower temperatures	The adsorption occurs at higher temperature
It produces a multilayer (Figure 1)	It produces a monolayer (Figure 1)

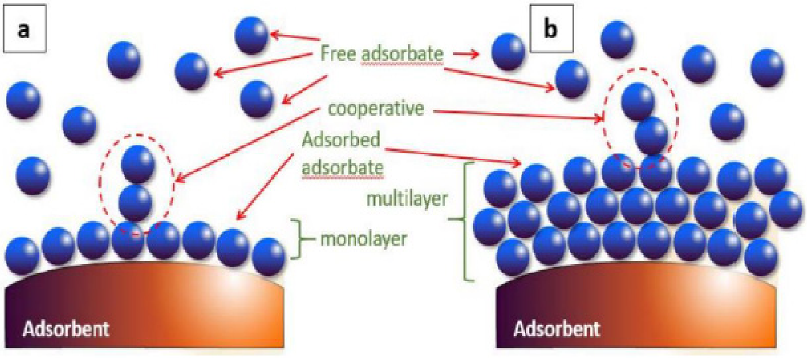


Fig. 1-1 Monolayer (a) and Multilayer Formation (Adopted from Ho (2022), open access)

There are two distinct categories of adsorbents: natural adsorbents and synthetic adsorbents Clay and zeolite are two examples of natural adsorbents that are both abundant and inexpensive. Alternatively, researchers have the ability to create artificial adsorbents, such as activated carbon, using materials derived from agricultural waste, industrial waste, and home waste. Each of these adsorbents possesses a distinct surface area and porosity structure that augment their adsorption capabilities.

1.3 Adsorption Isotherms & Fundamental Laws

Several adsorption isotherms have been documented for vapors on a diverse range of substances. Isotherms could be classified into xix main categories, namely kinds I to VI, as depicted in Figure 1.2

The graph depicting the variation in the quantity of adsorbed material relative to pressure or concentration is termed the adsorption isotherm. An isotherm is a graphical representation of equilibrium conditions at a fixed temperature. The experimentally obtained adsorption isotherms closely align with one of the six types of isotherm curves illustrated in Fig. 1.2. Several of these isotherms, primarily formulated for vapor-phase adsorption, are also applicable to solution adsorption.

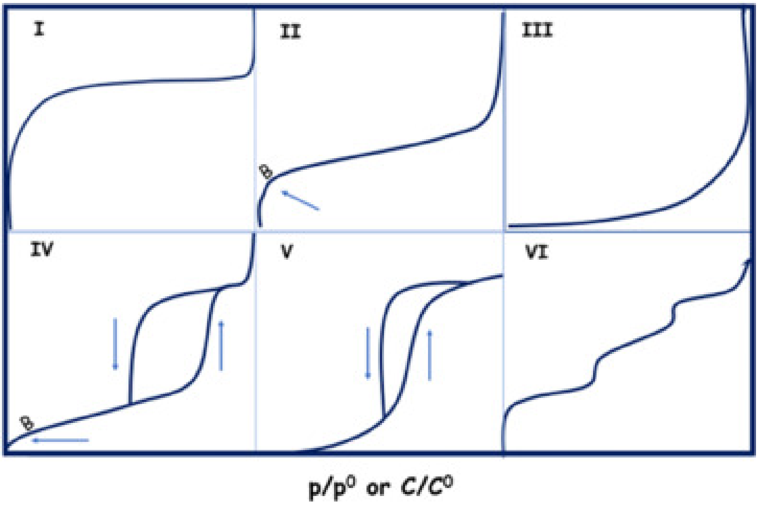


Fig. 1-2 Adsorption isotherms. (Al-Ghouti et al., 2020)

According to Al-Ghouti et al., (2020) the main characteristics of the above isotherms are:

- Type I isotherms (convex upward) are distinguished by a horizontal plateau that persists at elevated pressures and can be articulated using the Langmuir equation. Examples encompass the adsorption of water vapor on zeolite and the adsorption of hydrogen on charcoal.

