Sustainable Technologies for the Sequestration of Aqueous and Gaseous Pollutants: Role of Chitosan Based Biomaterials

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Abstract

The increasing pollution in aquatic systems with harmful substances and the persistent build-up of greenhouse gases in the atmosphere have emerged as major environmental concerns, necessitating sustainable and efficient remediation strategies. The aquatic pollutants in question are highly toxic, persistent, and not easily removed by conventional treatment methods and are therefore a serious threat to aquatic ecosystems and human health. At the same time, carbon dioxide (CO_2) levels in the atmosphere have risen, which have led to a strengthening of global warming and climate change. A number of physical, chemical and biological technologies have been developed to remove the aqueous pollutants and to capture CO_2, but because of high operating costs, energy consumption, generation of secondary waste, fouling of membranes, and poor regeneration, they are not widely used. Of all the available methods, adsorption is proven to be a simple and efficient method, as it is easily applicable to a wide range of contaminants, is energy efficient, and has a high removal efficiency. This review gives a brief overview of the major pollutants in the aqueous and gas phase, focusing on CO_2, their sources, environmental implications, and remediation technologies. The different classes of adsorbent material are discussed with respect to their use in the environment. A particular attention is given to chitosan, which is a renewable, biodegradable biopolymer extracted from abundant biomass containing chitin in nature. Different types of modification methods are discussed in the context of enhancing the adsorption capacity, stability, selectivity and reusability. New composites and hybrid biomaterials for heavy metals, dyes, surfactants, pharmaceuticals and CO_2 capture are also discussed. It illustrates the tremendous potential of modified chitosan and other biomaterial-based adsorbents as sustainable materials for the removal of pollutants, and

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points to the need for multi-functional, regenerable and scalable biomaterials for simultaneous removal of aqueous and gaseous pollutants.

Keywords: Water pollution; CO_2 Pollution; Adsorption; Chitosan; Chemical Modifications.

1. Water Pollution and Its Environmental Implications

Water pollution is a multifaceted environmental issue these days as that occurs when a diverse range of substances enters water bodies naturally or from human activities. These pollutants vary greatly in terms of their chemical composition, persistence, toxicity, source and can be grouped into inorganic contaminants, organic contaminants and emerging contaminants[1]. To design effective and targeted remediation strategies, they need to be fully understood and known about their sources and classification (Fig. 1).

The different types include one of the most dangerous aqueous pollutants, the heavy metal ions, because of their non-biodegradability and high toxicity. Contaminated water bodies are often contaminated with metals, including lead (Pb^{2+})[2], chromium (Cr (VI))[3], cadmium (Cd^{2+}), mercury (Hg^{2+})[4], arsenic (As (III)[5], nickel (Ni^{2+}) [6], etc,. The tendency of these metals to bioaccumulate and biomagnify results in serious health problems such as neurological disorders, renal dysfunction, and carcinogenic effects[7]. Heavy metal contamination sources are mostly from the industrial effluent of electroplating, metal finishing, battery manufacturing, as well as mining and smelting industries[8,9]. Also, releases from tanneries, pigment manufacturing facilities and agricultural uses of pesticides that contain metals are a major source of their occurrence in water systems [10,11]. Heavy metals also enter the environment as a result of natural processes like weathering of rocks and volcanic activities in small amounts [12].

Another major group of aqueous pollutants are the synthetic organic dyes, especially in areas that have a large number of textile and dyeing operations. The dyes are characterized by a complex aromatic molecule structure which gives high stability and resistance to degradation under environmental conditions. Their occurrence in water bodies creates aesthetic pollution due to their intense colouration, as well as a reduction in light penetration which will affect photosynthetic activity and therefore have an impact on the aquatic ecosystems [13]. Much of the dyes employed in industrial applications do not attach to the material and end up in effluent. The primary sources are textile dyeing and finishing facilities, paper and pulp factories, leather processing plants and some pharmaceutical and cosmetic production processes[14,15].

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The second major group of aqueous pollutants is the surfactants and detergents that are commonly found in the home and industries. Sodium dodecyl sulphate (SDS) is an example of an anionic surfactant that is often found in wastewater [16]. They decrease surface tension and can create stable foam at the water surface that disrupts oxygen transfer and impacts aquatic organisms. The ongoing release of surfactants into water systems are mainly from household sewage, laundering, industrial cleaning processes, textile processes and personal care products[17] . They are persistent and potentially toxic, therefore requiring effective removal strategies.

The use and ongoing release of personal care products and pharmaceuticals in water has led to their being a new class of contaminants of concern in recent years. These include antibiotics, analgesics, hormones, antiseptics and other bioactive compounds which are frequently found in very low concentrations, but have strong ecological effects [18,19]. They are derived from human and animal excretion of drugs, from the misuse of unused drugs, from effluents in pharmaceutical production industries and from hospital wastewater. These compounds have been linked to the emergence of antimicrobial resistance and endocrine disruption in aquatic organisms in water bodies [20].

Modern agricultural practices involve heavy usage of pesticides and herbicides that are also major sources of water pollution. The chemicals are intended to be biologically active, and can be persistent in the environment, causing long term contamination of soil and water systems [21]. They are mainly distributed in aquatic environments via agriculture runoff, particularly during periods of rain or irrigation, and can also enter the groundwater [22]. Other sources include poor handling, improper storage and use of pesticides, and spray drift when pesticides are used. The concentration of these can cause serious effects on aquatic life and can adversely impact humans due to drinking water sources.

Another important group of contaminants are industrial organic pollutants such as phenolic compounds, polycyclic aromatic hydrocarbons (PAHs) and chlorinated hydrocarbons. They are generally harmful, cancer-causing and are not easily removed from the environment. They are mainly emitted from the petrochemical, oil refinery, plastic/ polymer production plants, and coal processing industries [23–25]. These pollutants are hydrophobic, chemically stable, and remain in the environment and are concentrated in sediments and biota.

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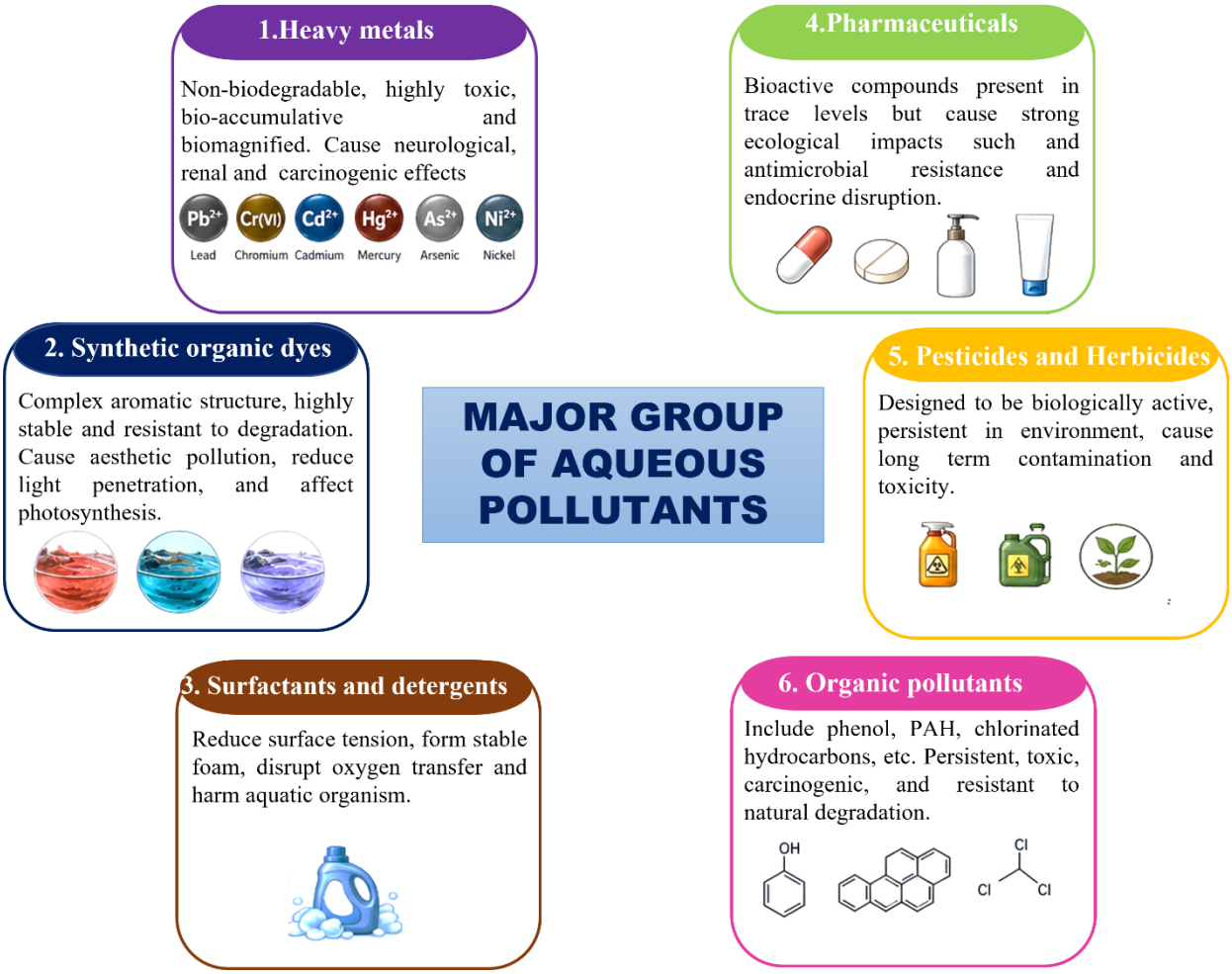


Fig. 1 Sources and causes of Water pollution.

2. Carbon Dioxide Pollution: Sources, Impacts, and Challenges

The gaseous phase pollution is an important aspect of environmental degradation and mostly occurs in the form of polluting gases being released into the air from human and natural sources. CO_2 is considered one of the most important gaseous pollutants worldwide due to its large contribution to the global warming potential and climate change. CO_2 is a naturally occurring part of the Earth's atmosphere, and has been a necessary part of the planetary energy balance, but is now being piled up in excess of natural levels due to human activities, thus contributing to severe environmental consequences [26].

