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Review

A review on phenomenon of adsorption of inorganic materials: Applications in veterinary pharmacology and material sciences

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Abstract: The inorganic compound water is the second most essential component after air for perpetuation of life on the planet. Due to human activity the natural resources of water are highly contaminated. The water reservoir contains physical, chemical and biological impurities. Sometimes radioactive materials are discharged in the reservoir creating even hazardous effects. The presence of heavy metal ions in drinkable water is a major global challenge for mankind. The heavy inorganic materials can be separated using various techniques. With the advancement in modern science, nanomaterials are found to be effective in removal of heavy inorganic materials from water. As surface area at nanoscale increases, the possibility of adsorption also gets increased. Therefore, nanomaterials are being effectively used in water purification techniques. In this review, we will focus on how heavy metals with negative environmental consequences may be removed using an adsorption approach that involves iron oxide nanoparticles, which has been shown to be effective in this field. We are going to discuss several methods along with current advancements in iron oxide nanoparticles for heavy metal ion adsorption from water. The discussion covers candidate synthesis of iron oxide nanoparticles, mechanisms that enable the applications, advantages, and limitations as compared to existing processes and their adsorption mechanism. Apart from this we have focused the application of adsorption particularly in veterinary science and animal husbandry. The phenomenon of adsorption is of paramount importance in veterinary pharmacology as well.

Keywords: adsorption; veterinary medicine; water purification; iron oxide nanomaterials; heavy metals

1. Introduction

The concept of adsorption was introduced by Scheele in 1783 during the discovery of uptake of gases by charcoal. However, the term adsorption was coined by Kayser in 1783. Further advancement in phenomenon adsorption was done by various scholars such as Michael Faraday, who studied adsorption of gas and established the foundation of modern adsorption theory. Van der Waal and Johannes developed the equation of states of gases and liquids laying the groundwork for adsorption. Langmuir and Irving introduced the concept of monolayer adsorption and developed Langmuir adsorption isotherm, Gibbs Josiah Willard formulated Gibb's equation describing relationship between surface tension and adsorption. If we consider a piece of material, then the surface particles behave in a different manner than the bulk materials. This is due to some reasons, at the surface, there are unbalanced or residual forces which act along the surface of a solid and have the tendency to attract molecules towards itself.

Now, consider a solution. The solute molecules present inside experience equal amounts of force from all directions. Therefore, it experiences a balanced force whereas the molecules at the top experience unbalanced forces. This means that the molecules at the surface are unstable. Thus, thermodynamically they are having more energy as compared to the molecules inside the solution. Thus, the molecules at the surface are (1) unstable; (2) unbalance; (3) and possess high energy. They try to acquire stability and remain in a balanced condition by losing energy. Thus, they try to attract some external molecules on its surface.

Let's consider another view of surface molecules. There may be covalent bonds between the atoms. Consider an example of carbon which is tetra-valent.

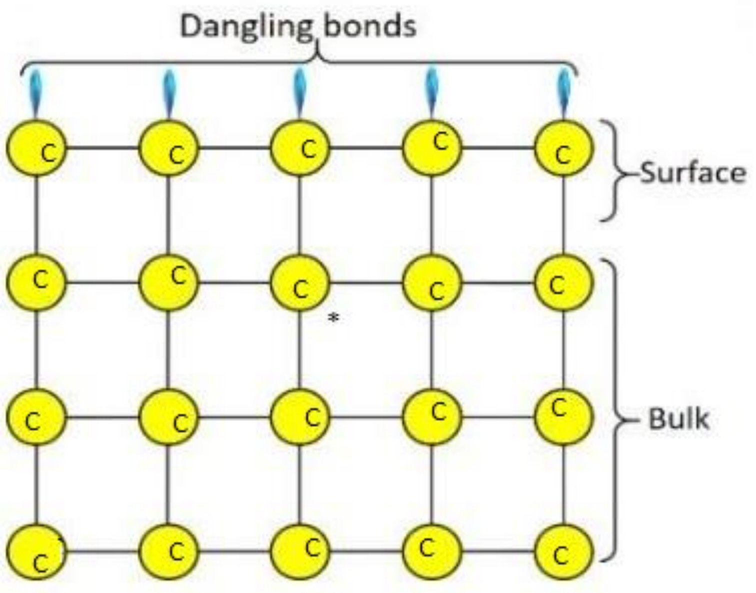

Figure 1. Dangling Bonds on the Surface and Tetra Valence Inside the Bulk.

The carbon atom marked by * (C*) is surrounded from all sides by another carbon atom. In such cases all the four valences of carbon are satisfied. However, the carbon atoms present on the surface or corners experience unsatisfied valances. These unsatisfied valances as shown in **Figure 1** are known as dangling bonds. Such dangling bonds are responsible for the phenomenon of adsorption. The key terminologies are defined in the following section.

Adsorption: This is the phenomenon of accumulation or collection of one substance on the surface of another substance.

Adsorbent: This is the surface on which adsorption takes place. e.g. charcoal.

Adsorbate: These are the substances which are adsorbed on the surface of another substance. e.g. coloring materials adsorbed on the charcoal.

Absorption: This is the phenomenon of penetration of one substance into the bulk or body of another substance.

Absorbent: This is substance into which another substance penetrates. e.g. Cotton, sponge etc.

Absorbate: These are the substances which get penetrated into the another substance. e.g. Water.

Sorption: This is the phenomenon in which adsorption and absorption takes place simultaneously.

Occlusion: The phenomenon of adsorption of a gas on the surface of metal is called as occlusion.

Desorption: This is the phenomenon in which adsorbed molecules gets removed from the surface of adsorbent. The force behind adsorption is basically van der Waals physical force of attraction. Therefore, the phenomenon of desorption is very common.

As adsorption is a surface phenomenon, it depends upon surface area. Thus, when a solid material is divided into small parts, it shows the phenomenon of adsorption to a greater extent. The colloidal particles are small and possess larger surface area, per unit mass, therefore acts as good adsorbent. The examples are charcoal, silica gel, clay, fuller's earth, etc. The distinction between the phenomenon of adsorption and absorption is represented in **Table 1**.

Table 1. Distinction between adsorption and absorption.

Sr. No.	Adsorption	Absorption
1	This is the phenomenon of accumulation of one substance on the surface of another substance	This is the phenomenon of penetration of one substance into the bulk or body of another substance
2	The concentration of adsorbed molecule is always greater on the interphase than in the bulk	The absorbed molecule is distributed uniformly throughout the bulk or body of another substance
3	Here the equilibrium is quickly attained	Here the equilibrium is slowly attained
4	This is an exothermic process	Here is no exchange of heat
5	This process depends upon pressure and temperature	This process is independent of temperature and pressure
6	This process depends upon atoms or molecules of the surface of adsorbent	This process depends upon porous nature of absorbent

Table 2. Distinction between physical adsorption and chemical adsorption.

Sr. No.	Physical Adsorption	Chemical Adsorption
1	This phenomenon takes place due to physical force of attraction like van der Waal's force of attraction	This phenomenon takes place due to chemical interaction that results in formation of chemical bonds
2	Here multilayer formation takes place	Here monolayer formation takes place
3	This process is reversible	This process is irreversible
4	Here heat of adsorption is low as much as 40KJ/mole	Here heat of adsorption is high as much as 400KJ/mole
5	This process takes place at ordinary temperature	This process takes place at higher temperature
6	This is a very fast process	This is a slow process
7	This is not specific but preferential	This is often very specific
8	Here insignificant energy of activation is required	Here substantial energy of activation is required
9	As pressure of Adsorbate increases the rate of adsorption increases	This type of adsorption there is no effect of pressure.

Further, the adsorption can be classified primarily in two types, viz. physical adsorption and chemical adsorption. The distinction between these two types is represented in **Table 2**.

Water is one of the most vital natural resources available on the planet which satisfies various needs of the humans including its survival [1] and is one of the most copious resources on earth. Though about 70% of the earth is covered with water, the maximum of it is present in ocean and seas and in the form of glaciers. And in fact less than 1% of fresh water is available for human consumption. The natural reservoir of water is being polluted due to various activities. The pollution has resulted in threats and affected aquatic life severely. The famous Minamata disease is due to pollution of water from heavy transition metal mercury. The water pollution due to mercury has resulted in several fish deaths. The heavy metal accumulation in the vital organs like liver and kidney results in severe internal organ damages.

The water pollution is increasing due to several man made factors such as industrialization and urbanizations. The exhaustive use of agrochemicals used in farming is responsible for water pollution. The discharge from textile industries are exposed in the freshwater sources and create water pollution in a wide range. The dyeing of fabric requires several synthetic and natural dyes. These dyes contain various heavy inorganic materials especially transition metals. These transition metals pollute the water body and affect the flora and fauna of the ecosystem [2–5]. The water polluted due to dissolved heavy metals such as Cadmium, Chromium, Mercury and lead are becoming a serious problem to mankind. Any metallic element with a relatively high density that is toxic and non-biodegradable even at low concentrations is referred to as a "heavy metal". This is due to the fact that many metals are non-biodegradable and may cause cancer even at low quantities. The heavy metals such as Cr(VI), Pb(II), and Cd(II), are widely observed in mining and battery effluents, have been classified by the United States Environmental Protection Agency (USEPA) as priority and harmful pollutants that must be cleaned before being discharged into discharge of sewage. The heavy metals are significant environmental pollutants, and their toxicity is a problem of increasing significance for ecological, evolutionary, nutritional and environmental reasons. These toxic metal ions are liberated into the natural environment as a result of numerous human activities [6–11].