- Type II isotherms characterize adsorption on mesoporous monolayer substances at low pressure and on multilayer materials at high pressure near saturation, exhibiting no hysteresis. It possesses a one inflection point. Furthermore, it is noted exclusively in microporous, nonporous, or dispersion materials having a pore diameter of less than 50 nm. Representative cases are the adsorption of nitrogen on silica gel or iron catalysts and the adsorption of water vapor on polymer-based absorbents.
- Type III isotherms (concave upward) arise when the interaction between adsorbates is significantly greater than the interaction between adsorbate and sorbent. For instance, it manifests in the adsorption of water on hydrophobic zeolites and activated carbon.
- Type IV isotherms characterize the adsorption behavior of specific mesoporous materials, indicating pore condensation. A hysteresis arises between the adsorption and desorption branches. It possesses two inflection points. Illustrative instances encompass the adsorption of benzene onto iron oxide and silica gel.
- Type V isotherms possess a single inflection point, indicating the presence of mesopores where pore condensation may occur during phase shift. It manifests in the adsorption of water on carbon molecular sieves and activated carbon fiber.
- Type VI isotherms exhibit many inflection points. It manifests at low temperatures where layers become more distinct, and the isotherms exhibit stepwise multilayer adsorption. Examples encompass the adsorption of noble gases onto the surfaces of planar graphite and the adsorption of butanol onto aluminum silicate.

The adsorption capacity at equilibrium (q_e, mmol/g) can be determined based on the following equation:

$$q_e = V(C_o - C_e)/M \qquad (1)$$

where V, M, C_o, and C_e represent the volume (L), mass of adsorbent (g), initial adsorbate concentration (mmol/L), and equilibrium adsorbate concentration (mmol/L). The Langmuir model and Freundlich model can be used to describe the adsorption data. The adsorption isotherm explains the amount of solute adsorbed on the surface of the adsorbent under constant temperature. The monolayer adsorption capacity and heterogeneous surface adsorption process can be represented by using the Langmuir isotherm and Freundlich model (see Table 1.2), respectively.

Considerable endeavors have been dedicated to formulating models for the adsorption isotherms (refer to Table 1.2). The Langmuir and Toth isotherm models are not applicable under high pressure conditions. Toth created an isotherm model that utilizes a power function to describe the relationship between the adsorption capacity and the adsorption potential of the adsorbent surface. It was found that the Toth model was inadequate in explaining the shift to the saturation region. The Dubinin-Radushkevich isotherm model exhibits good performance under high-pressure conditions but fails to accurately represent low-pressure experimental data. The interested reader for a complete description of the models depicted in Table 1.2 including applications and limitations, as well as symbols definitions has to resort to Al-Ghouti et al. (2020),

Table 1.2 Various models for adsorption isotherms (Soares et al. (2016), Lundstedt (2019), Al-Ghouti et al., (2020),)

Model	Equation	Key Assumptions	Applications
Langmuir	$q_e = \dfrac{q_{\max} K_L C_e}{1 + K_L C_e}$	Monolayer adsorption Uniform surface No interaction between adsorbate	Water treatment, gas adsorption, catalysts, surface coatings
Freundlich	$q_e = K_F C_e^{1/n}$	Heterogeneous surface Multilayer possible Empirical	Activated carbon adsorption, soil and environmental science
BET	$\dfrac{C_e}{\left(q_e\left(1 - \dfrac{C_e}{C_s}\right)\right)} = \dfrac{1}{q_m C_B} + \dfrac{(C_e/C_s)(C_B - 1)}{q_m C_B}$	Multilayer adsorption Homogeneous surface No lateral interactions	Surface area analysis (e.g. porous materials like zeolites, activated carbon)
Temkin	$q_e = \dfrac{RT}{b} \ln(K_T C_e)$	Adsorption energy decreases linearly with coverage Adsorbate-adsorbate interactions	Gas-solid systems Adsorption on heterogenous surfacesMetal ion adsorption, biosorption studies

Model	Equation	Key Assumptions	Applications
Dubinin-Radushkevich (DR)	$q_e = q_s \exp\left(-B\varepsilon^2\right)$, $\varepsilon = RT\ln\left(1+1/C_e\right)$	Porous adsorbents Assumes Gaussian energy distribution	Microprous filling Estimating Adsorption energy Distinguishing physical vs. chemical adsorption on porous solids
Sips	$q_e = \dfrac{q_{\max}\left(K_s C_e\right)^n}{1+\left(K_s C_e\right)^n}$	Heterogeneous surface Reduces to Langmuir when n=1 Combines Langmuir and Freundlich	Systems with mixed surface heterogeneity
Toth	$q_e = \dfrac{q_{\max} K_T C_e}{\left(1+\left(K_T C_e\right)^t\right)^{1/t}}$	Corrects Langmuir for high/low concentration deviation Heterogeneous surfaces	Porous adsorbents e.g. zeolites
Redlich-Peterson	$q_e = \dfrac{K_R C_e}{1+\alpha_R C_e^g}$	Hybrid model (Langmuir + Freundlich) Empirical	Applicable to wide concentration ranges empirical fit for various adsorbents