CO_2 is a major greenhouse gas that can absorb and re-emit infrared radiation and therefore is a heat trapper in the atmosphere [27]. Since pre-industrial times, the unusual increase in the concentration of CO_2 in the atmosphere has been accentuating this effect, leading to a gradual rise in global average temperatures. This has led to a chain reaction of environmental

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consequences such as melting of polar ice caps, sea-level rise, extreme weather events, and changes in ecosystems (Fig. 2).

CO_2 emissions come from a number of sources, but most of them are anthropogenic, most notably fossil fuel combustion. Energy generation, transportation and industrial use of coal, oil and natural gas emits huge amounts of CO_2. One of the greatest CO_2 point sources is power plants, especially those that are coal-fired [28]. Furthermore, cement plants make significant contributions to CO_2 emissions from the calcination of limestone, which also produces CO_2 as a by-product [29]. Additional sources of CO_2 emissions to the atmosphere are associated with other industrial processes such as steel-making and chemical production [30].

Changes in land use and deforestation are also important contributors to an increase in CO_2 levels in the atmosphere. Forests serve as a natural carbon sink, which means that they absorb CO_2 via photosynthesis and store it in biomass. However, the clearance of forests at large scale, due to agriculture, urbanization, and logging, decreases the earth's ability to store carbon, thus contributing to the increase of CO_2 in the atmosphere [31]. Biomass burning (agricultural clearing or from wildfires) also releases large quantities of stored carbon into the atmosphere.

In addition to anthropogenic sources, the atmosphere also contains CO_2 from natural sources like volcanic eruptions, decomposition of organic matter and respiration by living organisms. The natural emissions are generally compensated for by natural sinks, however, such as oceans and terrestrial vegetation [32]. The present environmental concern is based on the imbalance due to the number of emissions that we humans have added to the environment, which is higher than what the environment can naturally take off.

The rising levels of CO_2 in the air have implications beyond just climate change. The additional CO_2 can cause the oceans to become more acidic, since the CO_2 is transformed into carbonic acid when it enters the sea and the pH will drop. This has a negative impact on marine life, especially those animals that depend on the formation of their shells and skeletons from calcium carbonate like corals and mollusks [33]. In addition, higher concentrations of CO_2 in the atmosphere may affect the physiology and dynamics of the ecosystem, which can impact agricultural productivity and biodiversity. Due to the rising concerns of CO_2 emissions, considerable efforts have been put in developing efficient carbon capture and sequestration technologies.

The challenge of reducing both aqueous and gaseous pollutants require innovative, efficient and sustainable remediation strategies. While effective to a certain degree, conventional

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treatment technologies have some drawbacks like high operations cost, incomplete removal of contaminants, secondary pollution, and limited applicability under different environmental conditions. As such, attention must be paid to finding alternatives to this material and technique that are environmentally friendly and can overcome these drawbacks.

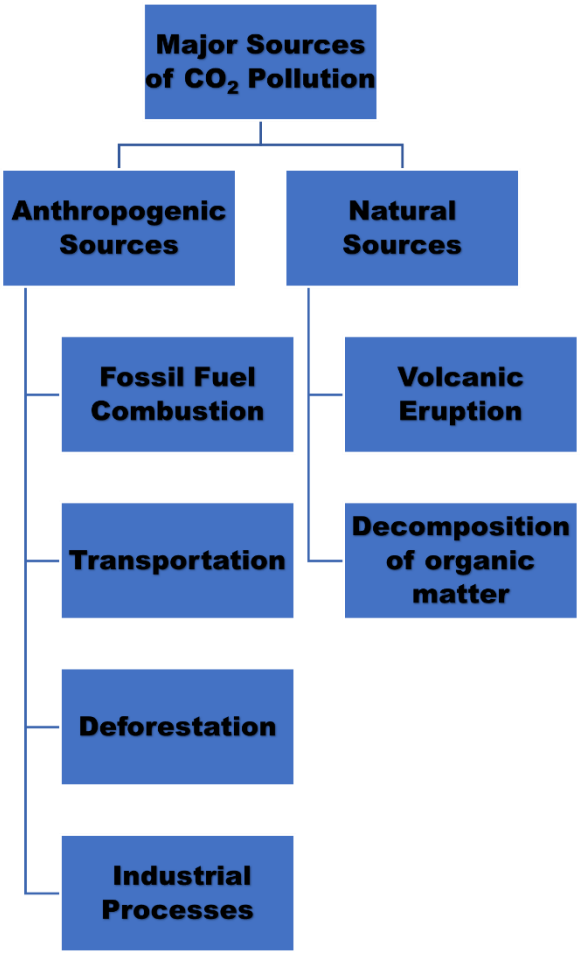


Fig. 2. Major sources of CO_2 Pollution.

3. Water treatment technologies

To remove pollutants from wastewater and contaminated water sources, a variety of physical, chemical and biological treatments have been developed. There are many differences between each technology, including mechanism, efficiency, operating conditions, and advantages and disadvantages.

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3.1 Sedimentation

One of the oldest and most widely used physical process for wastewater treatment is sedimentation. In this process, suspended particles present in water are removed due to the action of gravity. In a sedimentation pond, heavier particles settle, lighter particles remain in suspension or float on the water's surface, if they are not disturbed. The sediments that settle down are called sludge and are removed for additional processing or disposal. The primary or preliminary treatment process which is mostly employed is sedimentation, which is used to reduce the number of suspended solids that is present in the water prior to the advanced systems compared to many modern treatment technologies [34]. Sedimentation is commonly applied in municipal water treatment plants, industrial wastewater treatment systems and sewage treatment plants. The efficiency of sedimentation relies on the particle size, detention time, water flow rate and tank design. Settling is a good method to remove large and dense particles, but will not remove dissolved contamination, microorganisms and fine colloidal particles completely. Hence, it is frequently used in conjunction with coagulation and/or filtration or other advanced treatment technologies for purposes of enhancing overall treatment efficiency and water quality [35,36].

3.2 Filtration

The filtration is an important physical treatment process in which the suspended solids, fine particles, microorganisms, and impurities are removed from water. This technique involves filtering water through sand, gravel, activated carbon or membranes to remove impurities and purify the water [37,38]. The secondary or tertiary treatment of drinking water plants and wastewater plants is generally performed by filtration. Slow sand filters, rapid sand filters, pressure sand filters and membrane filters are all types of filtration systems. Rigobello et. al. reported granular activated carbon (GAC) filtration for the removal of diclofenac [39]. The effectiveness of the filtration is dependent on the size, media, flow rate and concentration of contaminants that are being filtered [40,41]. Sand filters are popular for their low cost and ease of operation, and membrane filters are more effective at removing small microorganisms. The filtration process can help to clarify the water, decrease turbidity, and eliminate pathogens from dirty water. Filters, however, can only be cleaned or replaced periodically because over time the filter becomes blocked by particles. Moreover, dissolved pollutants and toxic chemicals may not be totally filtered out of water. Hence, it is frequently employed in combination with

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coagulation, adsorption and/or disinfection processes, resulting in better water cleaning and assuring safe water quality for domestic, industrial and environmental uses [42].

3.3 Coagulation-Flocculation

The coagulation-flocculation is the most extensively used of the chemical treatment processes for removal of suspended particles, colloids, turbidity and organic matter from water and wastewater [43]. During the coagulation process, chemicals such as alum (aluminium sulphate), ferric chloride or polyaluminum chloride are introduced into the water, breaking the bonds on fine particles that have been held up by their electrical charge [44]. These particles are destabilized and start to come together during the flocculation stage, where gentle stirring brings them together to form larger particles known as flocs. These flocs can then readily be taken off by sedimentation or filtration. Coagulation-flocculation process is widely applied in the municipal drinking water treatment plants and industrial wastewater treatment plants. This process is extremely effective in removing turbidity, colour, microorganisms and some dissolved contaminants. Also facilitates more efficient subsequent treatment processes like filtration and disinfection. Coagulation-flocculation is influenced by water quality characteristics, pH, coagulant dosage, water mixing speed, etc [45]. The process is effective and is applied widely, but it has some drawbacks, such as the generation of high volume of sludge and chemical handling and disposal requirements. Effective sludge management is crucial to prevent environmental pollution and ensure sustainable operations of sludge treatment.

3.4 Chemical Precipitation

Dissolved contaminants, particularly heavy metals in wastewater can be effectively removed with chemical precipitation, which is also widely used [46]. During this process, chemicals are introduced to the wastewater and make the dissolved contaminants insoluble and form solid particles, called precipitates. The precipitates can then be removed from water by sedimentation, filtration or flotation. Common chemicals used for precipitation are lime, sodium hydroxide, sulphides and carbonates. The method is commonly used in several industries including electroplating, mining, battery production, metal processing and others where wastewater contains toxic metal ions, including lead, chromium, cadmium, and nickel. Chemical precipitation is a proven, easy and cost-effective method of treating high levels of metal contaminants. Factors affecting the efficiency of the process include pH, temperature,

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chemical dosage, and mixing conditions [47]. A good pH control is especially significant because the solubility of metals changes with pH. Chemical precipitation can give high level of removal, but also generate substantial quantity of sludge which needs further treatment and safe disposal. Moreover, if the precipitations aren't completed, it is possible that the treated water contains residual contaminants.

3.5 Ion Exchange

Ion exchange is an important water treatment process and is widely used to remove ionic impurities from water. This process is based on the principle of replacing the ions of the unwanted substances in water with the desired one with the help of special ion exchange resins. In general, positively charged ions like calcium and magnesium ions are exchanged with cation exchange resins and negatively charged ions like chlorides and sulphates are exchanged with anion exchange resins [48,49]. The method is very effective in softening hard water and obtaining demineralized water for industrial, pharmaceutical and domestic uses [50]. The process also has some drawbacks, such as high operation and maintenance costs, need to replace resin regularly, sensitivity to suspended impurities and organic matter, and not being able to remove microorganisms effectively. Also, chemical waste produced during regeneration could pose environmental issues [51].