In fact, the living organisms require these elements in trace amounts but their concentrations beyond a particular level is found to be fatal. Moreover, most of the heavy metals are carcinogenic and mutagenic [12,13]. Today cancer is one of the leading causes of death in the developed and developing nations. Hence, in order to provide healthy environmental conditions suitable for perpetuation of life on the planet it is essential to remove heavy inorganic materials from water sources. In an attempt to solve this problem various methods (**Figure 2**) like adsorption [14–19], photocatalytic oxidation [20–24], flocculation [25–29], electrochemical [30–34], bioremediation [35–39], ion exchange [40–42], membrane filtration [43–45], reverse osmosis [46–48] etc. are employed.

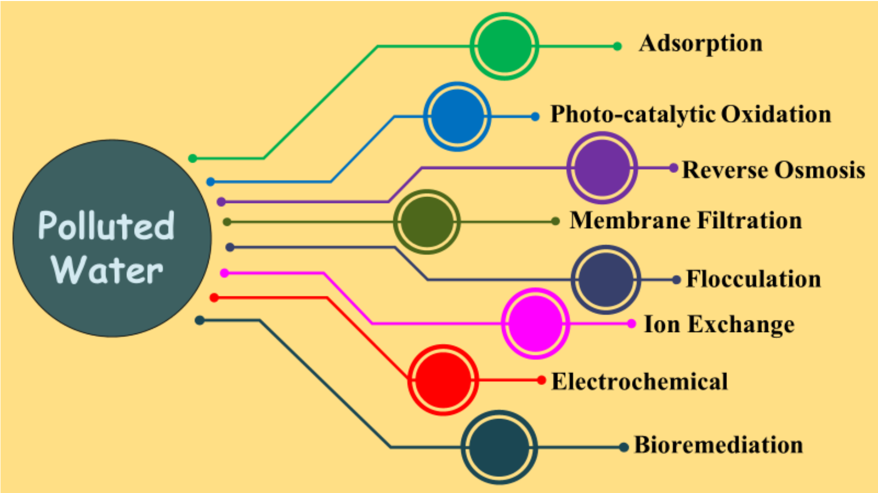

Figure 2. Schematic representation of various processes employed to treat polluted water [49].

Among the various methods available, adsorption stands out as one of the most promising technologies due to several advantages, including its simplicity, ease of operation, low operational costs, high retention capacity, and effective regeneration potential [50–53]. Adsorption is a surface phenomenon where a species accumulates on the surface of another phase, typically through physical and/or chemical interactions, and these phases are usually solids or liquids. The materials that facilitate this process are called adsorbents. The characteristics of these adsorbents can vary significantly based on factors such as surface area, particle size, number of active surface sites, low intraparticle diffusion rates, and high adsorption capacities [54].

A limitation of this method is that the adsorbent used should have a smaller size, as smaller adsorbents possess a larger surface area, which leads to higher adsorption capacity. However, the use of smaller adsorbents presents a challenge: they become difficult to recover once they reach their saturation adsorption capacity [55]. To address this issue, there is growing global research on the use of nanomaterials for environmental remediation applications [56–60].

Among these nanomaterials, magnetic ones are particularly favored due to their exceptional properties, including large surface area, small size, and unique magnetic characteristics [61]. These properties make magnetic nanomaterials ideal as nano adsorbents for removing various pollutants, including heavy metals, from water [49,50,62–69]. Additionally, their magnetic nature allows for easy separation of metal ions from solutions using an external magnetic field as illustrated in **Figure 3**. [70].

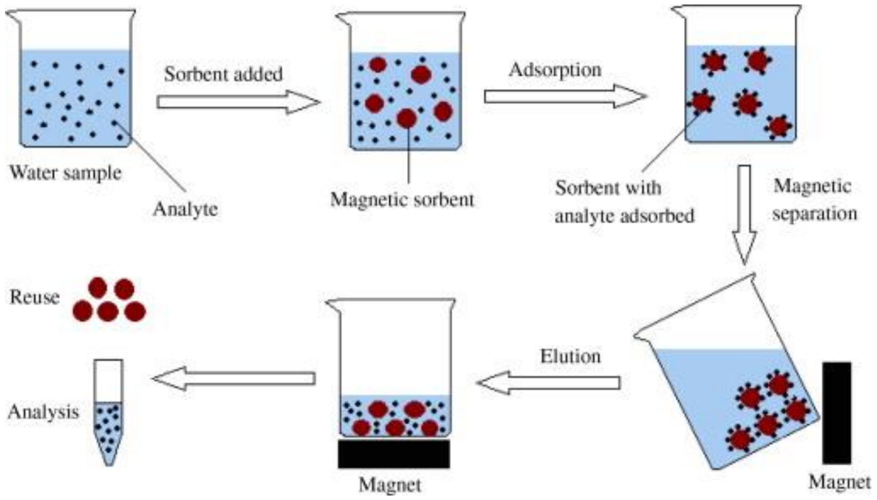

Figure 3. The procedure used for functionalized magnetic solid-phase extraction (MSPE) (reproduced with permission [70]. Copyright 2006, Elsevier Ltd.).

1.1. Factor’s influencing adsorption

The factors affecting rate of adsorption is discussed as below.

1) Adsorption and surface area: Adsorption being a surface phenomenon, the extent of adsorption depends on the surface area. The adsorption is found to increase with increase in surface area.
2) Nature of gas: The total amount of gas adsorbed on the surface depends upon the nature of gas. Easily liquefiable gas gets adsorbed readily.
3) Heat of adsorption: Heat of adsorption can be defined as the energy liberated when 1 gm mole of a gas is adsorbed on the solid surface. In physical adsorption, gas molecules concentrate on the solid surface. Therefore, it is similar to the condensation of a gas to liquid. Therefore, just like condensation, adsorption is also an exothermic process.
4) Reversible character: As we discussed there are two types of adsorption. The physical adsorption is the reversible process. But in the case of chemical adsorption as there is formation of chemical bonds it is an irreversible process.
5) Effect of temperature: We have discussed that adsorption is the exothermic process. Thus, in case of physical adsorption heat is realized. Therefore, the rise of temperature is a thermodynamically unfavorable condition. Thus, adsorption is favorable at lower temperature.
6) Effect of pressure: It is observed that increase in pressure increases the amount of gas adsorbed. Thus, pressure affects favorably in case of adsorption.
7) Thickness of adsorbed layer of gas: The physically adsorbed gas forms only one molecular thick layer. However, above the certain pressure, multi molecular thick layers are observed.

Postulates of adsorption

1) Solid surface is uniform energetically and has fixed number of adsorption sites.
2) One site adsorbs only one molecule. When the whole surface is completely covered by unimolecular layer, further adsorption is not possible.
3) There is no interaction between the adsorbed molecules on the surface.

4) The adsorbed gas behaves ideally.
5) Adsorption is the dynamic process. The adsorption is considered as the equilibrium between the condensation of Adsorbate molecules on the adsorbent and their evaporation from it. When adsorption starts the rate of condensation is maximum, which slows down as the adsorbed site gets filled by molecules. On the contrary, the rate of evaporation increases as the surface gets more covered. At equilibrium these two rates become identical.
6) The adsorption is localized instead of being mobile.

1.2. Demonstration of adsorption

The phenomenon of adsorption can be demonstrated by carrying out simple experiments:

1) Silica gel is taken in a beaker; Methylene blue solution is added in it. The resultant mixture is stirred for some time. With the progress of time the dye solution becomes faint in color and silica gel becomes bluish in color. Thus, the adsorption of dye takes place on the surface of silica gel.
2) Potassium permanganate is pink in color. When activated charcoal is added in the solution containing permanganate the solution becomes faint in color.

1.3. Characteristic of adsorption

1) Adsorption can occur in all interfacial surfaces i.e. adsorption can occur in between gas-solid, liquid-solid, liquid-liquid, solid-solid and gas-solid surfaces.
2) Adsorption is always accompanied with decrease in free energy of the system. When ΔG reaches zero equilibrium is attained.
3) Adsorption is the spontaneous process.
4) When molecules are adsorbed, there is always decrease in randomness of the molecule. Adsorption is the exothermic process and there is an interaction between adsorbate and adsorbent molecules.

2. Nanoscale phenomenon in adsorption

Any material lying in the range of 1 nm to 100 nm in any dimension and it's at least one property different from that of bulk is considered as nanomaterial. The nanomaterials were in existence much earlier than the term Nano was coined. The potential of the materials at nanoscale and its medicinal use was first time recognized in Ayurveda which is an ancient Indian system of medicine developed in peninsular India. Ayurveda is supposed to have originated from Atharvaveda. This is a holistic way of treatment. In the modern period American physicist and Nobel laureate Nario Taniguchi is considered to be the father of nanotechnology. He delivered the speech on 29 December 1929 and imagined that the entire encyclopaedia could be written on the tip of a pin. This speech seeded the concept of nanotechnology in the brain of researchers. Then after several researchers and group of researchers worked together to develop various materials at nanoscale with exotic properties. The synthesis of nanomaterials by different routes is shown below in **Figure 4**. These nanoscale materials could be successfully used for various applications in different branches of science and technology. One of the important part is adsorption. The materials at nanoscale can be successfully used as adsorbent. Iron oxide nanoparticles can be synthesized by a number of different methods. Iron oxide nanomaterials can be effectively used for the adsorption process.