Where

q_e: amount adsorbed per unit mass of adsorbent
C_e: equilibrium concentration of adsorbate
q_{max}: maximum monolayer adsorption capacity
K_L, K_F,K_T,K_s,K_R: adsorption constants
n,g,t: model specific constants
B: D-R constant related to adsorption energy
C_s: saturation concentration in (BET)
R: gas constant
T: temperature

Several adsorption kinetic models, including the pseudo-first-order (PFO) model, the pseudo-second-order (PSO) model, the Elovich model, and phenomenological mass transfer models, have been created to explain the adsorption process. Nevertheless, certain issues persist in the implementation of these kinetic models. The primary issue is that the most commonly used PFO and PSO models are empirical models that lack explicit physical interpretations.

These empirical kinetic models are inadequate for investigating the mass transfer pathways. Hence, it is necessary to establish the physical interpretations of the empirical kinetic models. The second point is that the differential kinetic models, such as the phenomenological external/internal and adsorption in active sites models, possess distinct physical interpretations, but their solution methods are intricate.

There is a limited amount of research that has examined the mass transfer mechanisms using these models. The intricate solution techniques impede the utilization of these models. The third issue is that several published works utilize or solve kinetic models in an incorrect manner. Furthermore, the linear regression method is extensively utilized for calculating model parameters due to its straightforwardness. Nevertheless, the process of linearization altered the variables that were independent and dependent. This procedure has the potential to introduce mistakes to the independent and dependent variables, which could result in erroneous estimations of the parameters.

The nonlinear technique can offer reliable and precise estimations for model parameters. Providing a nonlinear solving approach for the adsorption kinetic models is highly important. Table 1.3 summarizes the different adsorption kinetic models. A detailed description of the kinetic models for adsorption is given in Wang and Guo (2020).

Table 1.3 Various Kinetic models for adsorption (Wang and Guo (2020))

Model Name	Equation	Assumptions	Applications
Pseudo-first order (PFO)	$\frac{dq_t}{dt} = k_1(q_e - q_t)$	Adsorption rate proportional to number of unoccupied sites. Often valid for physisorption processes.	Removal of dyes, heavy metals in aqueous solutions where physical adsorption dominates.

Pseudo-second order (PSO)	$\frac{dq_t}{dt} = k_2(q_e - q_t)^2$	Adsorption depends on the square of unoccupied sites. Usually indicates chemisorption controlling the rate.	Adsorption of heavy metals, organic contaminants where chemical bonding is involved.
Elovich model	$q_t = \frac{1}{\beta}\ln(\alpha\beta) + \frac{1}{\beta}\ln t$	Chemisorption kinetics Rate decreases with coverage	Heterogeneous catalytic surfaces, diffusion-limited adsorption

Where

α: initial rate
β: desorption constant
k_1: pseudo first order rate constant
k_2: pseudo second order rate constant
q_e: amount of adsorbate at equilibrium
q_t: amount of adsorbate at time t
t: time

One of the most important measurements in chemical engineering is the specific surface area and pore size distribution and pore volume measurements by using adsorption models. The interested reader for a comprehensive description of these measurements has to resort to Bardestani et al. (2019).

1.4 Recent Advance in Adsorbents

In recent years, research has been fluorescent in the area of adsorbents, due to the introduction of novel materials such as fullerenes, graphene oxide, metal organic frameworks (MOF), covalent organic frameworks (COF), etc.

A fullerene is a carbon allotrope characterized by molecules composed of carbon atoms linked by single and double bonds, forming a closed or partially closed network with fused rings of five to six atoms. The molecules may exhibit hollow spherical, ellipsoidal, tubular, or other configurations.

Graphene oxide (GO) is the oxidized form of graphene. It is a monolayer material produced from the oxidation of graphite, which is inexpensive and abundantly accessible. Graphene oxide is readily processed due to its dispersibility in water and other solvents. Graphene oxide is nonconductive because of the presence of oxygen in its lattice; however, it may be chemically converted to graphene. Figure 1.3 illustrates the chemical formulas of graphene and graphene oxide.