3.6 Adsorption

Of all the water and wastewater treatment technologies, adsorption is one of the most effective and popular treatment methods employed for the removal of pollutants from contaminated water. Adsorption is a surface phenomenon, which is the process of accumulation of contaminants in the liquid or gaseous phase on the surface of solid material called the adsorbent. It takes place because of the physical or chemical interaction between the surface of the adsorbent and the adsorbate [52]. There are a number of adsorbents that have been tested extensively for environmental remediation applications including activated carbon[53], biochar [54], zeolites [55], clay minerals [56], and nanomaterials [57].

Adsorption technology has been attracting considerable interest due to its simplicity in design, ease of operation, high removal efficiency and economy. The sludge production and the requirement of large amounts of chemicals are minimal in adsorption compared to chemical precipitation and coagulation-flocculation processes. Advantages of adsorption are that it is

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more energy efficient and less expensive than membrane separation technologies and does not suffer from membrane fouling. The biological treatment process is not useful for non-biodegradable pollutants, or for heavy metals, while the adsorption process can effectively remove both organic and inorganic pollutants, even at low concentrations . In addition, adsorption systems are flexible, can be used in an environmentally friendly manner and are applicable for large-scale as well as small-scale treatment applications [58,59].

4. CO_2 Capture Technologies

Carbon dioxide (CO_2) capture technology is gaining on the list of most promising technologies for reducing greenhouse gas emissions and mitigating global climate change. There are several types of CO_2 capture technologies developed, and they can be classified as follows: Absorption method, Membrane Separation, Cryogenic separation, Chemical looping, Adsorption technology. They all have unique effects on the CO_2 source and concentration, along with strengths and weaknesses.

4.1 Absorption Method

The most advanced and commercial CO_2 capture technology is absorption technology. During this process, CO_2 is selectively dissolved in a liquid absorbent, usually aqueous amine solutions, e.g., monoethanolamine (MEA), diethanolamine (DEA), etc. The absorbent is fed into the flue gas inside an absorption column, during the operation when CO_2 is chemically absorbed [60]. The CO_2 enriched solvent is then sent to a regeneration unit where it is heated, liberating the captured CO_2 and the solvent is then returned for further use. The absorption technology has high capture efficiency and is widely used in industry; however, the main disadvantages are high energy consumption for the solvent regeneration, degradation of the solvent, corrosion problems and high operational costs.

4.2 Membrane Separation Method

The principle of membrane-based CO_2 capture is based on the selective permeation of the gas molecules through a semipermeable membrane. This separation is caused by the different diffusivity and solubility of gases in the material of the membrane. Several polymeric, inorganic and mixed-matrix membranes have been made to improve the separation efficiency [61]. The main advantages of membrane technology are compact design, the ease of operation,

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reduced energy consumption and no chemical additives. Membrane systems typically have several drawbacks, including membrane fouling, high sensitivity to the gas composition (low selectivity for some mixtures) and low efficiency for low concentration CO_2 streams [62].

4.3 Cryogenic Separation Method

Cryogenic separation is the liquefaction/solidification of CO_2 at very low temperatures. The process is a cooling method where the gas mixture is cooled down to the point that CO_2 condenses or turns to dry ice, enabling the separation of CO_2 from other gases. The cryogenic method is well suited for CO_2 containing gas streams containing very high CO_2 concentration and can yield very high-grade CO_2 products [63]. Although these benefits exist, it is economically less attractive for dilute flue gas applications because it requires significant energy consumption for cooling and compression. Therefore, the cryogenic separation is usually used in a small scale in specific industrial applications and not in the post-combustion CO_2 capture.

4.4 Chemical Looping Method

Chemical looping is a new CO_2 capture technology, where metal oxides are used as oxygen carriers. The process is carried out in two coupled reactors: fuel reactor and air reactor. The metal oxide releases oxygen to the fuel in the fuel reactor, forming CO_2 and water, but there is no direct contact between fuel and air. The metal oxide is then regenerated in the air reactor and returned to the system. Nitrogen from the air is excluded to the fuel reactor, leaving a concentrated CO_2 stream which aids in simpler capture and storage [64]. Although chemical looping is highly efficient and has low energy penalties, issues of oxygen carrier stability, reactor design and scale-up are still being studied.

4.5 Adsorption Method

Adsorption appears to be a promising and eco-friendly technology for CO_2 capture, and has been investigated intensely. In this, the CO_2 molecules are selectively trapped at the surface of porous solid adsorbents by physical or chemical attractions [65]. Various adsorbents materials such as activated carbon, zeolites, silica-based materials, metal-organic frameworks (MOFs), porous polymers and bio-based adsorbents have been investigated for CO_2 capture [66–68]. The adsorption process has a number of benefits including low energy consumption, ease of operation, high selectivity, ease of regeneration and low environmental impact. The efficiency of the adsorption depends upon the surface area, pore structure, surface functionality, and

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affinity of the adsorption material towards CO_2 molecule [69]. These benefits make adsorption CO_2 capture an attractive option compared to conventional capture methods and research on sustainable and cost-effective CCS is still a primary research focus on this process.

5. Adsorbents for Pollutant Removal

The materials that can be used in water remediation may be divided into natural, synthetic, and nanostructured materials. These are considered to be the most popular natural adsorbents as they are cheap, have a high surface area, and are environmentally friendly. Activated carbon, clay minerals, zeolites, agricultural wastes, and biochar are reported in literature for heavy metal, dye, pharmaceutical, and organic pollutant removal from wastewater [70,71]. By using synthetic adsorbents such as polymeric resins, metal-organic frameworks (MOFs), and functionalized silica materials researchers achieved improved selectivity and adsorption capacity [72,73]. Nanomaterials like carbon nanotubes, graphene oxide, magnetic nanoparticles and nanocomposites have been studied in recent years due to their high adsorption capacity, fast adsorption rate, and ease of regeneration [74–76]. The use of these adsorbent materials is significant in the context of sustainable water treatment technologies, as they are effective in removing contaminants and enhancing water quality.

Among all the biopolymer-based adsorbents researched extensively for water remediation applications, chitosan has emerged as one of the most promising materials for use in water remediation because of its biodegradability, non-toxicity, biocompatibility, and good adsorption properties [77]. Chitosan is obtained from chitin through deacetylation, which is a chemical process. It is made up mainly of glucosamine and N-acetyl-D-glucosamine residues linked by β-(1→4) glycosidic bonds (Fig. 3) [78]. Chitosan, a biodegradable and biocompatible material, is one of the most abundant renewable organic materials after cellulose, and has been the focus of great interest. Shell waste from crustaceans (shrimp, crab, lobster and other species) is the main raw material for chitosan production [79,80]. The world's shrimp-processing industries generate around 3.4 million tonnes of waste each year, of which almost 60% is comprised of shells and other waste products that can be used for chitin extraction [81]. Furthermore, the efficient utilization of these seafood processing residues can mitigate environmental pollution and provide a sustainable and cost-effective method for producing valuable products based on chitosan for various industrial, biomedical, and environmental applications. Chitosan contains many active binding groups, such as amino ($-NH_2$) and hydroxyl (-OH) groups on its surface, that allow the adsorption of a variety of contaminants from the wastewater [82].

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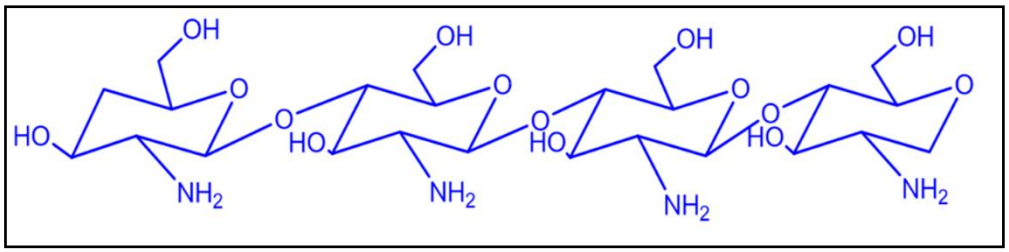


Fig. 3 Chitosan Structure.

So far, chitosan has been widely reported to remove some heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), chromium (Cr (VI), copper (Cu^{2+}), mercury (Hg^{2+}), and arsenic (As(III)) from aqueous solutions [83–87]. The amino groups present in chitosan have strong affinity towards metal ions and can be effectively used for heavy metal adsorption even at low concentration. Chitosan also has an ability to remove dyes, pesticides, pharmaceutical residues, fluoride, nitrate and other organic pollutants from industrial and municipal wastewater. The polycationic character of chitosan is useful under acidic conditions to attract negatively charged contaminants, thus increasing adsorption efficiency.

A number of chitosan adsorbents have been developed to improve the physicochemical properties and practical applications of chitosan. These include chitosan beads, hydrogels, membranes, fibres, nanoparticles, aerogels and composites. The researchers have also chemically and/or physically modified the chitosan to achieve better mechanical strength, thermal stability in acidic environments, adsorption capacity and reusability [88]. Common modifications include the use of crosslinking agents such as glutaraldehyde or epichlorohydrin, grafting of functional groups, and the incorporation of activated carbon, graphene oxide, biochar, magnetic nanoparticles, zeolites and metal oxides with chitosan.

Several operation and physicochemical parameters such as pH, adsorbent dosage, initial pollutant concentration, contact time, temperature, and ionic strength is known to influence the adsorption performance of chitosan-based adsorbents [89]. The pH is of significant importance as it would affect the electrostatic attraction, repulsion and other interactions between the amino groups of chitosan and the target pollutant, which in turn would affect the speciation or surface charge of the target pollutant. The dosage of the adsorbent will influence the percentage of the pollutants removed and it has been indicated that increase of dosages will increase the percentage of removal, however it can be seen that the adsorption capacity as a function of the active mass of the adsorbent will actually decrease at higher dosages due to site underutilization or aggregation of the particles. The contact time is also important, as the adsorption is normally fast in the initial period, as a large number of vacant active sites are

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available, but the rate becomes slower as these sites are filled up, leading to adsorption equilibrium. Hence, the efficiency of the process of adsorption is not linear with time, and does not always get better with the passage of time. Temperature can affect the adsorption process by changing the diffusion of the pollutants, the interaction between the pollutant and the adsorbent and the energetic parameters of the adsorption process, while ionic strength can affect the adsorption through competition for the active sites and electrostatic screening. Pollutant concentration is used to determine the driving force for mass transfer, but can also cause saturation of available adsorption sites at higher concentrations [90].