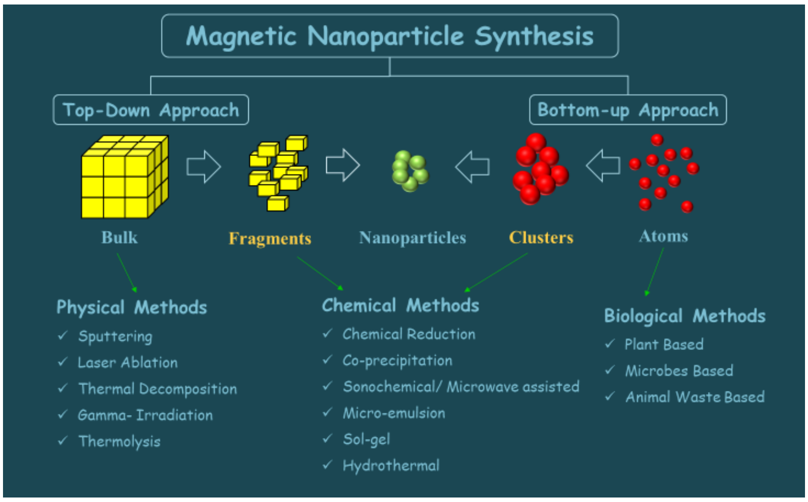

Figure 4. Different methods employed for the synthesis of nanoparticles (redrawn from ref. [71]).

3. Study of adsorption isotherms

In the adsorption, compound concentration (mg/L) and the compound concentration remaining on solid particles q (mg/g) can be investigated. The equation $q = f(C)$ gives rise to the sorption isotherm. Due to the uniqueness of this correlation, several requirements must be met: (I) all adsorption/desorption equilibria must be accomplished, and (II) All other physical and chemical parameters must remain unchanged. Because temperature is so important in sorption processes, the term “isotherm” was particularly adopted (temperature must be constant and specified) [71–73]. Sorption isotherms were classified by Giles et al. [74]. Based on their initial slopes and curvatures. They classified constant partition (C), Langmuir (L), high affinity (H), and sigmoidal-shaped (S) isotherm classes illustrated in **Figure 5** [75].

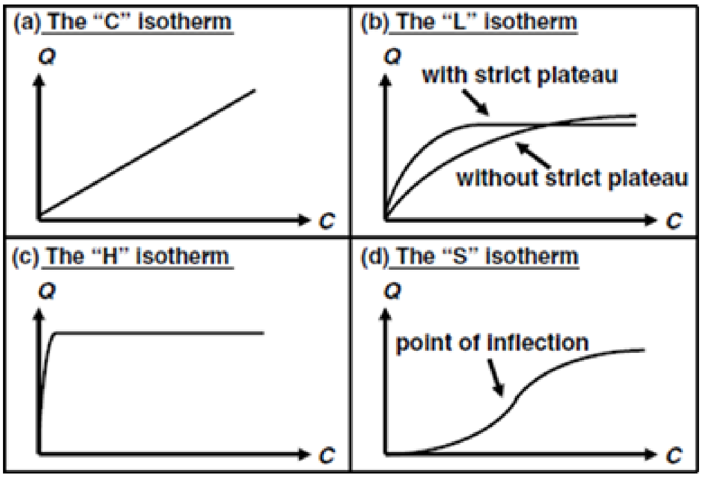

Figure 5. The four main (C, L, H, S) types of isotherms (reproduced with permission [75], Copyright 2006, Elsevier Ltd.). (**a**) The “C” Isotherm; (**b**) the “L” Isotherm; (**c**) the “H” Isotherm; (**d**) the “S” Isotherm.

3.1. Langmuir adsorption isotherms

In 1916, Irving Langmuir proposed another adsorption isotherm which explained the variation of adsorption with pressure. The equation was derived by Langmuir which depicts a relationship between the number of active sites of the surface undergoing adsorption and pressure. This adsorption isotherm was used to describe the equilibrium between adsorbate and adsorbent system. Here the adsorbate and adsorption is limited to a single molecular layer i. Langmuir adsorption is limited to the phenomenon of physical adsorption only.

Langmuir's adsorption isotherm is based upon certain assumption:

1) This theory believes formation of monolayer. There is no description about the formation of multilayer;
2) There is dynamic equilibrium between the adsorbed gaseous molecules and free gaseous molecules;

$$\mathrm{A(g)} + \mathrm{B(g)} \rightarrow \mathrm{AB}$$

where A(g) is an unabsorbed gaseous molecule, B(s) is the unoccupied metal surface and AB is the adsorbed gaseous molecule.

3) Fixed number of vacant or adsorption sites are available on the surface of solid;
4) Each site can hold a maximum of one gaseous molecule and a constant of heat energy is released during the process.

3.1.1. Derivation of Langmuir adsorption isotherm

The mathematical expression for Langmuir adsorption isotherm involves a single sorbing species and can be demonstrated in various ways: the kinetic approach, the thermodynamic approach and from statistical mechanics point of view. When two competing adsorbed species, the competitive adsorbed model is required to be established. The sorbed species dissociates into two distinct entities, the dissociative adsorption model needs to be used.

3.1.2. Thermodynamic deviation

The adsorption process between gas phase molecules A, vacant surface sites S and occupied surface sites SA, can be represented by the equation,

$$\mathrm{S} + \mathrm{A} \rightarrow \mathrm{SA}$$

Assuming that there are fixed number of surface sites present on the surface.

At equilibrium constant, K, can be written

$$\mathrm{K} = [\mathrm{SA}]/[\mathrm{S}][\mathrm{A}]$$

Q = fraction of surface sites occupied.

where,

[SA] is proportional to the surface coverage of adsorbed molecules or proportional to q;

[S] is proportional to the number of vacant sites (1−q);

[A] is proportional to the pressure of gas P.

Therefore, the proportionality constant b can be expressed as below:

$$\mathrm{B} = \frac{\theta}{(1-\theta)\mathrm{P}}$$

The rearrangement gives the expression for surface coverage.

3.1.3. Kinetic deviation

The rate of adsorption is proportional to the pressure of the gas and number of vacant sites for adsorption. If the total number of sites on the surface is N, then the rate of change of the surface coverage due to adsorption is:

$$\frac{d\theta}{dt} = K_a \mathrm{P\ N}(1-\theta)$$

The rate of change of the coverage due to the adsorbate leaving the surface (desorption) is proportional to the number of adsorbed species:

$$\frac{d\theta}{dt} = K_d \mathrm{N}\theta$$

In above equations K_a and K_d are rates of adsorption and desorption respectively, P is the pressure of the adsorbed gas. At equilibrium, the coverage is independent of time and thus adsorption and desorption rates are equal.

3.1.4. Limitation of Langmuir adsorption isotherm

1) The adsorbed gas is expected to behave ideally in the vapor phase. The condition is possible only at low pressure. Therefore, Langmuir adsorption is applicable only at low temperatures.
2) Langmuir adsorption isotherm believes formation of monolayer only. When multilayer formation takes place then the Langmuir adsorption isotherm is not applicable. At higher pressure conditions the assumption breaks down as gas molecules attract more and more molecules towards each other. Brunauer Paul Emmett, Edward Teller [BET] explained a more realistic multilayer adsorption process.
3) The sites on the solid surface are equal in size and shape and have equal affinity for adsorbate molecules i.e. the surface of solid is homogeneous. But we all know that in real solid surfaces are heterogeneous.
4) According to Langmuir's assumption there is no interaction among the various gaseous molecules. But in fact, at higher pressure even at normal pressure there is weak van der Waal's physical force of attraction.
5) The adsorbed molecules should be localized i.e. there should be no randomness. Thus, we can conclude that Langmuir's adsorption isotherm is applicable only in low pressure conditions.

The Langmuir isotherm models were chosen based on the premise that the adsorption sites on the catalyst's surface are monolayer, homogeneous, and finite, and that molecules adsorbed on nearby sites do not interact. There can be no further sorption at a surface site after it has been filled. As a result, the surface will ultimately approach a saturation point, at which point its maximum adsorption will be accomplished [76]. The Langmuir isotherm model equation's linear form is as follows:

$$\frac{C_e}{q_e} = \frac{1}{ab} + \frac{C_e}{a}$$

where, ‘q_e’ is amount of adsorbate adsorbed (mg. g^{-1}), ‘C_e’ is the adsorbate equilibrium concentration (mg/dm^3), ‘a’ is the monolayer coverage adsorption capacity (mg. g^{-1}), ‘b’ is the Langmuir constant (dm^3. $mole^{-1}$).

3.2. Freundlich adsorption isotherms

Freundlich is another scholar who proposed the theory for adsorption. He proposed an empirical equation representing isothermal variation of adsorption of a quantity of gas adsorbed by unit mass of solid adsorbent with pressure. The equation is known as Freundlich Adsorption Isotherm or Freundlich equation. The Freundlich adsorption isotherm is based on the assumption of non-linear, multi-layer heterogeneous adsorption and exponentially distributed active sites. The Freundlich isotherm is based on the idea that in both monolayer (chemisorption) and multilayer (physisorption) adsorption, the adsorbate adsorbs onto the heterogeneous surface of an adsorbent.

Mathematical Representation:

Freundlich’s equation is written as follows in linear form:

$$\log q_e = \log K_F + \frac{1}{n} logC_e$$

The Freundlich constants ‘K_F’ and ‘n’ represent the adsorption capacity and intensity, respectively. ‘q_e’ is the amount of adsorbate adsorbed (mg. g^{-1}), ‘C_e’ is the adsorbate equilibrium concentration (mg/dm^3) [77,78].

4. Adsorption of heavy metals by nanomaterials

As we have discussed adsorption is the surface phenomenon This means larger is the surface area, higher is the possibility of adsorption. We are aware that at nanoscale the surface to volume ratio highly increases. Thus, the possibility of adsorption increases to a great extent at nanoscale. In many gaseous reactions transition metal or metal oxides are successfully being used as effective catalysts. The phenomenon of catalysis actually takes place by adsorption of gas molecules on the surface of metals. If we increase the surface area, more will be sites available for the adsorption and hence higher will be the rate of adsorption. Therefore, we observe that at nanoscale the phenomenon of adsorption becomes more effective.