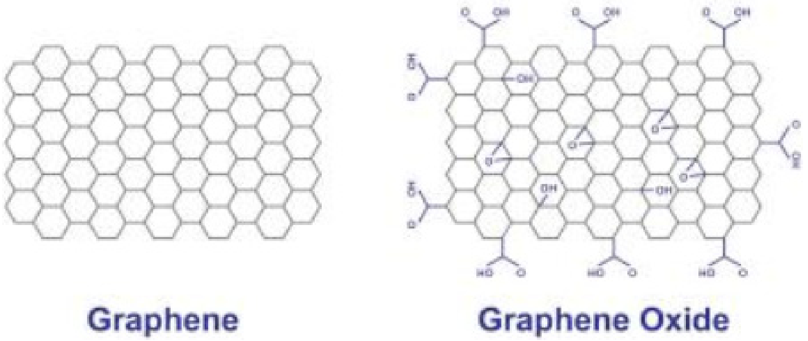


Fig. 1.3 Structure of Graphene and Graphene Oxide (Adopted from Graphene-info, 2025)

Metal–organic frameworks (MOFs) are a class of porous polymers consisting of metal clusters coordinated to organic ligands to form one-, two- or three-dimensional structures (Figure 1.4).

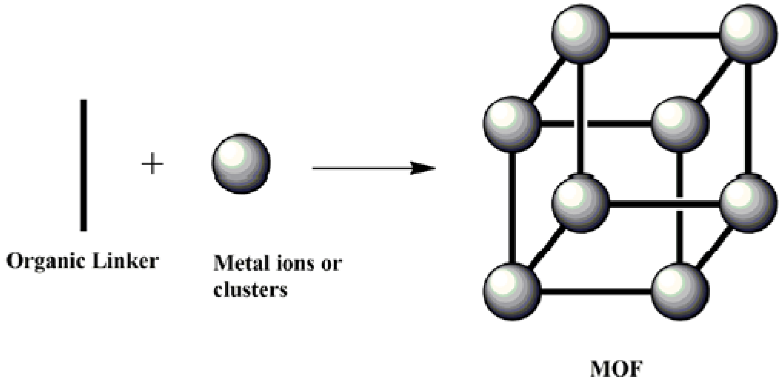


Fig. 1-4 Typical structure of a MOF (Adopted from Rafique (2020), open access)

Covalent organic frameworks (COFs) are a class of porous polymers that form two- or three-dimensional structures through reactions between organic precursors resulting in strong, covalent bonds to afford porous, stable, and crystalline materials (Figure 1.5).

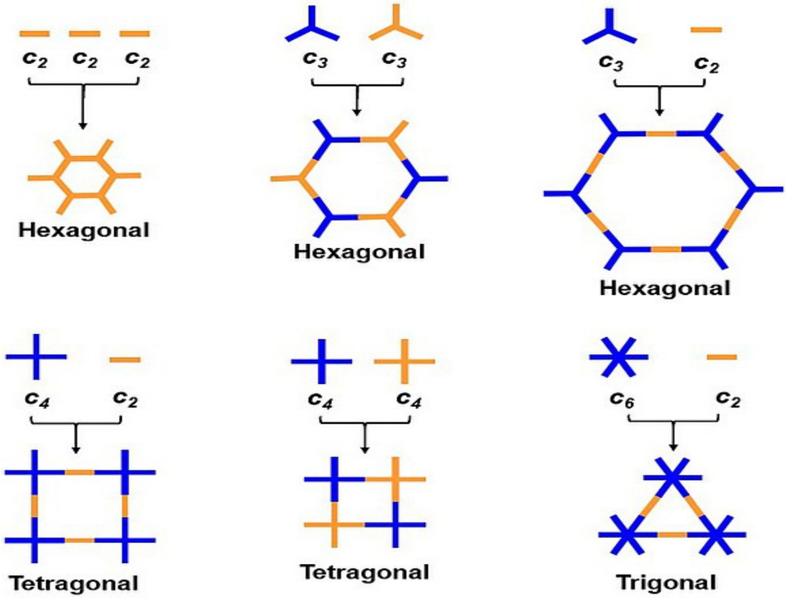


Fig. 1-5 Typical structure of a COF
(https://en.wikipedia.org/wiki/Covalent_organic_framework)

Other important materials used as adsorbents are carbon materials, inorganic materials such as minerals, synthetic and natural polymers, etc.

The review by Lee et al. (2006) provides a comprehensive summary of the advancements made in the synthesis of porous carbon materials. Diverse methods have been employed to synthesise porous carbon compounds with varying pore sizes and shapes. Microporous activated carbons have been produced by the activation method. Microporous carbon compounds have been produced by utilizing zeolites as templates. Mesoporous carbons with an unordered pore structure have been produced by many techniques, such as catalytic activation with metal species, carbonization of polymer/polymer blends, carbonization of organic aerogels, and template synthesis utilizing silica nanoparticles.

