Int. j. adv. multidisc. res. stud. 2025; 5(4):290-293

Received: 22-05-2025
Accepted: 02-07-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Adsorption Technique: A Narrative Review

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Abstract

The adsorption technique is a widely utilized process in environmental and industrial applications for the removal, separation, and purification of substances from liquids or gases. This surface phenomenon involves the accumulation of atoms, ions, or molecules from a fluid phase onto a solid surface, known as the adsorbent. Activated carbon, silica gel, zeolites, and bio-based materials are commonly used adsorbents due to their high surface areas and specific affinity for various adsorbates. Adsorption can be classified into physical adsorption, driven by van der Waals forces, and chemical adsorption, involving stronger covalent or ionic bonding. This technique is extensively applied in wastewater treatment, air purification, gas storage, and catalysis, particularly for removing pollutants like heavy metals, dyes, and volatile organic compounds. Factors influencing adsorption efficiency include temperature, pH, surface area, pore size distribution, and the nature of both the adsorbent and adsorbate. Isotherm models, such as Langmuir and Freundlich, help describe the adsorption behavior and capacity of systems under various conditions. Recent advancements focus on developing novel nanomaterials and bio-adsorbents that enhance adsorption capacity, regeneration ability, and environmental sustainability. The adsorption technique remains a cost-effective, efficient, and versatile method with growing potential in environmental protection and resource recovery, highlighting its continued significance in scientific and industrial sectors.

Keywords: Adsorption Technique, Separation Technique, Physical Adsorption, Chemical Adsorption, Covalent Bonding, Ionic Bonding

Introduction

Adsorption is a surface occurrence that involves the accumulation of atoms, molecules, or ions at the surface of a solid phase. It is a mass transfer process leading to the sorption of gases or solutes by solid or liquid surfaces [1]. Adsorption is one of the most promising heavy metal removal techniques because of its high efficiency and selectivity to remove certain type of metal, while requiring low capital and operation costs. This is so as the design of adsorption system is very simple and easy to operate [2]. Easy reuse or recovery of adsorbent after adsorption helps to minimize the operating cost. Adsorption process can be operated under a wide pH range (pH 2-9) and temperatures (4 – 90 ºC) [3].

Adsorption takes place at an interface between any two phases such as liquid-liquid, gas-liquid or solid-liquid interfaces [4]. It is also defined as separation process in adsorbent suspended with solid particles, which the adsorbate is transferred from the bulk fluid phase to the surface of the adsorbent particles. The molecules of bulk fluid phase tend to attach and accumulate on the surface of the solid particles when the solid surfaces are exposed to fluid phases. There are two different kinds of adsorption, which are physical adsorption and chemical adsorption [5].

Physical Adsorption

Physical adsorption is the adsorption of molecules on the adsorbent particles surfaces as a result of intermolecular forces of attraction [3]. It is also known as the Van der Waals adsorption. Physical adsorption is often an exothermic process. The energy involved between adsorbate and adsorbent is usually the same magnitude but is normally a bit higher than the energy condensation of the adsorbents. Thus, activation energy is not required because generally physical adsorption system can achieve thermodynamic equilibrium fairly and rapidly. The adsorption energy is usually within 80 kJ/mole, with typical energies being considerably less [6].

In physical adsorption, the molecules are not specifically adsorbed onto a binding site of the adsorbent surface. The molecules diffuse along the adsorbent surface. Physical adsorption is readily reversible because it is only weakly bound by Van der Waals forces [6]. This reversibility nature has been applied to several industrial adsorption operations such as regeneration of adsorbed substances, recovery of adsorbents to reuse and fractionation of mixtures [3]. Undoubtedly, it helps to minimise the extraction of virgin materials and maximise the potential of used materials. Molecules which are physically adsorbed will retain its identity and recover to its original form in the fluid phase when desorption is performed. Moreover, physical adsorption can occur on any interface as long as the temperature and pressure conditions are favourable. It occurs as a multilayer at relatively high pressure [6].

Physical adsorption is a simple enzyme immobilization method that preserves the enzyme's native conformation and activity (Fig. 1) It of.fers protection against aggregation, proteolysis, and hydrophobic interactions. Biosensors developed using this technique exhibit enhanced operational stability and improved storage performance. However, limitations include potential enzyme leaching and diffusion barriers, which can hinder overall sensor efficiency. Despite these drawbacks, the method remains attractive due to its ease of use and ability to maintain enzymatic functionality without complex chemical modifications.