4.1. Cadmium

Cadmium ion is a transition metal and one of the most toxic heavy metal ions found in industrial effluents along with arsenic and lead. They may enter through food, water and air into the human body and even tiny concentrations of these elements can cause damage to the internal vital organs of the body and thus they are recognized nephrotoxic agents [79,80]. It is a metal of more toxicological concern due its property of bioaccumulation and non-biodegradability even at minute concentration levels [81]. The United States Environmental Protection Agency classified cadmium as a group B1 carcinogen and is also responsible for the Itai-Itai disease [82]. This disease was first observed in Japan. Itai-Itai is a Japanese word which means pain. During the disease there is onset of severe pain. This disease is developed due to the hyper accumulation of cadmium [83]. The short-term exposure of heavy metal cadmium causes physiological disturbance leading to vomiting, nausea, impaired senses, and liver damage [84]. Actually, it is difficult to separate dissolved cadmium from water hence becomes necessary to develop a method that is feasible both economical and effective in removing cadmium from water.

Ghasemi et al. [85] investigated the adsorption properties of superparamagnetic EDTA-functionalized Fe_3O_4 nanoparticles for the removal of various metals, including Cd(II). Using the Box-Behnken Design (BBD) for optimization, they determined that the optimal pH for Cd ion removal was 7.9. At lower pH levels, the removal efficiency decreased, likely due to competition between excess H^+ ions and metal ions for active sites on the Fe_3O_4@EDTA nanoparticles. The optimal reaction time was found to be 17 min, with nanoparticles averaging a size of 35 nm. Under these conditions, a maximum removal efficiency of 99% was achieved.

Karami [86] synthesized magnetite (Fe_3O_4) nanorods using a pulsed current electrochemical method on iron-based electrodes immersed in an alkaline solution. The resulting nanorods had an average diameter of 60 nm, produced at a pH of 5.5 and a temperature of 298 K. The initial metal ion concentration was maintained at 5 mg L^{-1}, and the adsorption equilibrium was analysed using the Langmuir isotherm model. The Fe_3O_4 nanorods demonstrated a maximum adsorption capacity of 88.39 mg. g^{-1} for Cd(II).

A recent study by researchers developed sulfonated magnetic nanoparticles (Fe_3O_4-SO_3H) for the removal of cadmium and lead [87]. Characterization of the nanoparticles was performed using SEM, TEM, FT-IR, and BET techniques. The adsorption capacities of Fe_3O_4-SO_3H increased with ion concentration, reaching a maximum removal efficiency of 99%. Magnetic properties, measured using a superconducting quantum interference device (SQUID) at 300 K, showed saturation magnetization values of 80.3 emu. g^{-1} for Fe_3O_4 and 69.0 emu. g^{-1} for Fe_3O_4-SO_3H, confirming their superparamagnetic nature and ease of separation after treatment. The adsorbents were regenerated using a 1% HCl solution, with Fe_3O_4-SO_3H maintaining high removal efficiency even after 10 cycles, demonstrating its potential for further applications. The magnetic hysteresis loops of iron oxide nanomaterials are shown below in **Figure 6**.

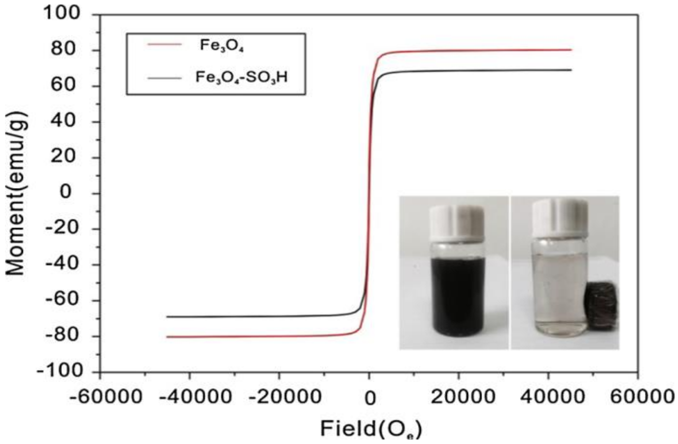

Figure 6. The magnetic hysteresis loops of Fe_3O_4 and Fe_3O_4-SO_3H MNPs (reproduced with permission [87], Copyright 2017, Elsevier Inc.).

Zhu et al. [88] synthesized and studied α-Fe_2O_3-coated volcanic rock for cadmium adsorption. Batch experiments revealed that the highest Cd(II) adsorption occurred at a pH of 6. Temperature significantly influenced adsorption capacity, with maximum values increasing from 127.23 mg. g^{-1} at 293 K to 146.41 mg. g^{-1} at 303 K and 158.48 mg g^{-1} at 313 K. The adsorption kinetics followed a pseudo-second-order model, with over 98% of dissolved Cd(II) removed within 240 min and equilibrium reached within 720 min. The adsorption mechanism involved both film and intra-particle diffusion. The BET surface area of the α-Fe_2O_3-coated volcanic rock was measured at 1.8701 m^2. g^{-1}, with a pore volume of 0.005627 cm^3 g^{-1}.

Ehrampoush et al. [89] synthesized iron oxide nanoparticles using a green method involving tangerine peel extract for cadmium removal. Their study demonstrated that increased contact time between cadmium ions and the nanoparticles enhanced removal efficiency due to greater interaction with the adsorbent surface, with equilibrium achieved at 90 min. They also investigated the effects of pH, initial cadmium concentration, and adsorbent mass, achieving a removal efficiency of approximately 90% at pH 4 with an adsorbent dose of 0.4 g per 100 mL.

An innovative study conducted in Spain highlighted the potential of magnetic core-shell Ce-Ti@Fe_3O_4 nanoparticles for treating contaminated water [90]. This nanocomposite exhibited a unique combination of properties, including magnetism, crystallinity, stability, and high adsorption capacity. While the nanoparticles showed strong effectiveness in removing anionic contaminants, their performance for cationic contaminants like cadmium was relatively lower, achieving a removal efficiency of 45.28% for an initial Cd^{2+} concentration of 10 mg. L^{-1} with a Ce-Ti@Fe_3O_4 dose of 1.0 g. L^{-1}.

4.2. Chromium

This is another transition metal having atomic number 24. This metal belongs to first transition series. Actually, chromium exits in various oxidation states such as metallic Chromium [Cr(I)], Chromos [Cr(II)], Chromic [Cr(III)] and Chromates [Cr(VI)]. Cr(IV) compounds are about 500 times more hazardous than Cr(III)compounds especially for living organisms [91,92]. The industrial production of chromium takes place from chromite ore. Chromium is considered to be mutagenic, teratogenic and carcinogenic [93,94]. The international agency for research on cancer (IARC) identified Cr(IV) to be a class 1 human carcinogen. It has adverse effects on human body such as skin ulcers, ulceration of the nasal mucosa along with perforation of the nasal septum [95].

Lei and colleagues [96] successfully synthesized graphene oxide foam-Fe_3O_4 nanocomposites for chromium removal. This 3D interconnected porous composites were fabricated using a combination of co-precipitation and microwave plasma chemical vapour deposition techniques. The nanocomposites facilitated the reduction of Cr(VI) to Cr(III), which was a key aspect of the adsorption mechanism. Their porous structure provided a large specific surface area of 574.2 m^2. g^{-1}, enabling exceptional adsorption performance. At a pH of 2, the nanocomposites achieved a maximum adsorption capacity of 258.6 mg. g^{-1} for Cr(VI) ions, as described by the Freundlich isotherm model.

Lingamdinne et al. [97] utilized a biogenic reduction method to synthesize iron oxide nanoparticles with an inverse spinel structure for the adsorption of Cr(III) and Pb(II). Atomic force microscopy (AFM) revealed an average particle size of 49.45 nm, closely aligning with the size determined by PXRD analysis at 45.4 nm. BET analysis indicated a surface area of 122.54 m^2 g^{-1}, while the degree of magnetic saturation was 54.60 emu g^{-1}. The nanoparticles exhibited stable maximum sorption capacity over four cycles, and their desorption efficiency remained above 95% for five cycles, though it decreased to below 80% for Pb(II) and Cr(III) after the fifth cycle. Batch experiments were conducted by varying the initial metal concentrations (10.0 and 25.0 mg. L^{-1}) and nanoparticle dosages (0.2 and 0.5 g. L^{-1}). For Cr(III) at an initial concentration of 10.0 mg. L^{-1}, the adsorption capacities were 55.94 ± 0.34 mg g^{-1} and 22.64 ± 0.17 mg. g^{-1} for dosages of 0.2 g. L^{-1} and 0.5 g. L^{-1}, respectively. At 25.0 mg. L^{-1}, the capacities were 82.53 ± 0.28 mg. g^{-1} and 32.24 ± 0.25 mg. g^{-1} for the same dosages.

Xiao et al. [98] recently demonstrated effective chromium removal using iron-based nanoparticles synthesized via a biogenic route. The spherical nanoparticles had an average size of 13.7 ± 5.0 nm and achieved a Cr(VI) removal efficiency of nearly 70% within the first minute, rising to 90% within 90 min. The study also examined the effect of Fe nanoparticle dosage on removal efficiency, revealing a significant increase from 26.13% to 99.45% as the Fe dosage was raised from 0.1 mL to 0.6 mL, while maintaining a constant Cr(VI) concentration. The nanoparticles exhibited an impressive maximum removal capacity of 983.2 mg. g^{-1}.