The main benefits of chitosan are that it has a renewable and environmentally friendly source, thus providing sustainable water treatment technologies. Moreover, desorption processes of chitosan-based adsorbents with appropriate eluents can let them be reused, which greatly decreases the operation cost. But chitosan has some drawbacks, such as low mechanical properties, unstable properties in acid, and lack of large-scale application. In order to address these shortcomings, considerable research is underway to create new chitosan composites and hybrid materials that are more high-performance, specifically with greater adsorption efficiency and durability [91].

Even though using chitosan as adsorbents is beneficial, there are a number of limitations that must be taken into consideration when using these materials. An important issue to consider is management and disposal of spent adsorbents, in which the adsorbed contaminants can be transferred to the solid phase and may cause a secondary environmental problem if the adsorbent is not properly regenerated, recovered or disposed. Regeneration can enhance the reusability of chitosan-based adsorbents but the reusability depends on the type and concentration of the regenerating agent, the efficiency of the regeneration, loss of adsorption capacity with repeated use, and the energy and chemical needs. Additionally, adsorption performance from laboratory solutions containing just one component may not necessarily reflect actual performance in real wastewater where other ions, dissolved organic matter, suspended solids, and multiple contaminants may affect the availability of the active sites and adsorption interactions. Competitive adsorption or synergistic effects between the various pollutants may thus not be observed when dealing with a single component system. The potential environmental effects of chemical modification should also be taken into account. Any leaching or residual crosslinking agents, e.g. glutaraldehyde, that are not removed from the modified product can cause toxicity concerns [92]. In addition, while chitosan is a renewable product, the overall environmental and economic benefits of chitosan cannot be determined just

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from the fact that it is a renewable product. The significance of comparison with traditional adsorbents like activated carbon needs to take into account raw material availability, synthesis and activation requirements, chemical consumption, regeneration, service life, adsorption capacity, waste management and life cycle impacts. Hence, the use of chitosan-based adsorbents in large-scale applications should be further strengthened by conducting studies under realistic wastewater conditions such as: long-term regeneration, multi-contaminant systems, leaching and toxicity evaluation, life-cycle and cost evaluation.

Besides aqueous-phase remediation, chitosan-based materials have been explored for CO_2 that can be captured by adsorption. The primary amino groups in the structure of chitosan offer interaction sites for CO_2 and make chitosan a suitable precursor for developing materials that capture CO_2 [93]. Chitosan, however, has relatively low CO_2 uptake and so several modification methods of chitosan (chemical modification, carbonization, activation and incorporation of inorganic or carbonaceous components) have been investigated to improve the adsorption capacity [94]. Chitosan-based composites of SiO_2 [95], zeolites [96], graphene oxide[97] and other functional materials have been found to exhibit better CO_2 uptake than unmodified chitosan. Specifically, porous and amine functionalized chitosan derived materials can be developed to enhance the number of active sites and adsorption of CO_2 by nitrogen containing functional groups [98]. In a recent literature, CO_2 uptake of up to about 7.84 mmol g^{-1} for Chitosan-bleaching earth clay composite was obtained, indicating the promising role of these materials as renewable adsorbents for CO_2 capture [99]. Surface area, pore size distribution, density of functional groups, pressure, temperature and moisture content have a strong effect on the adsorption performance.

In summary, chitosan has proven to be an excellent, cheap, and eco-friendly adsorptive material for water purification as well as CO_2 capture. Its excellent adsorption capacity, high modification potential and environmentally friendly property makes it a promising material for wastewater treatment and contaminated water remediation applications in the environment. Although several reviews have addressed chitosan-based adsorbents for pollutant removal, their primary focus has been on hazardous pollutants in aqueous solutions, modification strategies for pollutant adsorption, or dye removal from water and wastewater. In contrast, the present review provides an integrated perspective on the sequestration of both aqueous and gaseous-phase pollutants using chitosan-based biomaterials.

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5.1. Fundamentals of Adsorption: Isotherms and Kinetics

The adsorption performance is typically assessed by adsorption isotherms, and kinetic models give complementary information about the adsorption interactions between the adsorbate and adsorbent and the rate of pollutant adsorption. The relationship between the equilibrium concentration of the pollutant in solution and the amount of pollutant adsorbed per unit mass of adsorbent at a constant temperature is called adsorption isotherms. The Langmuir and Freundlich isotherms are important and widely used models. The Langmuir model assumes that the adsorption occurs at a limited number of equivalent sites, there is no interaction between the molecules that are adsorbed, and that the coverage is monolayer. It's non-linear equation can be represented by:

$$q_e = \frac{q_m \times K_L \times C_e}{1 + K_L \times C_e} \qquad \text{……..(1)}$$

Here, C_e (mg L^{-1}) is the equilibrium concentration. q_e (mg g^{-1}) is the equilibrium adsorption capacity, q_m (mg g^{-1}) is the theoretical maximum monolayer capacity and K_L (L mg^{-1}) is the Langmuir constant. Unlike the Freundlich model which is an empirical model widely used to describe adsorption on energetically heterogeneous surfaces. It is expressed as,

$$q_e = K_F (C_e)^{1/n} \qquad \text{……...(2)}$$

Here, K_F is the adsorption capacity-related constant and 1/n shows the adsorption intensity and surface heterogeneity. The value of 1/n as $0<1/n<1$ is frequently reported as being favourable for the adsorption range studied. None of these models can, however, be considered as proof of the adsorption mechanism and their fitness must be assessed by the use of adequate statistical parameters.

Adsorption kinetics refers to the adsorption rate to reach the equilibrium and it can be used to evaluate the effect of the contact time and mass transfer processes. An integrated linear form of the pseudo-first-order (PFO) model is typically written as,

$$q_t = q_e(1 - e^{-k_1 t}) \qquad \text{……. (3)}$$

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Here, q_t (mg g^{-1}) represents the capacity for adsorption at a specified time, t, and q_e is the equilibrium capacity; k_1 (min^{-1}) is called the PFO rate constant. The pseudo-second-order (PSO) model is described as,

$$q_t = \frac{k_2 \times {q_e}^2 \times t}{1 + k_2 \times q_e \times t} \qquad \ldots\ldots\ldots\ldots (4)$$

where k_2 (g mg^{-1} min^{-1}) is the PSO rate constant. These models are widely used for comparison of experimental kinetic data. The adsorption process can also be affected by external mass transfer, pore diffusion and interactions with surface functional groups. Hence, it is important to rely on several models of isotherms and kinetic models together with material characterization, mechanistic information and experimental conditions to better understand the pollutant sequestration by chitosan-based biomaterials.

6. Chitosan modification methods

6.1 Crosslinking Modification

One of the most common ways to modify chitosan for adsorption purposes is by crosslinking. This is done by chemically bonding the chitosan chains together with a crosslinking agent like glutaraldehyde, epichlorohydrin or tripolyphosphate [100–102]. The crosslinking process enhances the mechanical, thermal and chemical resistance of chitosan, particularly in acidic condition where pure chitosan tends to dissolve. This modification also increases the reusability and durability of the adsorbent in the wastewater treatment process.

6.2 Grafting Modification

The functional groups or polymer chains are introduced to the chitosan backbone, grafting, to enhance the adsorption properties [103]. To maximize the number of available binding site, the chitosan is often grafted with functional groups like amino, carboxyl, sulphonic, and thiol [104,105]. Grafted chitosan has better selectivity and adsorption capacity for heavy metals, dyes and organic pollutants [106]. This approach also allows to optimize chitosan for a particular contaminant in water remediation.

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6.3 Impregnation

Impregnation is a modification method that involves the addition of other materials (e.g., activated carbon, metal oxides, graphene oxide, biochar, clay minerals, or magnetic nanoparticles) to chitosan [107]. The surface area, porosity, adsorption capability and mechanical strength of chitosan are enhanced by incorporation of these materials. The magnetic chitosan composites have a high potential of particular importance due to the possibility of simple separation of the adsorbent from the treated water with an external magnetic field.

6.4 Membrane Formation

For membrane formation, chitosan is treated to form membranes or thin film which can be employed in filtration and separation technologies. Chitosan membranes have high permeability, high adsorption capacity and antimicrobial properties, which are suitable for applications in wastewater treatment. These membranes are capable of filtering dyes, heavy metal ions, micro-organisms and organic pollutants from water [108]. Chitosan materials with membranes have also been extensively investigated in the field of desalination and high-end purification[109].

6.5 Surface Functionalization

Surface functionalization is the process of chemically modifying the surface of chitosan to generate desired functional groups related to the adsorption behaviour. The uses of this method involve mechanisms of interaction between chitosan and target pollutants, including chelation, ion exchange and electrostatic attraction [110,111]. Functionalized chitosan materials exhibit greater affinity to toxic metal ions and complex organic contaminants and therefore are very effective materials for environmental remediation.

7. Recent Literature

The comparative assessment of the reported chitosan-based adsorbents shows that chitosan is a versatile functional platform for the removal of various environmental contaminants such as heavy metal ions, synthetic dyes, residues of pharmaceuticals, anionic surfactants and carbon dioxide. The adsorption capacity of these materials not only depends on the properties of the materials such as specific surface area and pore structure of the material, but also depends on the properties of the pollutants to be adsorbed, including chemical functionality, degree of modification, stability of the adsorbent, and physicochemical properties of the adsorbent, as

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summarized in Table 1. Magnetic particles, carbonaceous materials, metal-organic frameworks (MOFs) and other functional groups have been incorporated yielding adsorbents with properties that suit the various treatment needs. The maximum capacities that are listed should however be viewed in conjunction with the experiments used and performance indicators, and should not be taken on their own. Saberi-Zare et al. reported that the adsorption capacities of chitosan-grafted magnetic biochar for the removal of Pb(II) and Cd(II) were 394 and 391mg g^{-1} respectively. The effect of the high uptake was ascribable to the availability of amino and hydroxyl groups and the magnetic component allowed the adsorbent to be recovered. Likewise, the malic acid modified chitosan hydrogel beads reported by Zhang et al. showed 383.2 and 183.8 mg g^{-1} capacities for Cr(VI) and Cu(II) respectively. The results show the need to adjust surface functionality with regard to pollutant chemistry. The reported capacity of Pb(II) of 934 mg g^{-1} by chitosan extracted from T. dichotomus is also remarkable. However, interpretation of such high capacities is always demanding careful consideration of the starting concentration of the pollutant, pH, equilibrium conditions and analytical validation.