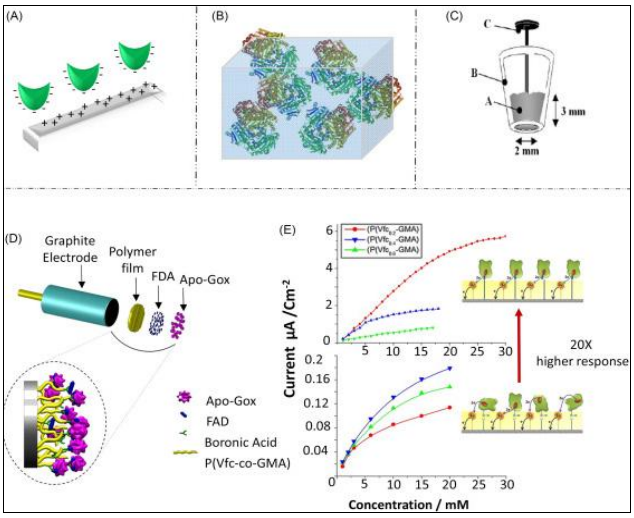

Fig 1: Physical adsorption [7]

Chemical Adsorption

Chemical adsorption, also known as chemisorption, involves chemical interaction between the adsorbate and adsorbent surface [3]. It has higher adsorption energy than purely physical adsorption. Heat of adsorption for C-N bond can reach up to 600 kJ/mole and 800 kJ/mole for chemical bonds [6]. The chemical bonds are formed by electrons sharing between the adsorbate and adsorbent, and the bonds result in formation of surface compound.

In chemisorption, chemical reaction takes place so that the molecules are able to attach onto specific binding sites of the adsorbents. Unlike physical adsorption, chemisorption is irreversible due to its bond strength. Chemically adsorbed molecules will lose their identities and cannot return to original form by desorption. Furthermore, chemisorption is highly selective. It only occurs between specific pairs of adsorbate and adsorbent or when chemically active surface is free of previously adsorbed species [6]. Chemisorption is a single-layer process, which only occurs when the adsorptive species makes direct contact with the surface except for highly polar adsorptive like NH_3 [6].

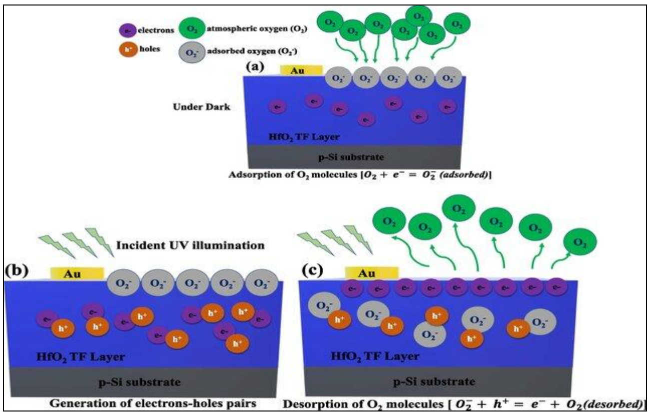

Fig 2: Diagrammatic representation of the Chemisorption process (a) Adsorption of O2 molecules under dark conditions (b) Electrons-Holes generation under UV illumination (c) Desorption of O2 molecules under UV illumination [8]

Factors Affecting Adsorption

There are some factors that will have impact on the adsorption. This include:

1. Surface area of adsorbent (particle size)
2. pH
3. Initial concentration
4. Adsorbent dosage
5. Contact time.

Surface Area of the Adsorbents

Surface area of the adsorbents is a key factor that affects the adsorption process. Smaller particles size of adsorbents will have larger surface area exposed, thus, improves the adsorption performance. Hence, more heavy metal ions can be removed. Larger particle size will have lower adsorption performance as large metal ions are unable to enter every initial pore of the adsorbent [3].

pH

pH value also greatly affects the adsorption performance. The active sites of the adsorbent surface as well as the property of adsorbents will be affected by pH. The influence of pH is indicated by the charge on the adsorbent surface [3].

At low pH, negatively charged adsorbent surface will be neutralized by large number of H^+ ions. This enhances diffusion and adsorption process. On contrary, at high pH, competition happens between the H^+ ions and the positively charged adsorbent surface and leads to a decline in adsorption performance [9].

Initial Metal Ions

Initial metal ions concentration is also another factor which affects adsorption. The initial concentration of metal ions delivers a driving force that enables the transport of heavy metal ions from the adsorbate to the adsorbent surface [10]. When the initial metal ions concentration increases, the adsorption performance of the adsorbent increases.

Adsorbent Dosage

Adsorbent dosage also has major effect on the adsorption process. When adsorbent dosage increases, the adsorption of metals also increases. There are several reports that proved this statement. For example, according to a study conducted by Kumar and Chauhan [11], it is discovered that the removal of Cd (II) increased quickly with the increase in cashew nut shell dosage. This is explained by the high number of adsorption sites due to high adsorbent dosage.