Zhou et al. [99] synthesized highly active Fe/Ni bimetallic nanocomposites using a liquid-phase reduction method and employed an ultrasound-assisted system for Cr(VI) removal, as illustrated in **Figure 7**. Morphological characterization revealed that the pristine Fe/Ni nanocomposites were quasi-spherical with diameters ranging from 30 to 50 nm. Post-treatment characterization showed a slightly rough surface morphology, attributed to Fe^0 corrosion, with flocculent clusters forming on the particle surfaces after Cr(VI) reduction. The impact of GA loading on removal of mercury is shown as below in **Figure 8**.

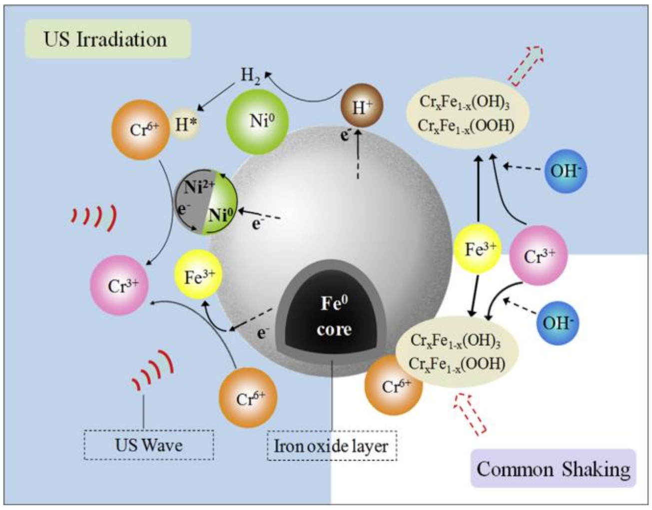

Figure 7. Schematic of Cr(VI) removal pathways in US-assisted Fe/Ni bimetallic system (reproduced with permission [99], Copyright 2016, Elsevier Ltd.).

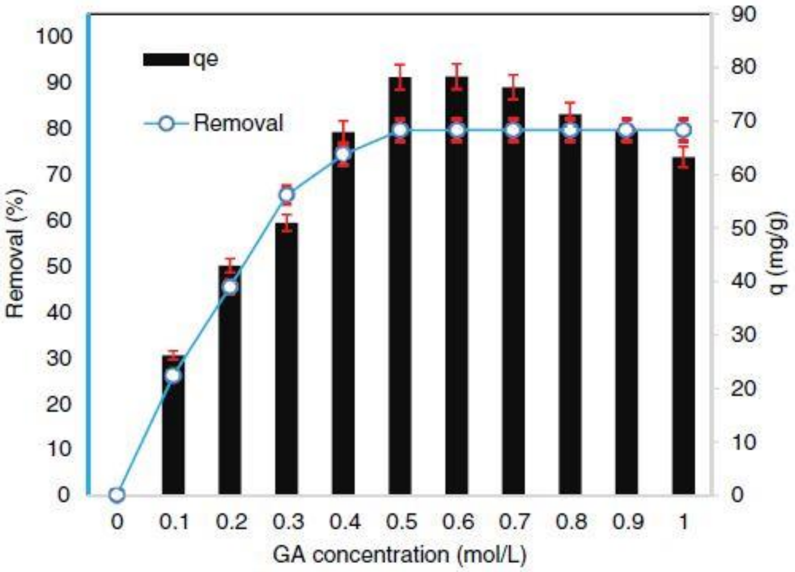

Figure 8. Impact of GA loading on Hg(II) removal efficiency (conditions: Contact time 60 min, initial Hg(II) concentration 25 mg L^{-1} and temperature 20 °C) (reproduced with permission [100], Copyright 2016, society of chemical industry).

The removal efficiency of Cr(VI) in aqueous solution was tested at 303 K. For an Fe^0 dosage of 0.1 g L^{-1}, the removal efficiency was 66.0%, increasing to 96.1% when the Fe^0 concentration was raised to 0.15 g L^{-1} and the Ni^0 content increased from 0 wt% to 5.0 wt%. At an initial Cr(VI) concentration of 20 mg L^{-1}, nearly 100% removal efficiency was achieved. However, the efficiency dropped to 76.7% and 61.0% as the concentration increased to 30 mg L^{-1} and 40 mg L^{-1}, respectively. Equilibrium was reached within 10 min with ultrasonic radiation, significantly faster than the 60 min required under shaking conditions.

Wei et al. synthesized non-zero valent iron (nZVI) nanoparticles using a green method and investigated their effectiveness in Cr(VI) removal [101–111]. Batch experiments revealed that the as-prepared Fe nanoparticles, with diameters ranging from 20 to 80 nm, removed 89.9% of Cr(VI). The nanoparticles demonstrated stability, as indicated by a zeta potential value of +30.7 mV, which reflects the stability of a colloidal system. Additionally, they compared the adsorption capacity of nano-Fe_3O_4 for Cr(VI) removal, which was 47.3%, approximately half of the removal efficiency observed with the green-synthesized Fe nanoparticles. The authors concluded that Fe^0 played a crucial role in the removal of Cr(VI).

Another study used a combination of electrospinning and the hydrothermal method to fabricate PA6@FexOy nanofibrous membranes for chromium removal, demonstrating excellent performance in removing chromium from a $K_2Cr_2O_7$ solution [101].

4.3. Lead

Lead is the silvery white, greyish coloured metal in group 14 of periodic table. Lead is very malleable, ductile and dense and is poor conductor of electricity. Lead is highly resistant to corrosion. The Latin word for lead is Plumbum. Lead is mainly discharged from battery manufacturing companies. Lead contamination in the environment primarily results from the discharge of lead-containing wastewater from industries such as battery manufacturing, mining, and metallurgy. Even in small quantities, its presence poses significant concerns [112]. Lead accumulation in the body can lead to a range of health issues, including neurological, cardiovascular, and renal problems, as well as nausea, cancer, and convulsions, among others [113]. Due to its high toxicity, the USEPA has established a maximum contaminant level of 15 µg L^{-1} for lead in drinking water [114].

Lingamdinne et al. [97] conducted similar tests for the adsorption of lead from water, using the same parameters as for chromium. The results showed that the adsorption capacity was 33.28 ± 0.26 mg g^{-1} and 6.540 ± 0.35 mg g^{-1} for nanoparticle dosages of 0.2 g L^{-1} and 0.5 g L^{-1}, respectively, at an initial Pb(II) concentration of 10.0 mg L^{-1}. For a Pb(II) concentration of 25.0 mg L^{-1}, the adsorption capacities were 88.92 ± 0.29 mg g^{-1} and 35.06 ± 0.32 mg g^{-1} for dosages of 0.2 g L^{-1} and 0.5 g L^{-1}, respectively. The authors also determined the thermodynamic parameters for Pb(II) adsorption on the prepared magnetic inverse spinel structure nanoparticles. For a dosage of 0.2 g L^{-1} at 298 ± 2.0 K, the values were ΔG^0 = x5.61 ± 0.11 kJ mol^{-1}, ΔH^0 = 2.141 ± 0.11 kJ mol^{-1}, and ΔS^0 = 0.026 ± 0.02 kJ mol^{-1} K^{-1}.

Recently, Xiang et al. [115] developed a 3D hierarchical flower-like $NiFe_2O_4/MnO_2$ nanocomposite for lead removal from aqueous solutions. SEM images of $NiFe_2O_4$ and $NiFe_2O_4/MnO_2$ are shown in **Figure 9**.

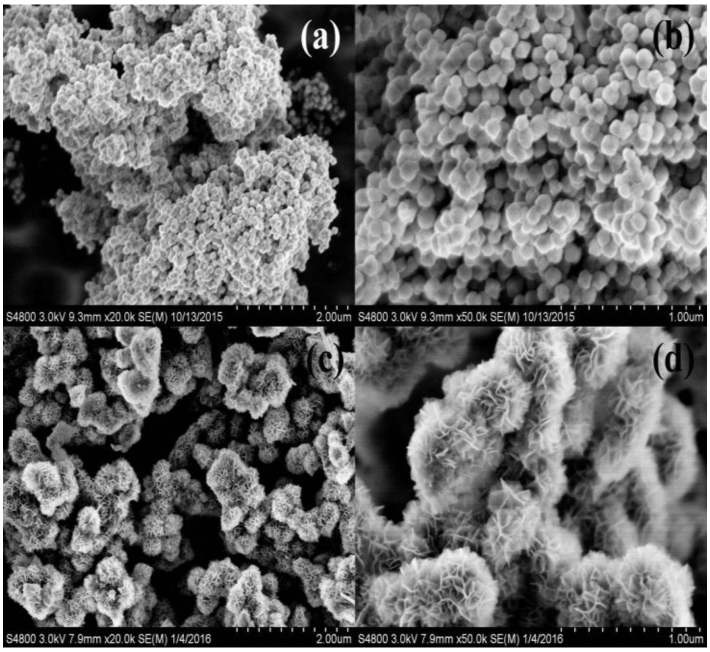

Figure 9. SEM images of (**a**) $NiFe_2O_4$; (**b**) $NiFe_2O_4$; (**c**) $NiFe_2O_4/MnO_2$; **(d)** $NiFe_2O_4/MnO_2$ (reproduced with permission [115]. Copyright 2016, Elsevier).

These nanocomposites demonstrated rapid lead adsorption, achieving a maximum adsorption capacity of 85.78 mg. g^{-1} as determined by the Langmuir model, with a saturation magnetization of 15.7 emu g^{-1}. The authors found that 100% removal efficiency was achieved for an initial Pb(II) concentration of less than 15.0 mg. L^{-1}, with efficiencies of 92.2%, 74.9%, and 42.5% for initial concentrations of 20.0 mg.

L^{-1}, 25.0 mg. L^{-1}, and 50.0 mg. L^{-1}, respectively. Thus, they concluded that the removal capacity is dependent on the initial concentration of Pb(II).