The GO/MnO_2/chitosan nanocomposite is promising for the removal of dyes, as it shows the ability of chitosan to be combined with inorganic materials. The surface functionalization of graphene oxide can enhance the surface properties, and the properties of the final composite can be enhanced in terms of structural properties. The MSe-MOF loaded chitosan/alginate hydrogel beads and Fe_3O_4@CS-P(AM-DMDAAC) composite have been evaluated for the removal of ciprofloxacin and doxycycline hydrochloride, respectively. MOFs, magnetic particles, and modified polymer matrices can be combined to enhance the surface functionality, ease of separation and interaction between pollutants and MOFs. The use of chitosan derivatives for a number of pharmaceutical products also indicates that the adsorption property is a function of the chemical structure and charge of each contaminant. However, the selectivity that can be achieved using individual pharmaceutical solutions cannot be confirmed under realistic conditions where pharmaceutical products are found in co-existence with other natural organic matter, inorganic ions and other organic contaminants. Further studies of mixed-contaminant solutions, real wastewater matrices and continuous-flow systems are therefore required to determine real-world applicability of these materials.

Chitosan-based adsorbents have also been shown to be effective in removing anionic surfactants. It has been reported that primary amino crosslinked chitosan microspheres (ACCMs) could be used to effectively adsorb anionic surfactants due to interaction between the protonated amino groups of the microspheres and the anionic sulfonate groups of the anionic

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surfactants. This mechanism highlights the importance of surface charge and protonation in adsorption control with respect to pH. In surfactant adsorption, however, there are analytical difficulties because micelle formation, aggregation and variations in the concentration of the surfactant can affect the adsorption measured. The initial surfactant concentration relative to its CMC, solution composition, and analytical method should therefore be taken into consideration when making comparisons. In addition, the ability to reduce the adsorption of surfactants in complex industrial effluents with competing organic matter and electrolytes is not reflected by adsorption capacity.

It is notable that chitosan derived porous carbon materials are a class of adsorbents that is different from those used in aqueous pollutants removal for CO_2 capture. Here chitosan can be used as a carbon precursor with nitrogen and extra heteroatom doping or amine impregnation can alter the surface chemistry of the resulting carbon. For the N-doped microporous carbon based on chitosan, Fan et al. reported 169.87 mg g^{-1} CO_2 uptake at 1 bar and 298K. Other reported systems are heteroatom-doped porous carbon synthesized from shrimp-shell waste, porous carbon synthesized from chitosan and impregnated with pentaethylenehexamine, and N-doped porous carbon synthesized using $NaNH_2$. The results indicate that CO_2 capture involves the synergistic effect of pore accessibility, micropore volume, presence of nitrogen-containing surface groups, and CO_2 affinity to the adsorbent surface.However, it is not appropriate to compare the maximum CO_2 uptake without taking into account the pressure and temperature under which it was measured. CO_2 adsorption on many porous materials is exothermic and therefore adsorption capacities measured at low temperatures could be higher than those measured at high temperature. Likewise, the capacity measured at relatively high CO_2 pressures may not be representative of the performance in dilute flue-gas.

Although the research on adsorption properties of chitosan is advanced, there are still some deficiencies. First, most studies have been batch experiments that involve only one-pollutant solution, restricting the predictability of treatment performance under realistic treatment conditions. Secondly, the relationship between surface area and adsorption capacity is by no means linear because the accessibility and chemical nature of the active sites also influence the capacity of adsorption. Thirdly, the long-term environmental safety of modified adsorbents, such as the release of the incorporated metals and/or crosslinkers or functionalizing agents, must be investigated.

In general, the literature suggests that chitosan-based materials are a versatile medium for creating adsorbents for water and gas pollutants. Their major benefits are that surface

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functionality, structure and composition can be customized to the desired pollutant. But high adsorption capacity must be taken as a preliminary assessment parameter rather than a criteria for practical use. Standardized performance comparison, multicomponent adsorption, flow-through studies, regeneration over multiple cycles and techno-economic and environmental evaluations should be considered as future research priorities. These measures would allow for a more suitable assessment of the viability of chitosan materials for use on a larger scale for water treatment and CO_2 capture.

Table 1. Reported chitosan-based materials for the adsorption of pollutants and CO_2 capture.

Adsorbent	Adsorbate	Adsorption Capacity (mg g^{-1})	Operating conditions	Reference
Chitosan-grafted magnetic biochar	Pb(II)	394	pH:7.0 Time: 60 min	[112]
Chitosan-grafted magnetic biochar	Cd(II)	391	pH:7.0 Time: 60 min	[112]
GO/MnO_2/CS nanocomposite	Cr(VI)	179.28	pH:2.0 Time:180 min	[113]
Crosslinked chitosan beads	Reactive Black 5 dye	379.90	pH:3.6 Time: 480 min	[114]
MSe-MOF-loaded chitosan/alginate hydrogel beads (MSCA)	Ciprofloxacin	440	pH: 8.0 Time:60 min	[115]
Fe_3O_4@CS-P(AM-DMDAAC) composite	Doxycycline hydrochloride	566.82	pH:9.0 Time: 90 min	[116]
Primary amino crosslinked chitosan microspheres (ACCMs)	SDS	888	pH:3.0 Time 48 h	[117]
Malic acid-crosslinked chitosan-based hydrogel	Cr(VI)	427	pH:2.0 18 min	[118]
Malic acid-enhanced chitosan hydrogel beads (mCHBs)	Cr(VI)	383.2	pH:3.0 2 h	[119]
Malic acid-enhanced chitosan hydrogel beads (mCHBs)	Cu(II)	183.8	pH:5.0 24 h	[119]
Chitosan sourced from Trypoxylus dichotomus larvae/adults	Pb(II)	934	500 min	

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Chitosan sourced from Trypoxylus dichotomus larvae/adults	Cu(II)	462	500 min	
Chitosan-derived nitrogen-doped microporous carbon	CO_2	169.87	298K 1 atm	[120]
Boron-doped chitosan-derived porous carbon	CO_2	335.36	273K 1bar	[121]
ZIF-67/chitosan composite beads	CO_2	53.25	273K 1bar	[122]
Shrimp-shell-waste-derived (N, S, O)-doped chitosan-based porous carbon	CO_2	236.8	273K 1bar	[123]
Chitosan-derived mesoporous carbon impregnated with pentaethylenehexamine (PEHA/CDMC composite)	CO_2	163.71	373K 1 bar	[124]
Chitosan-derived N-doped porous carbon prepared using $NaNH_2$	CO_2	278.58	273K 1bar	[125]
Chitosan-based three-dimensional nitrogen-doped porous carbon (3D-NPCs)	CO_2	260.54	273K 1bar	[126]

8. Conclusion

Water resources contamination and greenhouse gases emission is a serious environmental issue that needs effective and environment-friendly treatment measures. Of the different methods available, adsorption provides flexibility of operation, has the potential for relatively low energy consumption and is one of the few methods that is easily regenerable when using an adsorbent, although the overall performance and sustainability of the process will depend on the properties of the adsorbent and conditions under which the process is operated. Chitosan has been gaining great interest in this context due to its novel properties such as being a renewable, biodegradable and chemically modifiable biopolymer that has amino and hydroxyl functional groups that can interact with a large variety of pollutants.

The literature search revealed that surface chemistry, porosity, stability, and adsorption can be modified by chemical modification, crosslinking, grafting, blending and incorporation of organic, inorganic and carbonaceous components of chitosan-based materials. These changes have demonstrated the possibility to enhance the elimination of a number of different aqueous pollutants such as metal ions, dyes or other pollutants. Their efficacy, however, relies on the nature of the pollutant, pH, dosage of the adsorbent, contact time, competing species and composition of the material to be adsorbed. Thus, the adsorption activity of the system should

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be evaluated per pollutant and per adsorbent. Issues of adsorbent stability, regeneration, co-occurring contaminants and spent adsorbent management still apply to real-world water treatment applications. The use of chitosan-based materials in CO_2 capture has also been explored, such as preparation of functionalized sorbents and porous carbonaceous materials from chitosan. They are influenced by the availability and chemical characteristics of the adsorption sites, the pore structure, the operating pressure and temperature, the composition of the gases to be adsorbed and the requirements for regeneration. However, positive laboratory CO_2 uptake results do not imply suitability for industrial carbon capture.

Evaluation of modified chitosan adsorbents in real wastewater and multicomponent systems must be further carried out and systematic investigations concerning the selectivity and material durability must be conducted in the future. Studies of CO_2 capture should consider gas compositions and operating conditions, and the effects of humidity and relevant impurities, in realistic conditions and evaluate both the uptake and selectivity. The literature reviewed indicates that chitosan-based biomaterials are a potential platform for aqueous pollutant removal and emerging option for CO_2 capture. These are, however, to be validated on a case-by-case basis by a proper application-specific performance evaluation, long-term testing, and full sustainability assessment. To assess the applicability of these materials for future environmental remediation and carbon capture applications, it will be critical to demonstrate these attributes under realistic conditions.

Authors Contribution

Tejaswini A. Rathi: Conceptualization; Visualization, Validation; Writing - original draft.

Ravin Jugade: Conceptualization; Visualization; Investigation; Supervision, Writing – review & editing.

Conflict of Interest

The authors declare no conflict of interest for this manuscript.