Commercial activated carbon is the ideal substance for adsorbing micropollutants from water, but its application is limited since it is expensive. In order to reduce the expenses associated with treatment, efforts have been undertaken to discover low-cost substitute materials for activated carbon (AC) production, such as waste products. The study conducted by Dias et al. (2007) critically examines and assesses existing literature that focuses on the production of activated carbon through the recycling of various waste materials, as well as its utilization in diverse treatments involving water-based solutions. In this study, Gautam et al. (2014) investigated the techniques of modifying and activating adsorbents, as well as regenerating them, for the purpose of sequestering metal ions.

In their study, Jain et al. (2016) conducted a thorough investigation into the hydrothermal conversion process of biomass waste, specifically focusing on the production of activated carbon with exceptional porosity. In their respective studies, Wang and Wu (2006), Ahmaruzzaman (2010), and Blissett et al. (2012) examined the use of coal fly ash for the purpose of adsorbing NOx, SOx, organic compounds, and mercury in air, as well as dyes and other organic compounds in water. The study conducted by Lam et al. (2010) examines the properties of municipal solid waste incineration (MSWI) ashes and their potential use as adsorbents. Vassilev et al. (2013) provided a comprehensive examination of the composition and uses of biomass ash as adsorbents.

Red mud (RM) is a residual substance that is produced as a result of the bauxite processing method known as the Bayer process. The proper disposal of garbage continues to be a matter of utmost importance, given the substantial environmental considerations involved. Over the past few decades, much study has been conducted to explore the potential of red mud for environmentally-friendly purposes, such as its use as an additive in building materials and for recovering metals. Red mud has been investigated for its potential applications in gas purification and wastewater remediation in recent times. Wang et al. (2008) conducted a comprehensive analysis of the diverse uses of red mud as a coagulant and adsorbent in the treatment of water and gas.

In 2011, Ahmaruzzaman conducted a review on the utilization of industrial wastes as inexpensive adsorbents for treating wastewater with high levels of heavy metals. Bhatnagar et al. (2015) investigated the utilization of agricultural waste peels as a versatile biomass for the purpose of water treatment.

Biochar has been proposed as a method for remedying polluted soil and water. Further enhancements are required to improve the practical applications of conventional biochar for the immobilization and removal of contaminants. Therefore, there has been significant emphasis on altering biochar by including new configurations and surface characteristics to enhance its effectiveness in remediation and its positive impact on the environment. Engineered or designer biochars are frequently used phrases to describe the modification or synthesis of biochar with specific applications and desired outcomes. In their study, Qian et al. (2015) conducted a thorough analysis of the progress made in the use of biochar as an adsorbent.

The review conducted by Cha et al. (2016) specifically examines the processes involved in the creation and application of biochar. The review conducted by Rajapaksha et al. (2016) provides a comprehensive analysis and assessment of various techniques used to modify biochar, the underlying mechanisms involved, and the advantages of using biochar for the management of contaminants in soil and water. In their study, Fang et al. (2018) discussed the possible uses of hydrochar produced during the hydrothermal carbonization process of biomass. Zhang et al. (2019) conducted a comprehensive analysis of the production and utilization of biochar and hydrochar. Xiang et al. (2020) provided an in-depth evaluation of the application of biochar as an adsorbent in wastewater treatment.

Danish and Ahmad (2018) conducted a thorough investigation on the use of wood biomass as a sustainable source for producing and applying activated carbon. In their study, Dai et al. (2018) explored the use of agricultural waste as an adsorbent for the purpose of removing pollutants. In their study, Suhas et al. (2016) examined the utilization of cellulose as an adsorbent in its native, modified, and activated carbon forms.In their study, Hokkanen et al. (2016) conducted a comprehensive assessment of the many techniques used to enhance the adsorption capacity of cellulose-based adsorbents.The review conducted by Suhas et al. (2007) consolidates the research conducted on the application of lignin and lignin-based chars and activated carbons as adsorbents for removing substances from water. The review specifically emphasizes the utilization of lignin as an adsorbent, its transformation into chars and activated carbons, and the application of these materials as adsorbents. Li et al. (2020) conducted a thorough examination of the process and advanced application of biochar produced through selective pyrolysis of lignocellulosic biomass. Norgren and Edlund (2014) documented the latest progress in the field and the developing uses of lignin as an adsorbent.