Shipley et al. [116] synthesized Fe_3O_4 magnetite nanoparticles with an average size of 37.0 nm for the adsorption of Pb(II), along with Cd(II), Zn(II), and Cu(II). The study demonstrated that complete lead removal (100%) was achieved at a pH of 8 and a contact time of 120 min, with an initial Pb(II) concentration of 500 µg L^{-1}. The adsorbent dosage varied between 0.05 and 0.5 g. L^{-1}, and it was found that increasing the adsorbent dosage enhanced the adsorption rate, likely due to an increase in the number of available sites for metal ion binding.

In a separate study, Mahdavi et al. [117] explored the relationship between reaction time and adsorbent dosage for the adsorption of Pb(II) using magnetite nanoparticles. They determined that the optimal adsorbent dosage was 2 g. L^{-1}, with equilibrium reached after 180 min. The maximum adsorption capacity was found to be 101.4 mg. g^{-1}, and the adsorption process followed second-order kinetics.

In 2014, a team of scientists [118] synthesized Fe_3O_4 combined with xanthan gum (XG) to create the Fe_3O_4@salica-XG nanocomposite. This nanocomposite achieved 100% Pb^{2+} removal within a pH range of 5 to 6. Using the Langmuir adsorption isotherm, they calculated the maximum adsorption capacity to be 21.32 mg. g^{-1}. The nanocomposite was also used to treat effluent from the battery industry, achieving an impressive 97% removal efficiency after 21 continuous adsorption-desorption cycles, with regeneration achieved using a 0.05 mol L^{-1} HCl solution.

In another study, Fe_3O_4 was combined with sodium alginate gel beads to form the Fe_3O_4@Sa-Zr nanocomposite, with zirconium aiding the process [119]. When exposed to a lead-containing solution, it achieved 100% Pb(II) removal, with an adsorption capacity of 333.33 mg. g^{-1}, although this capacity decreased as the temperature increased.

5. Applications of adsorption

5.1. Water purification

Water is an essential inorganic compound required for the perpetuation of life on the planet. About 70% part of the planet is occupied with water. This water is available as surface water and also underground water. However, from the total amount of water available only about 1% is suitable for consumption. The contaminated water is responsible for various water borne communicable diseases. There are various types of physical, chemical and biological impurities present in the water. The physical impurities may be radioactive materials etc. The chemical impurities may be chloride contents, sulphate etc. The biological impurities are micro-organisms and metabolic waste materials. It is important to separate the impurities from water sources. Since ancient times adsorption has been the simple and effective technique to separate impurities from the water sample. When the contaminated water sample is passed through the charcoal, then the impurities like coloring materials and heavy inorganic metals can be separated. The colloidal impurities can be removed by adding alum to water. When alum is added then formation of aluminum hydroxide takes place. Aluminum hydroxide is good adsorbent. It adsorbs suspended impurities and gets settled down easily. The hard water can be softened when passed through the column containing zeolite. The calcium and magnesium ions responsible for hardening get adsorbed on zeolite. The cation and anion exchange resins can be used for softening of water.

5.2. Catalyst

These are the materials that alter the rate of chemical reactions without undergoing a permanent change in its nature. The materials which accelerate the rate of chemical reaction are called positive catalysts whereas the materials which retard the rate of chemical reactions are called negative catalysts. The catalyst is an alternative reaction pathway with lower energy of activation. They do not disturb the overall thermodynamics or equilibrium of reaction but enable the reaction to reach the equilibrium faster. The catalyst can be classified in a number of ways. One of the ways to classify is homogeneous catalyst and heterogeneous catalyst. Enzymes are considered as biocatalysts. The enzymes facilitate various biochemical reactions taking place inside the living systems. They are highly efficient and selective in nature. The enzymes operate under the normal physiological conditions of temperature and pressure. The adsorption plays an important role in catalysis.

Mechanism of catalysis

As discussed, adsorption plays a crucial role in the phenomenon of catalysis. The reactant molecules are adsorbed on the surface of the catalyst. The adsorbed reactants undergo chemical transformations forming reaction intermediates. After this the reactant molecules, desorbs and products are formed. The catalyst again undergoes its initial state and can again work. Only the physical form of the catalyst may alter during the course of reaction. Catalysts play a vital role in various industrial processes such as organic transformation reactions, synthesis of heavy inorganic chemicals, environmental remedies, pharmaceutical manufacturing etc. Catalysts are essential for sustainable development and green chemistry initiatives by facilitating cleaner and more resource efficient chemical processes.

5.3. In veterinary pharmacology

Actually, mainly four key physiological processes that govern the time course of the drug's fate in the body are absorption, distribution, metabolism and elimination. Pharmacokinetics is the study of the time course of the drug concentration in the body which provides the means of quantitating absorption, distribution, metabolism and elimination. When applied to the clinical situations, pharmacokinetics provides the practitioners with the useful tool to design optimally beneficial drug doses scheduled for each individual patient. The drug adsorption hypothesis, the drug binds to the RMC membrane and the antibody is largely directed against the drug itself. In the drug adsorption mechanism, the drug is adsorbed directly onto the surface of RBC. The antibody is formed against the drug itself. This results in drug coated RBCs becoming coated with IgG.

5.4. In removal of colorings matters

Activated charcoal is the adsorbent used to remove coloring matter from the solution. The coloring matter is adsorbed on the activated charcoal. Dye is the coloring material used to impart color to the fabric. The dyes are generally high molecular weight organic compounds. Sometimes dye molecules contain heavy metal also. The waste water discharged from industries especially textile industries contain a number of synthetic dyes also. The natural degradation of dye is a very slow phenomenon. These dyes create hazardous effects and destroy flora and fauna. Therefore, it is very much essential to remove these high molecular weight organic compounds. The various dye removal techniques are classified into different groups such as physical technique, chemical technique and biological techniques. The physical method includes adsorption, ion-exchange and filtrations/coagulation methods. The chemical method includes ozonization, Fenton reagent, photo catalytic reactions and biological method include aerobic degradation, anaerobic degradation, bio-sorption etc. The dye removal methods can be summarized in **Table 3**.

Table 3. Dye removal methods.

Physical Method	Chemical Method	Biological Method
Adsorption	Fenton’s Reagent Technique	Aerobic Degradation
Ion-exchange	Ozonisation	Anaerobic Degradation
Filtration	Photocatalytic Methods	
Coagulation/flocculation		

Among these methods, adsorption is found to be a very effective and economical method for removal of dyes from the solution. The experimental evidence reveals that the effective removal of dye is possible through several cheaply available non-conventional adsorbents also. The experimental results reveal that activated rice husk can be used as an effective adsorbent for the removal of dyes from waste water discharged from industries. Wood-shaving bottom ash is used for the separation of azo reactive and red reactive 141 dyes. Wood-shaving bottom ash/H_2SO_4 adsorbent were made by treating Wood-shaving bottom ash with 0.1M H_2SO_4 and water respectively so as to increase the adsorption capacity. The effect of various parameters such as Ph of the solution, contact time, dissolved metals and elution studied.

Table 4. Adsorption capacity and pH for different dyes.

Dye	Adsorption Capacity	pH
Remazol Brilliant Blue	91.0 mg/g	7
Reactive Red 120	45.87 mg/g	8
Reactive Red 2	61.73 mg/g	9
Congo Red	513 mg/g	3
Reactive Red 2	7.99 mg/g	7
Reactive Blue 4	4.48	7
Reactive Dyes	85.81	7
Rhodamine B	42.19	7
Direct Blue 85	600 mg/g	4

It is reported that dyes from textile waste water can be separated using fly ash as adsorbent. Congo-red dye can be successfully removed using calcium rich fly ashes under different conditions. The experimental studies reveal that up to 93% of the dissolved dyes can be separated through this method. We will discuss various dye removal techniques and adsorption capacity developed by different scholars. **Table 4** shows absorption capacity and pH for different dyes.

Further, it is observed that more than 40 different types of zeolites are available in nature. The researchers observed that clinoptilolite is the hydrated alkali aluminate which easily available and most commonly used zeolite, belonging to the heulandite group. This is an economical zeolite having high surface area and high ion—exchange capacity. Zeolites have different cavity structures and are highly porous in nature.

Adsorption mechanism for removal of dyes

The adsorption of dyes onto the surface of the fabric may be a physical or chemical process. In the physical mechanism the dye molecules are adsorbed onto the surface of adsorbent under the influence of van der Waals force of attraction through the phenomenon of Hydrogen bonding. The phenomenon of adsorption takes place when the particle on the surface and the particle in the adsorbent’s bulk are not in the same environment. The unbalanced force is popularly known as residual forces, act on the particle on the surface. Due to these unbalanced forces, the adsorbent’s surface particles attract the Adsorbate particles. Adsorption has a fundamental role in ecology. It regulates the exchange between geosphere and hydrosphere and atmosphere, accounts for the transport of the substances in the ecosystems and triggers other important processes like ionic exchange and enzymatic processes. The technological, environmental and biological importance of adsorption can never be in doubt. Also, its practical applications in industry and environmental protection are of paramount importance. The adsorption of a substance is the first stage in several catalytically important reactions.

Due to the simplicity in the process and lower cost involved as compared to the other processes, the phenomenon of adsorption becomes very popular among the various researchers. Development of adsorbent from various biomass wastes as replacement of commercially activated carbons further adds to the cost effectiveness of the process.