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Reference

1. N. B. Jadeja, T. Banerji, A. Kapley and R. Kumar, ‘Water pollution in India – Current scenario’, Water Secur., 16, 100119, 2022.
2. K. Raj and A. P. Das, ‘Lead pollution: Impact on environment and human health and approach for a sustainable solution’, Environ. Chem. Ecotoxicol., 5, 79–85, 2023.
3. M. N. Georgaki, M. Charalambous, N. Kazakis, M. A. Talias, C. Georgakis, T. Papamitsou and C. Mytiglaki, ‘Chromium in Water and Carcinogenic Human Health Risk’, Environments, 10, 33, 2023.
4. P. Li, X. B. Feng, G. L. Qiu, L. H. Shang and Z. G. Li, ‘Mercury pollution in Asia: A review of the contaminated sites’, J. Hazard. Mater., 168, 591–601, 2009.
5. K. Khosravi-Darani, Y. Rehman, I. A. Katsoyiannis, E. Kokkinos and A. I. Zouboulis, ‘Arsenic Exposure via Contaminated Water and Food Sources’, Water, 14, 1884, 2022.
6. H. Koçyiğit, G. Gök and H. Çelebi, ‘From garbage to biosorbent: overview raw and hexane purified almond shells for nickel (II) ions removal’, Appl. Water Sci., 15, 165, 2025.
7. Z. Wang, P. Luo, X. Zha, C. Xu, S. Kang, M. Zhou, D. Nover and Y. Wang, ‘Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil’, J. Clean. Prod., 379, 134043, 2022.
8. V. Kumar and S. K. Dwivedi, ‘Toxicity potential of electroplating wastewater and its bioremediation approaches: a review’, Environ. Technol. Rev., 10, 238–254, 2021.
9. P. Sahu, A. R. Patel, A. Pandey, M. Hait and G. K. Patra, ‘Assessment of heavy metal ion toxicity in wastewater: A comprehensive review’, Inorg. Chim. Acta, 585, 122751, 2025.
10. A. Arti and R. Mehra, ‘Analysis of heavy metals and toxicity level in the tannery effluent and the environs’, Environ. Monit. Assess., 195, 554, 2023.
11. R. M. Madjar and G. Vasile Scăețeanu, ‘An Overview of Heavy Metal Contamination in Water from Agriculture: Origins, Monitoring, Risks, and Control Measures’, Sustainability, 17, 7368, 2025.
12. H. Ali, E. Khan and I. Ilahi, ‘Environmental Chemistry and Ecotoxicology of Hazardous Heavy Metals: Environmental Persistence, Toxicity, and Bioaccumulation’, J. Chem., 2019, 1–14, 2019.
13. M. Farhan Hanafi and N. Sapawe, ‘A review on the water problem associate with organic pollutants derived from phenol, methyl orange, and remazol brilliant blue dyes’, Mater. Today Proc., 31, A141–A150, 2020.
14. K. Maheshwari, M. Agrawal and A. B. Gupta, ‘Novel Materials for Dye-containing Wastewater Treatment’, in *Novel Materials for Dye-containing Wastewater Treatment*, edited by S. S. Muthu and A. Khadir, Springer, Singapore, pp. 1–25, 2021

.

15. S. Madhav, A. Ahamad, A. K. Singh, J. Kushawaha, J. S. Chauhan, S. Sharma and P. Singh, 'Sensors in Water Pollutants Monitoring: Role of Material', in *Sensors in Water Pollutants Monitoring: Role of Material*, edited by D. Pooja, P. Kumar, P. Singh and S. Patil, Springer, Singapore, pp. 43–62, 2020.

16. D. Kulkarni and D. Jaspal, 'Surfactants in waste water: Development, current status and associated challenges', Mater. Today Proc. 11, 1, 2023.

17. S. Rebello, A. K. Asok, S. Mundayoor and M. S. Jisha, 'Pollutant Diseases, Remediation and Recycling', in *Pollutant Diseases, Remediation and Recycling*, edited by E. Lichtfouse, J. Schwarzbauer and D. Robert, Springer International Publishing, Cham, vol. 4, pp. 277–320, 2013.

18. V. Chander, B. Sharma, V. Negi, R. S. Aswal, P. Singh, R. Singh and R. Dobhal, 'Pharmaceutical Compounds in Drinking Water', J. Xenobiotics, 6, 5774, 2016.

19. R. Gothwal and T. Shashidhar, 'Antibiotic Pollution in the Environment: A Review', CLEAN – Soil Air Water, 43, 479–489, 2015.

20. Y. Ma, M. Li, M. Wu, Z. Li and X. Liu, 'Occurrences and regional distributions of 20 antibiotics in water bodies during groundwater recharge', Sci. Total Environ., 518–519, 498–506, 2015.

21. M. Syafrudin, R. A. Kristanti, A. Yuniarto, T. Hadibarata, J. Rhee, W. A. Al-onazi, T. S. Algarni, A. H. Almarri and A. M. Al-Mohaimeed, 'Pesticides in Drinking Water—A Review', Int. J. Environ. Res. Public Health, 18, 468, 2021.

22. R. M. de Souza, D. Seibert, H. B. Quesada, F. de Jesus Bassetti, M. R. Fagundes-Klen and R. Bergamasco, 'Occurrence, impacts and general aspects of pesticides in surface water: A review', Process Saf. Environ. Prot., 135, 22–37, 2020.

23. I. Gutierrez-Urbano, M. Villen-Guzman, R. Perez-Recuerda and J. M. Rodriguez-Maroto, 'Removal of polycyclic aromatic hydrocarbons (PAHs) in conventional drinking water treatment processes', J. Contam. Hydrol., 243, 103888, 2021.

24. D. Rosner and G. Markowitz, 'Persistent pollutants: A brief history of the discovery of the widespread toxicity of chlorinated hydrocarbons', Environ. Res., 120, 126–133, 2013.

25. H. I. Abdel-Shafy and M. S. M. Mansour, 'A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation', Egypt. J. Pet., 25, 107–123, 2016.

26. F. A. Rahman, M. M. A. Aziz, R. Saidur, W. A. W. A. Bakar, M. R. Hainin, R. Putrajaya and N. A. Hassan, 'Pollution to solution: Capture and sequestration of carbon dioxide (CO_2) and its utilization as a renewable energy source for a sustainable future', Renew. Sustain. Energy Rev., 71, 112–126, 2017.

27. A. Sharma, J. Jindal, A. Mittal, K. Kumari, S. Maken and N. Kumar, 'Carbon materials as CO_2 adsorbents: a review', Environ. Chem. Lett., 19, 875–910, 2021.

28. C.H. Huang and C.-S. Tan, 'A Review: CO_2 Utilization', Aerosol Air Qual. Res., 14, 480–499, 2014.

.

29. L. Shen, T. Gao, J. Zhao, L. Wang, L. Wang, L. Liu, F. Chen and J. Xue, ‘Factory-level measurements on CO_2 emission factors of cement production in China’, Renew. Sustain. Energy Rev., 34, 337–349, 2014.

30. L. Holappa, ‘A General Vision for Reduction of Energy Consumption and CO_2 Emissions from the Steel Industry’, Metals, 10, 1117, 2020.

31. N. Ramankutty, H. K. Gibbs, F. Achard, R. Defries, J. A. Foley and R. A. Houghton, ‘Challenges to estimating carbon emissions from tropical deforestation’, Glob. Change Biol., 13, 51–66, 2007.

32. V. V. Yurak and S. A. Fedorov, ‘Review of natural and anthropogenic emissions of carbon dioxide into the earth’s atmosphere’, Int. J. Environ. Sci. Technol., 22, 2719–2736, 2025.

33. H. O. Pörtner, M. Langenbuch and A. Reipschläger, ‘Biological Impact of Elevated Ocean CO_2 Concentrations: Lessons from Animal Physiology and Earth History’, J. Oceanogr., 60, 705–718, 2004.

34. N. K. Shammas, I. J. Kumar, S.-Y. Chang and Y.-T. Hung, ‘Physicochemical Treatment Processes’, in *Physicochemical Treatment Processes*, edited by L. K. Wang, Y.-T. Hung and N. K. Shammas, Humana Press, Totowa, NJ, pp. 379–429, 2005.

35. J. J. Lee, J. H. Cha, R. Ben Aim, K. B. Han and C. W. Kim, ‘Fiber filter as an alternative to the process of flocculation–sedimentation for water treatment’, Desalination, 231, 323–331, 2008.

36. C. R. O’Melia, ‘Coagulation and sedimentation in lakes, reservoirs and water treatment plants’, Water Sci. Technol., 37, 129–135, 1998.

37. M. F. Hamoda, I. Al-Ghusain and N. Z. Al-Mutairi, ‘Sand filtration of wastewater for tertiary treatment and water reuse’, Desalination, 164, 203–211, 2004.

38. G. Pearce, ‘Introduction to membranes: Filtration for water and wastewater treatment’, Filtr. Sep., 44, 24–27, 2007.

39. E. S. Rigobello, A. D. B. Dantas, L. Di Bernardo and E. M. Vieira, ‘Removal of diclofenac by conventional drinking water treatment processes and granular activated carbon filtration’, Chemosphere, 92, 184–191, 2013.

40. M. Salman, M. Shakir and M. Yaseen, ‘Industrial Wastewater Treatment’, in *Industrial Wastewater Treatment*, edited by T. Karchiyappan, R. R. Karri and M. H. Dehghani, Springer International Publishing, Cham, pp. 1–25, 2022.

41. Y. Wu, S. Xia, B. Dong, H. Chu and J. Liu, ‘Study on surface water treatment by hybrid sand filtration and nanofiltration’, Desalin. Water Treat., 51, 5327–5336, 2013.

42. J. D. Lee, S.-H. Lee, M.-H. Jo, P.-K. Park, C.-H. Lee and J.-W. Kwak, ‘Effect of Coagulation Conditions on Membrane Filtration Characteristics in Coagulation−Microfiltration Process for Water Treatment’, Environ. Sci. Technol., 34, 3780–3788, 2000.

43. J. Q. Jiang, ‘The role of coagulation in water treatment’, Curr. Opin. Chem. Eng., 8, 36–44, 2015.

.

44. O. S. Amuda and I. A. Amoo, ‘Coagulation/flocculation process and sludge conditioning in beverage industrial wastewater treatment’, J. Hazard. Mater., 141, 778–783, 2007.

45. J. P. Wang, Y.-Z. Chen, Y. Wang, S.-J. Yuan and H.-Q. Yu, ‘Optimization of the coagulation-flocculation process for pulp mill wastewater treatment using a combination of uniform design and response surface methodology’, Water Res., 45, 5633–5640, 2011.

46. Q. Chen, Y. Yao, X. Li, J. Lu, J. Zhou and Z. Huang, ‘Comparison of heavy metal removals from aqueous solutions by chemical precipitation and characteristics of precipitates’, J. Water Process Eng., 26, 289–300, 2018.