Zeolites are crystalline minerals characterized by a well-organized network of micropores at the molecular scale, making them effective adsorbents. Li et al.. (2017) provided a comprehensive overview of the diverse applications of zeolites in adsorption processes.

In parallel, recent advancements have been made in the synthesis and application of nanoporous carbon spheres, which range in size from nanometers to micrometers. Liu et al. (2015) reviewed the primary synthesis methods, key research contributions driving this field, and potential applications of these materials. The study also identified the current challenges and future directions for the development of nanoporous carbon spheres.

The article by Khim et al. (2012) provides a comprehensive overview of the utilization of nanomaterials in the process of environmental restoration. Nanomaterials have the ability to efficiently remove pollutants and biological contaminants in the field of environmental remediation. Nanomaterials of different shapes and structures, including nanoparticles, tubes, wires, and fibers, serve as adsorbents and catalysts. These materials, when combined with polymers, are utilized for the identification and elimination of gases (such as SO_2, CO, NO_x), polluted chemicals (like arsenic, iron, manganese, nitrate, heavy metals), organic pollutants (both aliphatic and aromatic hydrocarbons), and biological substances such as viruses, bacteria, parasites, and antibiotics. Nanomaterials exhibit superior efficacy in environmental cleanup compared to conventional procedures due to their elevated surface area (surface-to-volume ratio) and correspondingly heightened reactivity. The work of Khim et al. (2012) focuses on the development of new nanoscale materials and processes for treating contaminated drinking water, industrial waste water, and air. These materials and processes are designed to remove toxic metal ions, radionuclides, organic and inorganic solutes, bacteria, and viruses. Furthermore, this article also explores the latest developments in utilizing polymer nanocomposite materials for the remediation of pollutants and the surveillance of contaminants.

Gehrke et al. (2015) presented a comprehensive review of recent advances in nanotechnologies for water and wastewater treatment, highlighting the use of nanomaterials such as nanoadsorbents. They discussed both the benefits and technical challenges of these materials compared to conventional methods. Sadegh et al. (2017) explored the effectiveness of nanomaterials as adsorbents and their potential in wastewater treatment applications. Grishkewich et al. (2017) focused on emerging developments in the use of cellulose nanocrystals, while Thomas et al. (2018) provided an in-depth analysis of nanocellulose as a promising adsorbent.

Kefeni et al. (2017) investigated the utilization of spinel ferrite nanoparticles as adsorbents for the treatment of water and wastewater. Reddy and Yun (2016) conducted a review on magnetic adsorbents made of spinel ferrite. Saleh (2021) documented the procedures for producing nanomaterials, polymers, and environmentally friendly materials to be used as adsorbents in water treatment technologies. Researchers worldwide have been drawn to the production of magnetic biochar from biomass and the potential for creating magnetic nanomaterials. The transformation of this biomass into a more promising form has effectively mitigated the waste management problem without any difficulty. Magnetic biochar, obtained from different biomass sources, demonstrates excellent magnetic characteristics, together with a large surface area and distinctive form, achieved through diverse manufacturing techniques. The magnetic biochar demonstrated significant potential as an adsorbent for diverse wastewater treatments and were incorporated into specific polymer composites for use in supercapacitors. The research conducted by Thines et al. (2017) and Yi et al. (2020) offer a comprehensive overview of different techniques for producing magnetic biochar, as well as its utilization in wastewater treatment and environmental applications.Covalent organic frameworks (COFs) are a recently produced type of crystals that are characterized by their chemical stability, well-structured porous framework, adjustable skeleton, and in certain cases, luminescent properties. Due to their inherent benefits, stable COFs have a wide range of functions in environmental applications, including the adsorption, separation, detection, and catalytic degradation of pollutants. The primary emphasis of the review conducted by Wang and Zhuang (2019) was on the latest advancements in the creation of stable COFs for environmental applications, particularly in the field of adsorption.

Hydroxyapatite (HAp), a calcium phosphate biomaterial with the chemical formula $Ca_{10}(PO_4)_6(OH)_2$, shows considerable promise for mitigating air, water, and soil pollution. Its unique structure imparts several advantageous properties, including high adsorption capacity, acid-base buffering ability, ion exchange capability, and excellent thermal stability. Additionally, HAp plays a vital role in resource recovery strategies. Ibrahim et al. (2020) provided a detailed review of the structural and functional characteristics of HAp, emphasizing its potential as an adsorbent for wastewater and soil remediation.