5.5. Adsorption indicator

Detection of end point in precipitation titration is critical. Fajan introduced the phenomenon of adsorption indicators for titration. These are termed as adsorption indicator e.g. Fluorescein, eosin, methylene blue, Rose Bengal, Rhodamine 6G etc. In the titration of NaCl against $AgNO_3$, fluorescein indicator is used. Here we are adding $AgNO_3$ solution from the burette to NaCl solution in the conical flask. The reaction takes place as under:

$$NaCl + AgNO_3 \rightarrow AgCl + NaNO_3$$

When $AgNO_3$ is added to NaCl solution indicator, the white AgCl gets precipitated. After completion off reaction, the excess Cl^- ions common to AgCl are adsorbed on the surface of precipitate which form the primary adsorption layer. This one is surrounded by Na^+ ions to form a secondary adsorption layer.

As soon as the end point is reached, due to lack of Cl^- ions, now excess Ag^+ ions hold primary adsorption and acquire positive charge. Now at the end point fluorescein ions strongly adsorb on NO_3 ions and form secondary adsorption. Thus, white precipitate gets converted into rosy-red in color.

5.6. Adsorption chromatography

Adsorption chromatography is the separation technique which relies on differential adsorption of an analyte onto a stationary phase to achieve the separation.

Principle: In adsorption chromatography a stationary phase typically, a solid adsorbent material is packed into the column. The sample containing the analyte of interest is then introduced into the column. The analytes in the sample interact with the stationary phase through adsorption, where they adhere to the surface of the stationary phase based upon their affinity for the adsorbent material. Analyze stronger interactions with stationary phase based upon their affinity for adsorbed materials. Analytes with stronger interactions with stationary phase are retained for longer time in the column, whereas the analytes with weaker interactions are eluted quickly. It is possible to monitor separation of analytes based upon variables such as temperature, mobile phase i.e. eluent etc.

Stationary phase: The stationary phase in adsorption chromatography is typically a solid material with high surface area and specific adsorption properties. The commonly used materials for adsorption are silica, alumina, porous polymers etc. These materials have high surface area and facilitate adsorption phenomena. The stationary material is generally packed into a column or can be coated on a solid support such as glass plate or silica gel plate in a thin layer of chromatography.

Mobile phase: The mobile phase is also known as eluents. These are liquid solvents or mixtures of liquids forming the eluents. The eluents can be passed through thin film chromatography or column so as to separate the adsorbed material. The components, concentrations, temperature, speed of release, angle of poring etc. actively affects the rate of analyte elution.

By varying the reaction conditions such as temperature, solvent, ionic strength etc. the rate of separation can be monitored.

Applications: Adsorption chromatography is widely used for separation and analysis of organic compounds, natural products, pharmaceuticals and environmental samples. The separation techniques based upon adsorption are column chromatography, thin layer chromatography, paper chromatography etc. The preferential adsorptive power of adsorbent can be used to separate the component mixture by using different chromatographic techniques as shown as.

5.6.1. Paper chromatography

This is used for analysis of food colors in synthetic drink and beverages, ice-creams, jelly etc. Paper is used as adsorbent. The separated components on paper are cut and dissolved in suitable solvent and analyzed.

5.6.2. Column chromatography

The solution containing a mixture of cations Fe^{+2}, Cu^{+2}, Co^{+2} is passed through an adsorbent column of silica gel. The column is run by suitable solvent. After some time, three separate color bands are observed. Fe^{+3} ions are strongly adsorbed on silica gel, which forms a yellow band at the top. Cu^{+2} ions are less adsorbed, which forms the blue band just below the yellow colored band. The other ion Co^{+3} are least adsorbed, which form pink color band at the bottom of the column. Thus, it is possible to separate the ions based upon preferential adsorption.

5.7. Separation of gas mixture

The mixture of gases can be separated up to certain extent by the preferential adsorption of charcoal. Helium, Neon, Krypton and Xenon can be separated over charcoal obtained from *Cocoa nucifera*.

5.8. In dialysis

Dialysis is a procedure to remove waste products and excess fluid from the blood when the kidneys stop working properly. It often involves diverting blood to a machine to be cleaned. Dialysis was first used in 1940 successfully and then after became the standard treatment protocol for the patients suffering from renal disorder. Dialysis is useful in treatment of acute kidney injury and kidney failure. The phenomenon of adsorption works in certain cases of dialysis like hemo-dialysis and hemofiltration.

5.8.1. Membrane properties

Dialysis membranes are a critical component of both hemodialysis and peritoneal dialysis systems. These membranes serve as barriers that allow the exchange of solutes and fluids across them while retaining blood cells and larger proteins. Here are the main types of membranes used in dialysis: The membrane used in dialysis may be of different types such as cellulose membrane, synthetic membrane, high flux membrane, hemodiafilteration membrane, peritoneal dialysis membrane, adsorptive dialysis membrane etc. This removes uremic toxins and waste products from the blood of patients suffering from kidney disorder. The dialysis membrane contains adsorptive properties which can successfully isolate small molecular weight toxins which cannot be effectively cleared with conventional routine dialysis techniques.

5.8.2. Selective adsorption

The selective adsorption binding energies can supply information on the gas-surface interaction potentials by yielding the vibrational energy spectrum of the gas atom bound to the surface. Starting from the 1970s, it has been extensively studied, both theoretically and experimentally. The phenomenon of selective adsorption can be successfully applied in the process of dialysis. Certain dialysis membrane or adsorbent materials can exhibit selective adsorption. This means they preferentially remove certain substances as compared to another depending upon the size, shape or molecular structure. For example, activated charcoal based membrane or resin based membrane can selectively adsorb uremic toxins or inflammatory cytokinins and allow other essential solutes to pass through it.

5.8.3. Removal of protein bound toxins

In the patients of chronic renal disease and kidney failure, certain waste products, toxins and drugs are bound to the plasma proteins and it becomes difficult to remove by conventional dialysis methods. Here the adsorption based techniques such as use of adsorbent materials in the dialysis circuit may assist in the removal of protein bound toxins by disrupting their bindings to the protein moiety and promoting their transfer from blood to the dialysate.

5.8.4. Complementary therapy

Adsorption based dialysis techniques are many times used in complementary therapies which can enhance the clearance of specific toxins, or improve efficacy of treatment, especially in patients with refractory uremic symptoms or complications. These strategies may include use of specialized dialysis membrane, adsorbent membrane, hybrid dialysis systems, incorporating both adsorption and diffusion based mechanisms.

Thus, we observe that the phenomenon of adsorption plays a crucial role in enhancing solute clearance in dialysis. The contribution of overall solute removal may vary depending upon several factors such as membrane characteristics, blood flow rate, dialysate composition and patient specific factors. Apart from this use of adsorption based techniques in the process of dialysis requires careful consideration of potential risks, including removal of essential solutes and the removal of essential solutes and the introduction of adsorbent related complications.

5.9. Activated charcoal

The activated charcoal also known as activated carbon is the highly porous material. It is processed in such a way to have low volume with rise in surface area. This porous structure imparts special characters to the activated charcoal. This porous structure allows activated charcoal to entrap and remove wide a range of impurities, toxins and chemicals from the gas, liquid and solutions. Activated charcoal has wide range of applications in medicine also.

5.9.1. Treatment of poisoning and overdoses

Activated charcoal is commonly used in case of poisoning and overdoses. It works by adsorption of toxins and drugs in gastrointestinal tracts, prevent the diffusion in the blood stream and allows the elimination of toxins from feces. Activated charcoal is effective for adsorption of many types of drugs, chemicals and toxins and pesticides.

5.9.2. Gastrointestinal decontaminant

Activated charcoal may be administered to the individuals who have consumed poisonous materials or toxins, or overdosed with medications. Activated charcoal is administered orally in the form of slurry or suspensions. Activated charcoal is often mixed with water and administered in a single dose or repeated doses depending upon the patient's condition and decision taken by the practitioners.

5.9.3. In treatment of flatulence and bloating

Bloating is the common condition observed in elderly people and bed ridden patients. There may be several reasons or abdominal distension or bloating. Activated charcoal may be used as dietary supplements to alleviate symptoms of gas, flatulence and blotting etc. Activated charcoal supplements are available in the form of powder, tablet, capsules etc.

5.9.4. Odor control

Activated charcoal can be effectively used in the control of odor from the wound. It can be effectively used in wound dressing, deodorizer, medical filter to adsorb foul odor. The adsorptive properties of charcoal reduce the malodour and can accelerate wound healing in certain cases.

Thus, we observe various medical uses of activated charcoal. The effectiveness of activated charcoal may vary depending upon factors such as concentration of toxins, or the substance ingested, the timing of administration and the individual patient's characteristics. It is recommended to use activated charcoal under veterinary supervision only.

5.10. Hemo-perfusion

This is the process of removal of toxins from the bloodstream. Hemo-perfusion involves passing the blood of affected individuals through the activated charcoal and synthetic resins. These adsorbent selectively remove toxins or unwanted substances from the bloodstream. Thus, it helps to detoxify the body. Hemo-perfusion is often performed in acute poisoning, drug overdose or toxicological emergencies, where quick removal of toxins from the bloodstream becomes essential in order to save the life of the patient and avoid further complications and organ damages. The complications related to hemo-perfusion includes hemodynamic instability, electrolyte imbalance, bleeding, access site related complications.