47. I. G. A. A. Rashed, H. A. Afify, A. E.-M. Ahmed and M. A. E.-S. Ayoub, ‘Optimization of chemical precipitation to improve the primary treatment of wastewater’, Desalin. Water Treat., 51, 7048–7056, 2013.

48. J. Gregory and R. V. Dhond, ‘Wastewater treatment by ion exchange’, Water Res., 6, 681–694, 1972.

49. K. Vaaramaa and J. Lehto, ‘Removal of metals and anions from drinking water by ion exchange’, Desalination, 155, 157–170, 2003.

50. A. Amini, Y. Kim, J. Zhang, T. Boyer and Q. Zhang, ‘Environmental and economic sustainability of ion exchange drinking water treatment for organics removal’, J. Clean. Prod., 104, 413–421, 2015.

51. S. Rengaraj, K.-H. Yeon and S.-H. Moon, ‘Removal of chromium from water and wastewater by ion exchange resins’, J. Hazard. Mater., 87, 273–287, 2001.

52. I. Ali and V. K. Gupta, ‘Advances in water treatment by adsorption technology’, Nat. Protoc., 1, 2661–2667, 2006.

53. A. Bhatnagar, W. Hogland, M. Marques and M. Sillanpää, ‘An overview of the modification methods of activated carbon for its water treatment applications’, Chem. Eng. J., 219, 499–511, 2013.

54. N. Jagadeesh and B. Sundaram, ‘Adsorption of Pollutants from Wastewater by Biochar: A Review’, J. Hazard. Mater. Adv., 9, 100226, 2023.

55. S. Wang, H. Li, S. Xie, S. Liu and L. Xu, ‘Physical and chemical regeneration of zeolitic adsorbents for dye removal in wastewater treatment’, Chemosphere, 65, 82–87, 2006.

56. P. H. Chang, Z. Li, W.-T. Jiang and B. Sarkar, ‘Modified Clay and Zeolite Nanocomposite Materials’, in *Modified Clay and Zeolite Nanocomposite Materials*, edited by M. Mercurio, B. Sarkar and A. Langella, Elsevier, pp. 167–196, 2019.

57. P. Jangid and M. Prabhu Inbaraj, ‘Applications of nanomaterials in wastewater treatment’, Mater. Today Proc., 43, 2877–2881, 2021.

58. N. B. Singh, G. Nagpal, S. Agrawal and Rachna, ‘Water purification by using Adsorbents: A Review’, Environ. Technol. Innov., 11, 187–240, 2018.

.

59. K. M. AlAqad, M. M. Abdelnaby, A. Tanimu, I. Abdulazeez and A. M. Elsharif, ‘Adsorbent materials for water treatment: A review of current trends and future challenges’, Environ. Pollut. Manag., 2, 1–13, 2025.

60. B. Freeman, P. Hao, R. Baker, J. Kniep, E. Chen, J. Ding, Y. Zhang and G. T. Rochelle, ‘Hybrid Membrane-absorption CO_2 Capture Process’, Energy Procedia, 63, 605–613, 2014.

61. R. Hou, C. Fong, B. D. Freeman, M. R. Hill and Z. Xie, ‘Current status and advances in membrane technology for carbon capture’, Sep. Purif. Technol., 300, 121863, 2022.

62. Z. Dai and L. Deng, ‘Membranes for CO_2 capture and separation: Progress in research and development for industrial applications’, Sep. Purif. Technol., 335, 126022, 2024.

63. A. Hart and N. Gnanendran, ‘Cryogenic CO_2 capture in natural gas’, Energy Procedia, 1, 697–706, 2009.

64. J. Li, H. Zhang, Z. Gao, J. Fu, W. Ao and J. Dai, ‘CO_2 Capture with Chemical Looping Combustion of Gaseous Fuels: An Overview’, Energy Fuels, 31, 3475–3524, 2017.

65. A. L. Chaffee, G. P. Knowles, Z. Liang, J. Zhang, P. Xiao and P. A. Webley, ‘CO_2 capture by adsorption: Materials and process development’, Int. J. Greenh. Gas Control, 1, 11–18, 2007.

66. S. Jribi, T. Miyazaki, B. B. Saha, A. Pal, M. M. Younes, S. Koyama and A. Maalej, ‘Equilibrium and kinetics of CO_2 adsorption onto activated carbon’, Int. J. Heat Mass Transf., 108, 1941–1946, 2017.

67. R. V. Siriwardane, M.-S. Shen, E. P. Fisher and J. Losch, ‘Adsorption of CO_2 on Zeolites at Moderate Temperatures’, Energy Fuels, 19, 1153–1159, 2005.

68. T. Ghanbari, F. Abnisa and W. M. A. Wan Daud, ‘A review on production of metal organic frameworks (MOF) for CO_2 adsorption’, Sci. Total Environ., 707, 135090, 2020.

69. J. Yang, N. Cao, Y. Liu and Y. Lu, ‘CO_2 capture with adsorption strategies: Achievements, challenges, and prospects’, J. Clean. Prod., 515, 145798, 2025.

70. A. S. Mestre, J. Pires, J. M. F. Nogueira and A. P. Carvalho, ‘Activated carbons for the adsorption of ibuprofen’, Carbon, 45, 1979–1988, 2007.

71. B. Yao, Z. Luo, S. Du, J. Yang, D. Zhi and Y. Zhou, ‘Sustainable biochar/$MgFe_2O_4$ adsorbent for levofloxacin removal: Adsorption performances and mechanisms’, Bioresour. Technol., 340, 125698, 2021.

72. A. Li, Q. Zhang, G. Zhang, J. Chen, Z. Fei and F. Liu, ‘Adsorption of phenolic compounds from aqueous solutions by a water-compatible hypercrosslinked polymeric adsorbent’, Chemosphere, 47, 981–989, 2002.

73. R. Liu, J. Song, J. Zhao, Z. Wang, J. Xu, W. Yang and J. Hu, ‘Novel MOF(Zr)–on-MOF(Ce/La) adsorbent for efficient fluoride and phosphate removal’, Chem. Eng. J., 497, 154780, 2024.

.

74. A. Stafiej and K. Pyrzynska, ‘Adsorption of heavy metal ions with carbon nanotubes’, Sep. Purif. Technol., 58, 49–52, 2007.

75. Y. Gao, Y. Li, L. Zhang, H. Huang, J. Hu, S. M. Shah and X. Su, ‘Adsorption and removal of tetracycline antibiotics from aqueous solution by graphene oxide’, J. Colloid Interface Sci., 368, 540–546, 2012.

76. H. Li, D. Xiao, H. He, R. Lin and P. Zuo, ‘Adsorption behavior and adsorption mechanism of Cu(II) ions on amino-functionalized magnetic nanoparticles’, Trans. Nonferrous Met. Soc. China, 23, 2657–2665, 2013.

77. M. A. Kaczorowska and D. Bożejewicz, ‘The Application of Chitosan-Based Adsorbents for the Removal of Hazardous Pollutants from Aqueous Solutions—A Review’, Sustainability, 16, 2615, 2024.

78. S. Gabriel Kou, L. M. Peters and M. R. Mucalo, ‘Chitosan: A review of sources and preparation methods’, Int. J. Biol. Macromol., 169, 85–94, 2021.

79. M. N. V. Ravi Kumar, ‘A review of chitin and chitosan applications’, React. Funct. Polym., 46, 1–27, 2000.

80. K. V. Harish Prashanth and R. N. Tharanathan, ‘Chitin/chitosan: modifications and their unlimited application potential—an overview’, Trends Food Sci. Technol., 18, 117–131, 2007.

81. J. Naibaho, H. Manikyaparambil, S. Hannon, S. Pathania, C. McDonagh and B. K. Tiwari, ‘Trends in shrimp shells valorization for bioactive ingredients extraction: Opinion and perspectives towards circular biorefinery approaches’, Clean. Food Syst., 3, 100017, 2026.

82. G. Crini, ‘Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment’, Prog. Polym. Sci., 30, 38–70, 2005.

83. F. Zhao, E. Repo, D. Yin and M. E. T. Sillanpää, ‘Adsorption of Cd(II) and Pb(II) by a novel EGTA-modified chitosan material: Kinetics and isotherms’, J. Colloid Interface Sci., 409, 174–182, 2013.

84. Y. A. Aydın and N. D. Aksoy, ‘Adsorption of chromium on chitosan: Optimization, kinetics and thermodynamics’, Chem. Eng. J., 151, 188–194, 2009.

85. W. S. Wan Ngah, A. Kamari and Y. J. Koay, ‘Equilibrium and kinetics studies of adsorption of copper (II) on chitosan and chitosan/PVA beads’, Int. J. Biol. Macromol., 34, 155–161, 2004.

86. C. Jeon and K. Ha Park, ‘Adsorption and desorption characteristics of mercury(II) ions using aminated chitosan bead’, Water Res., 39, 3938–3944, 2005.

87. K. C. M. Kwok, L. F. Koong, G. Chen and G. McKay, ‘Mechanism of arsenic removal using chitosan and nanochitosan’, J. Colloid Interface Sci., 416, 1–10, 2014.

88. I. O. Saheed, W. D. Oh and F. B. M. Suah, ‘Chitosan modifications for adsorption of pollutants – A review’, J. Hazard. Mater., 408, 124889, 2021.

.

89. P. Mahdavi, A. Siol and J. Thöming, ‘Adsorption-based removal of pharmaceutical from water: A critical review on adsorbent performance’, J. Environ. Chem. Eng., 13, 117520, 2025.

90. T. A. Aragaw and A. N. Alene, ‘A comparative study of acidic, basic, and reactive dyes adsorption from aqueous solution onto kaolin adsorbent: Effect of operating parameters, isotherms, kinetics, and thermodynamics’, Emerg. Contam., 8, 59–74, 2022.

91. M. Vakili, M. Rafatullah, B. Salamatinia, A. Z. Abdullah, M. H. Ibrahim, K. B. Tan, Z. Gholami and P. Amouzgar, ‘Application of chitosan and its derivatives as adsorbents for dye removal from water and wastewater: A review’, Carbohydr. Polym., 113, 115–130, 2014.

92. D. P. Speer, M. Chvapil, C. D. Eskelson and J. Ulreich, ‘Biological effects of residual glutaraldehyde in glutaraldehyde-tanned collagen biomaterials’, J. Biomed. Mater. Res., 14, 753–764, 1980.