Layered double hydroxides (LDHs), composed of positively charged stacked layers, possess the ability to exchange interlayer anions, making them effective for environmental clean-up. Recent studies have explored the use of LDHs in removing toxic oxyanions—such as arsenate, chromate, and phosphate—from contaminated water through both surface adsorption and anion exchange mechanisms. Goh et al. (2008) offered a comprehensive review covering LDH synthesis methods, characterization techniques, and advances in their application for oxyanion removal, while also highlighting ongoing challenges in the field. Li et al. (2014) further examined the efficacy of LDH-based nanomaterials as highly effective adsorbents for environmental remediation.

1.5 Adsorption in Water Purification and Wastewater Treatment

Water supplies worldwide have become polluted as a result of the discharge of significant amounts of harmful pollutants, including dyes, heavy metals, surfactants, personal care products, pesticides, and medications, from agricultural, industrial, and municipal sources into water streams. The global dilemma of water contamination and its remediation has become increasingly urgent. In recent years, significant efforts have been undertaken to tackle the obstacles associated with wastewater treatment. Table 1.4 provides a comprehensive overview of recent research advancements in various treatment approaches using adsorption to eliminate different types of water impurities (Fu and Wang, 2011; Ali, 2012; Kyzas and Kostoglou, 2014; Singh et al., 2018; Crini et al., 2019; Li et al., 2019, Gusain et al., 2020; Qasem et al., 2021; Rashid et al., 2021, Sen, et al. 2023)

Table 1-4 Adsorption materials in water purification and wastewater treatment.

Material	**Contaminant**	**Reference**
Activated carbon	Dyes	Demirbas (2009), Mezohegyi et al. (2012), Gupta et al. (2013)
	Miscellaneous	Rivera-Utrilla et al. (2011), Bhatnagar et al. (2013), Wong et al. (2018)
Carbon based adsorbents: Carbon nanotubes, porous carbon, graphitic carbons (Graphene, Graphene Oxide), Covalent Organic Frameworks (COF), Fullerene, Melal Organic Frameworks (MOF)	Heavy Metals & Dyes	Ihsanullah et al. (2016), Peng et al. (2017) , Yang et al. (2019), Duan et al. (2020), Liu et al. (2019), Sherlala et al. (2018), Jiang et al. (2019), Velusamy et al. (2021), Santoso et al. (2020)
	Miscellaneous	Ren et al. (2011), Gupta and Saleh (2013), Kyzas et al. (2014), Ersan et al. (2017), Li et al. (2018), Ali et al. (2019), Dhaka et al. (2019), Fiyadh et al. (2019), Gao et al. (2019), Rasool et al. (2019), Thakur and Kandasubramanian (2019), Yang et al. (2019) , Du (2021), Liu et al. (2021), Upadhyay et al. (2014)
Chitosan	Dyes & Heavy Metals	Crini and Badot (2008), Reddy and Lee (2013), Vakili et al. (2014, 2019), Zhang et al. , (2016), Upadhyay et al. (2021)
	Miscellaneous	Wu et al. (2010), Wan Ngah et al. (2011), Kyzas and Bikiaris (2015),Mohammadzadeh and Peighambardoust (2018). , Saheed et al. (2021)
Low cost adsorbents: natural, industrial, as well as synthetic materials/wastes	Antibiotics/Phamaceuticals	Peiris et al. (2017), De Andrade et al. (2018), Quesada et al. (2019)
	Chromium ions	Miretzky and Cirelli (2010)
	Dyes	Crini (2006) , Gupta Suhas (2009), Rafatullah et al. (2010), Salleh et al. (2011), Sharma et al. (2011), Adegoke et al. (2015), Bulgariu et al. (2019)