5.11. In drug delivery

Drug is the English word derived from Greek origin 'Drogue' which means dry herbs. Traditionally herbs were widely used for treating the ailment of human and animals. Drug can be defined as 'A substance which can alter physiological activity of an individual'. Thus, the drug can be well classified into two main categories i.e. (1) Recreational drug; and (2) Medicinal drug. Herein, in the domain of veterinary medicine we are concern only with medicinal drugs. The drug delivery can be defined as formulations and systems for transportation of a pharmaceutical compound in the body as needed to safely achieve its desired therapeutic effect. The medicinal drugs can be administrated to the animal through various routes such as oral route, inhalation, dermal application such as oil massage, nasal drops, eye drops and of course the most important route of administration is injection. The injection can again be classified into different types such as (1) intramuscular; (2) subcutaneous; (3) intraperitoneal; (4) intravenous. What the doctors observed that the bioavailability of the drug in all route of administration other than intravenous is far less. Therefore, in order to maintain higher bioavailability intravenous system of drug administration is preferred. Whenever a veterinary doctor tries to administer he may find some difficulties like insolubility in aqueous medium, non-specific delivery, poor bioavailability, administration of higher dose due to poor absorption, lack of drug release profile, toxicity due to chronic exposure etc. Hence, there was hope for nanotechnology based drug delivery systems. Nanotechnology based drug delivery is based upon three facts: (1) efficient encapsulation of a drug; (2) successful delivery of the drug to the targeted region of the body; (3) successful release of that drug there.

Adsorption is widely used in drug delivery in pharmacokinetics, bioavailability and therapeutic efficacy of drug. The applications of adsorption in drug delivery can be enlisted as below.

5.11.1. Controlled drug release

The phenomenon of adsorption controls the rate of release of the drug. The drugs can be adsorbed on the porous surface of nanoparticles and allow the gradual release of the drug through diffusion or desorption mechanisms. By modulating various factors such as pore size, surface area and drug carrier interactions adsorption based systems enables precise control over drug release kinetics and minimizes fluctuations in plasma drug concentrations and accelerates therapeutic outcomes.

5.11.2. Enhanced drug stability

It is essential that drugs should be in stable condition and should not degrade. If the drug is degraded, then its activity will be lost. The adsorption of the drug on the solid carrier or nanoparticles can protect the drug from degradation and improve their stability during storage and administration. The various materials such as silica, clay nanoparticles or polymeric nanomaterials can be successfully used as an efficient adsorbent and provide the protective environment for the drug, shielding them from the protecting factors such as moisture, oxygen, light, temperature fluctuations etc. This prolongs the self-life, ensuring the consistent potency and efficacy over the time.

5.11.3. Targeted drug delivery

Adsorption based drug delivery system can be tailored to the target specific tissues, cells or organs within the body which enables enhanced drug localization and target effects can be minimized. The functionalized adsorbent or nanoparticles can be engineered to selectively bind to the molecular targets or receptors overexpressed in diseased tissue which facilitate site specific drug delivery. The targeted approach can improve the drug efficacy, reduces symptom toxicity and enhances patient’s compliances by minimizing adverse effects on healthy tissues.

5.11.4. Drug solubility and bio-availability

These are the crucial factors which influences the efficacy and pharmacokinetics of pharmaceutical formulations.

Drug solubility

Drug solubility refers to the ability of the drug to dissolve in solvent to form a homogeneous solution. Sparingly soluble will show limited dissolution rates and reduce bioavailability, posing challenges in drug formulation and delivery. The solubility of a drug in a particular solvent is affected by various factors such as chemical structure of the drug, temperature, whether it is hydrophilic or hydrophobic in nature, crystallinity, size and pH of the medium etc. Enhancing drug solubility is an essential condition for improving drug dissolution, absorption and bioavailability particularly in oral route of administration.

Bio-availability

Bio-availability signifies to the fraction of administered dose of drug that reaches systematic circulations in an unchanged form and is available to exert its pharmacological effects. In fact, it is the actual part of the drug which is responsible for curative effects. The remaining part is just waste part. Thus, it is always desirable to have good bioavailability. The phenomenon of bioavailability is influenced by various factors such as solubility of the drug, stability, permeability across biological barriers, and first pass metabolism. Bioavailability is generally expressed in terms of percentage bioavailability. The phenomenon of bioavailability varies on several factors such route of drug administration such as intravenous, subcutaneous, intra-peritoneal, intra-muscular, oral or some another.

Drug absorption

Drug absorption is a pharmacokinetic parameter that refers to the way a drug is absorbed from a pharmaceutical formulation into the blood stream. Several factors can affect absorption of a drug into the body as below:

1) Physicochemical properties;
2) Drug formulation e.g. tablets, capsules and solution;
3) The route of drug administration e.g. oral, sub-lingual, buccal, rectal, parenteral, topical or inhaled;
4) The rate of gastric emptying.

The main pharmacokinetic parameters for absorption include Absorption rate constant and Bioavailability. A drug must be solubilized in order to cross the semipermeable cell membrane to reach the systemic circulation. These biological barriers exist to selectively allow or inhibit the passage of native or foreign particles through them.

Phenomenon of adsorption in toxin and drug removal in veterinary treatment

Adsorption is a powerful method for removing toxins and drugs from the body, playing a significant role in veterinary treatment. This technique involves the attachment of harmful substances to the surface of adsorbent materials, preventing their absorption and mitigating their toxic effects. Adsorbents such as activated carbon, clays, and synthetic materials like zeolites and metal oxides are commonly used in veterinary medicine for detoxification.

One of the primary applications of adsorption in veterinary treatment is the management of poisoning in animals. Many substances, including pesticides, heavy metals, and certain drugs, can be highly toxic to animals if ingested or absorbed into their system. Activated carbon, for example, is widely used in cases of accidental poisoning, as it can adsorb a wide range of organic toxins. It is often administered orally to animals to bind toxins in the gastrointestinal tract, reducing their absorption into the bloodstream and limiting the systemic damage they could cause.

Heavy metal poisoning, such as lead, mercury, and cadmium, is another area where adsorption proves beneficial. Metal oxide nanoparticles, such as Fe_3O_4, have shown promising results in adsorbing these metals from animal bodies. These adsorbents can be used in veterinary treatments to help detoxify the bloodstream, preventing the harmful accumulation of metals that can damage organs like the kidneys, liver, and nervous system.

Adsorption is also used to control drug levels in veterinary care. In some instances, animals may overdose on prescribed drugs or be exposed to drugs that are contraindicated. Adsorbents can help reduce the concentration of these drugs in the bloodstream by adsorbing the drug molecules, limiting toxicity, and preventing side effects. For example, activated charcoal is often used in cases of drug overdoses, as it can adsorb a variety of pharmaceuticals, including painkillers, antidepressants, and sedatives.

Moreover, adsorbents are utilized in veterinary care to improve the safety and effectiveness of drug delivery systems. Controlled-release formulations can be designed using adsorbents to gradually release medications into an animal's system over time, ensuring consistent therapeutic levels and reducing the risk of toxicity or side effects. Overall, adsorption serves as an essential tool in veterinary medicine, offering a non-invasive, cost-effective solution for removing harmful toxins and controlling drug concentrations, thereby improving animal health and treatment outcomes.

Adsorbents in animal feed for binding mycotoxins and reducing contaminant intake

Mycotoxins are toxic secondary metabolites produced by certain molds, commonly found in contaminated animal feed ingredients such as grains, silage, and legumes. These toxins, including aflatoxins, ochratoxins, and fumonisins, pose serious health risks to livestock, poultry, and other animals, leading to diseases, poor growth, reproductive issues, and even death. One of the most effective strategies to mitigate the impact of mycotoxins on animal health is the use of adsorbents in animal feed to +ind these toxins and reduce their absorption in the gastrointestinal tract.

Adsorbents are materials that can selectively bind mycotoxins, preventing their passage into the bloodstream and subsequent distribution to organs. Common adsorbents used in animal feed include clay minerals (such as bentonite and montmorillonite), activated carbon, zeolites, and biochar. These materials have large surface areas and high adsorption capacities, allowing them to effectively trap a wide range of mycotoxins and limit their bioavailability to animals.

Clay minerals, particularly smectite clays, are among the most widely used adsorbents for mycotoxin binding. Their layered structure and negative charge make them highly effective in adsorbing positively charged mycotoxins like aflatoxins. When added to animal feed, these clays form complexes with mycotoxins, preventing their absorption in the intestines and reducing the risk of toxicity. Studies have shown that including bentonite or montmorillonite in animal feed can significantly reduce the harmful effects of aflatoxins in poultry, pigs, and ruminants.

Activated carbon and zeolites also have high adsorption capacities for mycotoxins and are used in animal feed to mitigate the effects of contamination. Activated carbon is particularly effective at binding a broad spectrum of organic contaminants, including mycotoxins. It is often included in animal feed formulations to reduce the burden of environmental toxins. Zeolites, with their microporous.

6. Limitations

Employing these magnetic metal nanoparticles as adsorbents for heavy metal removal has certain drawbacks which also needs to be considered. One such factor is when there is a transition from bulk to nanoscale the nanoparticles in spite of offering high surface area also causes instability [120]. This instability ultimately leads to the agglomeration of the nanoparticles mainly caused by the interactions due to van der Waals forces. This agglomeration results in the nanoparticles to lose their desired capacity and selectivity. Therefore, to avoid this phenomenon, nanoparticles are usually incorporated into other bulk adsorbents or into porous supports [120]. The advantages of these magnetic nanoparticles are counteracted with its ability to enter into organisms during ingestion or inhalation as reported by Holsapple et al. [121] and has the potential to translocate within various organs and tissues in the body [122,123] where they can cause toxicological effects.

7. Conclusion

The experimental studies reveal that adsorption is the economical and effective phenomenon for the removal of impurities from the solution. The phenomenon of adsorption is effective in removal of coloring materials from the solution. The odour in the solution can also be removed from the phenomenon of adsorption. This is a widely used technique that has been adopted from ancient time for the removal of impurities from solution. The adsorption process requires very cheap materials which can be acquired from natural resources. The heavy inorganic materials which create potential toxicity can be easily separated through the phenomenon of adsorption. There are some inorganic materials like zeolite which have high porosity and can be thus easily used to remove the dissolved materials from the solution. The nanomaterials can be effectively used to separate dissolved impurities present in the solution.

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