93. J. A. O. Chagas, G. O. Crispim, B. P. Pinto, R. A. S. San Gil and C. J. A. Mota, ‘Synthesis, Characterization, and CO_2 Uptake of Adsorbents Prepared by Hydrothermal Carbonization of Chitosan’, ACS Omega, 5, 29520–29529, 2020.

94. S. Y. Foong, Y. H. Chan, C. L. Yiin, S. S. M. Lock, A. C. M. Loy, J. Y. Lim, P. N. Y. Yek, W. A. Wan Mahari, R. K. Liew, W. Peng, M. Tabatabaei, M. Aghbashlo and S. S. Lam, ‘Sustainable CO_2 capture via adsorption by chitosan-based functional biomaterial: A review on recent advances, challenges, and future directions’, Renew. Sustain. Energy Rev., 181, 113342, 2023.

95. N. Hsan, D. Ji, H. Byun, S. Kumar, M. M. Rahman, I. Hong, R. Saba, H. Lee and J. Koh, ‘Ionic interfacial engineering of chitosan–Fe_3O_4@mesoporous silica hybrids for CO_2 adsorption and epoxide cycloaddition’, J. CO_2 Util., 110, 103494, 2026.

96. E. Luzzi, P. Aprea, M. Salzano de Luna, D. Caputo and G. Filippone, ‘Mechanically Coherent Zeolite 13X/Chitosan Aerogel Beads for Effective CO_2 Capture’, ACS Appl. Mater. Interfaces, 13, 20728–20734, 2021.

97. Y. Khadiri, A. Legrand, C. Volkringer, A. Anouar, S. Royer, A. El Kadib, T. Loiseau and J. Dhainaut, ‘Graphene oxide-containing chitosan@HKUST-1 beads with increased chemical stability for CO_2 capture’, Mater. Today Sustain., 28, 100998, 2024.

98. C. Rahmatunnisa, R. I. Chaerun, C. S. Budi and N. S. Gultom, ‘Transforming Chitosan into N-Doped Carbon for Efficient CO_2 Capture: A comprehensive Review’, Appl. Surf. Sci. Adv., 27, 100774, 2025.

99. M. Azharul Islam, Y. L. Tan, M. Atikul Islam, M. Romić and B. H. Hameed, ‘Chitosan–bleaching earth clay composite as an efficient adsorbent for carbon dioxide adsorption: Process optimization’, Colloids Surf. Physicochem. Eng. Asp., 554, 9–15, 2018.

100. D. Y. Pratt, L. D. Wilson and J. A. Kozinski, ‘Preparation and sorption studies of glutaraldehyde cross-linked chitosan copolymers’, J. Colloid Interface Sci., 395, 205–211, 2013.

.

101. A. Babakhani and M. Sartaj, ‘Removal of Cadmium (II) from aqueous solution using tripolyphosphate cross-linked chitosan’, J. Environ. Chem. Eng., 8, 103842, 2020.

102. O. A. C. Monteiro and C. Airoldi, ‘Some studies of crosslinking chitosan–glutaraldehyde interaction in a homogeneous system’, Int. J. Biol. Macromol., 26, 119–128, 1999.

103. I. Tahira, Z. Aslam, A. Abbas, M. Monim-ul-Mehboob, S. Ali and A. Asghar, ‘Adsorptive removal of acidic dye onto grafted chitosan: A plausible grafting and adsorption mechanism’, Int. J. Biol. Macromol., 136, 1209–1218, 2019.

104. D. Fu, G. Wang, L. Zhao, Y. Hong, B. Yang and H. Cheng, ‘Design of ion-imprinted amino-modified chitosan for selective chromium (III) ion removal’, Sep. Purif. Technol., 336, 126341, 2024.

105. Y. Hamid, L. Liu, M. Haris, M. Usman, Q. Lin, Y. Chen, M. S. Rashid, Z. Ulhassan, M. I. Hussain and X. Yang, ‘Novel thiol-grafted composite of chitosan and rice straw biochar (TH@CT-BC): A two-step fabrication for highly selective adsorption of cadmium from contaminated water’, J. Environ. Chem. Eng., 11, 110527, 2023.

106. L. Zhang, S. Tang, F. He, Y. Liu, W. Mao and Y. Guan, ‘Highly efficient and selective capture of heavy metals by poly(acrylic acid) grafted chitosan and biochar composite for wastewater treatment’, Chem. Eng. J., 378, 122215, 2019.

107. J. Lu, S. Su, Z. Ma, T. Liu, K. Xu, J. Xu, L. Jiang, Y. Wang, S. Hu and J. Xiang, ‘Enhanced CO_2 adsorption on amine-impregnated fly ash modified by Chitosan: Performance and mechanistic insights’, Fuel, 402, 135884, 2025.

108. A. R. Nesic, S. J. Velickovic and D. G. Antonovic, ‘Characterization of chitosan/montmorillonite membranes as adsorbents for Bezactiv Orange V-3R dye’, J. Hazard. Mater., 209–210, 256–263, 2012.

109. A. Y. Alyami and A. Mahmood, ‘Synthesis, characterization and application of chitosan functionalized and functional graphene oxide membranes for desalination of water by pervaporation’, Environ. Res., 251, 118589, 2024.

110. Q. Gao, H. Zhu, W.-J. Luo, S. Wang and C.-G. Zhou, ‘Preparation, characterization, and adsorption evaluation of chitosan-functionalized mesoporous composites’, Microporous Mesoporous Mater., 193, 15–26, 2014.

111. D. Kołodyńska, ‘Adsorption characteristics of chitosan modified by chelating agents of a new generation’, Chem. Eng. J., 179, 33–43, 2012.

112. M. Saberi-Zare and M. A. Bodaghifard, ‘A Schiff base-functionalized chitosan magnetic bio-nanocomposite for efficient removal of Pb (II) and Cd (II) ions from aqueous solutions’, Int. J. Biol. Macromol., 296, 139794, 2025.

113. Q. Manzoor, M. A. Farrukh, M. T. Qamar and A. Sajid, ‘Efficient adsorption and photocatalytic removal of hexavalent chromium using chitosan-functionalized graphene oxide-MnO_2 nanocomposite’, Int. J. Biol. Macromol., 311, 144009, 2025.

.

114. O. Martínez-Rico, L. Blanco, Á. Domínguez and B. González, ‘Accessible Eco-Friendly Method for Wastewater Removal of the Azo Dye Reactive Black 5 by Reusable Protonated Chitosan-Deep Eutectic Solvent Beads’, Molecules, 29, 1610, 2024.

115. A. Guesmi, N. B. Hamadi, W. A. El-Fattah, A. Subaihi, A. A. Alluhaybi, M. G. El-Desouky and A. A. El-Bindary, ‘Efficient removal of ciprofloxacin in aqueous solutions by magnetic Se-MOF embedded within a biopolymer (chitosan/alginate): Adsorptive behavior, mechanism study, and optimization using Box-Behnken design’, Int. J. Biol. Macromol., 314, 144274, 2025.

116. X. Zheng, Y. Liu, C. Pan and Y. Guo, ‘Cationic chitosan-based magnetic adsorbent for efficient and selective doxycycline hydrochloride removal: Performance and mechanisms’, Process Saf. Environ. Prot., 208, 108499, 2026.

117. C. Zhang, H. Wen, Y. Huang and W. Shi, ‘Adsorption of anionic surfactants from aqueous solution by high content of primary amino crosslinked chitosan microspheres’, Int. J. Biol. Macromol., 97, 635–641, 2017.

118. S. Sethi, S. Thakur, D. Sharma, G. Singh, N. Sharma, B. S. Kaith and S. Khullar, ‘Malic acid cross-linked chitosan based hydrogel for highly effective removal of chromium (VI) ions from aqueous environment’, React. Funct. Polym., 177, 105318, 2022.

119. Y. Zhang, S. Lin, J. Qiao, D. Kołodyńska, Y. Ju, M. Zhang, M. Cai, D. Deng and D. D. Dionysiou, ‘Malic acid-enhanced chitosan hydrogel beads (mCHBs) for the removal of Cr(VI) and Cu(II) from aqueous solution’, Chem. Eng. J., 353, 225–236, 2018.

120. X. Fan, L. Zhang, G. Zhang, Z. Shu and J. Shi, ‘Chitosan derived nitrogen-doped microporous carbons for high performance CO_2 capture’, Carbon, 61, 423–430, 2013.

121. C. Yang, L. Luo, T. Zhao, J. Cao and Q. Lin, ‘Chitosan-Based Porous Carbon Materials with Built-In Lewis Acid Boron Sites for Enhanced CO_2 Capture and Conversion via an Electron-Inducing Effect’, ACS Appl. Mater. Interfaces, 17, 8644–8656, 2025.

122. N. Hammi, N. Couzon, T. Loiseau, C. Volkringer, A. El Kadib, S. Royer and J. Dhainaut, ‘Hierarchically porous ZIF-67/chitosan beads with high surface area and strengthened mechanical properties: Application to CO_2 storage’, Mater. Today Sustain., 22, 100394, 2023.

123. G. Nazir, A. Rehman and S.-J. Park, ‘Valorization of shrimp shell biowaste for environmental remediation: Efficient contender for CO_2 adsorption and separation’, J. Environ. Manage., 299, 113661, 2021.

124. H.L. Peng, J.-B. Zhang, J.-Y. Zhang, F.-Y. Zhong, P.-K. Wu, K. Huang, J.-P. Fan and F. Liu, ‘Chitosan-derived mesoporous carbon with ultrahigh pore volume for amine impregnation and highly efficient CO_2 capture’, Chem. Eng. J., 359, 1159–1165, 2019.

125. C. Yang, T. Zhao, H. Pan, F. Liu, J. Cao and Q. Lin, ‘Facile preparation of N-doped porous carbon from chitosan and $NaNH_2$ for CO_2 adsorption and conversion’, Chem. Eng. J., 432, 134347, 2022.

.

126. C. Yang, L. Luo, T. Zhao, J. Cao and Q. Lin, ‘Chitosan-based porous carbon material with lamellar stacking structure for efficient CO_2 adsorption and catalytic conversion’, Chem. Eng. J., 512, 162597, 2025.

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