Material	Contaminant	Reference
	Heavy metals	O’Connell et al. (2008), Sud et al. (2008) , Wan Ngah et al. (2008), Nguyen et al. (2013), Tan et al. (2015) . Inyang et al. (2016), , Sizmur et al. (2017), Ge et al. (2018), Joseph et al. (2019), Wang et al. (2019), Qiu et al. (2021), Chakraborty et al. (2022)
	Miscellaneous	Gupta et al. (2009) ,Bhatnagar and Sillanpää (2010), Ali (2012), Hadi et al. (2015), De Gisi et al. (2016), , Mo et al. (2018), Cheng et al. (2021)
	Phenolic copounds	Ahmaruzzaman (2008)
Minerals: kaolinite and montmorillonite, layered double hydroxides (LDH), zeolites, clays,silica	Heavy metals	Bhattacharyya and Gupta (2008), Malamis and Katsou (2013), Uddin (2017) , Da’na et al. (2017) Siyal et al. (2018), Gu et al. (2019), Zhang et al. (2021)
	Miscellaneous	Wang and Peng (2010), Zhu et al. (2016), Adeyemo et al. (2017), Ngulube et al. (2017), Zubair et al. (2017), Jiang et al. (2018),
Miscellaneous	Antibiotics/Phrmaceuticals	Ahmed et al. (2015), Yu et al. (2016)
	Arsenic/Chromium,/Antimony	Mohan et al. (2007), Ungureanu et al. (2015), Lata et al. (2016),Hao et al. (2018), Karimi-Maleh et al. (2021),
	Bisphenol A	Bhatnagar and Anastopoulos (2017)
	Dyes	Yagub et al. (2014), Zhou et al. (2019), , Katheresan et al. (2018), Dutta et al. (2021)

Material	Contaminant	Reference
	Fluoride & its compounds	Ayoob et al. (2008), Mohapatra et al. (2009) , Bhatnagar et al. (2011), Loganathan et al. (2013), Du et al. (2014),Gagliano et al. (2020)
	Heavy metals	, Kurniawan et al. (2006), Renu et al. (2017), Burakov et al. (2018), Chai et al. (2021), Shrestha et al. (2021)
	Nitrate	Bhatnagar and Sillanpää (2011)
	Pesticides	Saleh et al. (2020)
	Phenol	Busca et al. (2008) , Lin and Juang (2009)
	Phosphorus	Bacelo et al. (2020)
	Polycyclic aromatic hydrocarbons (PAHs)	Lamichhane et al. (2016)
Other Nanomaterials	Heavy Metals	Sharma et al. (2009) , Hua et al. (2012), Gómez-Pastora et al. (2014), Lata et al. (2016), Basheer (2018), Wadhawan (2020)
Polymers	Heavy metals	Samiey et al. (2014), Ekramul Mahmud et al. (2016), Zare et al. (2018), , Zhao et al. (2018), Gao et al. (2020a)

1.6 Gas Adsorption

Global warming driven by greenhouse gas emissions, particularly CO_2, has become a major global concern in recent years. Among the various CO_2 capture technologies proposed, chemical adsorption is considered one of the most promising for post-combustion power plant applications. Several studies have reviewed the operation and effectiveness of adsorption-based CO_2 removal, including those by Choi et al. (2009), Wang et al. (2011a), Bae and Snurr (2011), Yu et al. (2012), Lee and Park (2015), Oschatz and Antonietti (2018), Gao et al. (2020b), and Singh et al. (2020).

Shafeeyan et al. (2010) investigated the effect of gaseous ammonia surface modification of activated carbon on its CO_2 adsorption capacity. Singh et al. (2019) reviewed advances in biomass-derived porous carbon materials for CO_2 capture, while Wang et al. (2011b) focused on the use of alkali-metal-based oxides for the same purpose.

Emerging materials such as metal-organic frameworks (MOFs) have also garnered significant attention. Reviews by Chaemchuen et al. (2013), Zhang et al. (2014), Patel et al. (2017), Ghanbari et al. (2020), and Islamoglu et al. (2020) provided a comprehensive overview of MOFs for CO_2 storage and separation. Wen et al. (2019) examined MOF-based nanomaterials for gaseous pollutant adsorption, while Adil et al. reviewed their application in gas and vapor separation using ultra-microporous frameworks.

The removal of hydrogen sulfide (H_2S) remains a persistent economic and environmental challenge in the oil and gas industry. Adsorption-based H_2S separation methods were reviewed by Shah et al. (2017). Volatile organic compounds (VOCs), which pose serious health and ecological risks, have also driven the development of numerous abatement technologies over recent decades. Zou et al. (2019) discussed VOC removal using carbon-based nanocomposites, while Zhang et al. (2017) focused on the adsorption of VOCs onto engineered carbon materials. Another critical application of adsorption is mercury removal from coal-fired boiler flue gas, as reported by Yang et al. (2007).

The versatility of adsorbents extends across various sectors. Notable emerging applications include water desalination (Teow and Mohammad, 2019), uranium recovery from seawater (Kim et al., 2013; Abney et al., 2017; Xie et al., 2019a), iodine capture (Xie et al., 2019b), separation of rare metals (Anastopoulos, 2016), and gas storage such as hydrogen (Van Den Berg et al., 2008), natural gas (Mason et al., 2014), and methane (Li, 2016).