Contact Time

When the contact time between adsorbent and adsorbate increases, the adsorption of heavy metal ions also increases until it reaches equilibrium. Equilibrium time is achieved whenever the adsorption reaches a state of dynamic equilibrium with desorption. It is a very critical factor because it indicates the maximum adsorption capacity of adsorbent, which all the adsorption sites are occupied with the metal ions to be adsorbed [12]. Longer contact time does not entirely represents better adsorption. The optimum contact time for better adsorption actually corresponds to the types of adsorbents used.

Mechanism of Adsorption

Generally, adsorption is a surface technique; the success of an adsorbent depends on its surface chemistry. Therefore, mechanism of modified adsorbent involves surface modification. This is a process by which a material's physical, chemical, or biological characteristics are modified from its original form, leading to higher uptake capacity [13]. In modification procedures, surface impurities may be removed, producing physical and chemical changes. After modification of surface charge, surface energy, surface area, roughness, hydrophobicity, and functional groups, reactivity is improved [14].

Modification is mainly carried out by mechanical, thermal, or chemical processes. In the thermal process, porosity is developed, whereas surface area is increased in the chemical process. In the chemical modification process, the use of acid, alkali, or salts are involved and the surface functional groups are introduced or improved. Similarly, in the physical modification process, density and solubility increase. Surface modification can also be carried out using different methods, such as thermochemical or mechano-chemical methods [15]. Chemical surface modification is better compared to the physical surface modification process. Because it is less time-consuming, and the material's surface chemistry is also influenced directly [16]. Chemical surface modifications also add some new surface properties [17]. After modification, an inexpensive material can be transformed into a valuable product with high adsorption capacity.

Chemical Modification

The chemical modification provides a substantial effect on the skeleton and properties of materials surfaces due to chemical interactions of a modifying agent and the surface of material (Rostami *et al.*, 2018). Numerous modifying chemical agents exploited in recent times for tailoring the properties of adsorbents include [18]: i. Acid, ii. Alkaline, and iii. Impregnation and Organic Solvents.

Acid Modification

This is a wet oxidation modification process. Acid modification is carried out using mineral acids and other oxidizing agents like HCl, H_2SO_4, HNO_3, H_3PO_4, H_2O_2, HClO, etc [19]. After modification, the adsorbent surface becomes more acidic, and the adsorbent's hydrophilic nature also increases due to the reduction of mineral contents [20]. Acidification increases the polar oxygen-containing functional groups on the surface like carboxyl, quinine, hydroxyl, carbonyl, carboxylic anhydride, nitro, and lactone, etc [21]. It increases the negative charge properties of the adsorbent surface and increases the adsorption of positively charged pollutants. Acid treatment also introduces H^+ ions on the adsorbent surface. Consequently, there is an increase in the adsorption of negatively charged pollutants. The introduction of H_2SO_4, HNO_3, H_3PO_4 also increases the functional groups such as CN, NO, S, and P [19].

Alkaline Modification

The surface functional groups of adsorbents can be significantly influenced by modifying with reducing agents. This process can improve the relative content of alkali groups and improve the non-polar surface, hence, enhances the adsorption capacity of the material for non-polar substances [22]. An adsorbent with alkali treatment adsorbs a positive charge on the surface that enhances the adsorption of negatively charged species [22]. The surface reduction can be made by treatment with NH4OH, NaOH, KOH, LiOH, Na_2SiO_3, Na_2CO_3 and oxides.

Impregnation and Organic Solvents Modification

Impregnation is another type of adsorbent modification process in which uniform distribution of one type of chemical occurs on the porous adsorbent's internal surface. Metal impregnation is carried out by ferric chloride, zirconium, cerium, carbonates, hydroxides, nitrates, etc [23]. Organic solvents like ethanol can also be used for the modification of adsorbent surfaces. They introduce some species onto the adsorbent surface so that their adsorption capacity increases. However, its practical application is limited because of its high cost, unsafe and unstable nature. Organic solvents introduce a large number of functional groups on the adsorbent surface [24].

Adsorbent

An adsorbent is a solid material that allows liquid or gaseous molecules to bind to its surface. There is a variety of adsorbents that are employed in the industry for heavy metal removal. These adsorbents can be categorised into activated carbon (AC), natural source adsorbents, agro-waste adsorbents, biomass adsorbents and by-product adsorbents. Many materials have been used for adsorbents for various applications such as treatment of water, separation, catalysis, indicators, and desiccants. Some commonly used adsorbents include biochar, agriculture and industrial wastes, activated carbon, clays, biopolymers and nanomaterials [25].

Conclusion

The adsorption technique is a highly effective method for removing contaminants from liquids and gases, widely used in environmental and industrial applications. It relies on the surface attraction of molecules to solid materials like activated carbon or zeolites. Its simplicity, cost-effectiveness, and high efficiency make it a preferred choice for purification and separation processes. As environmental concerns grow, adsorption continues to play a crucial role in advancing sustainable and eco-friendly solutions for pollution control.

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