Chitosan and Graphene Oxide-based Nanocomposites for Water Purification and Medical Applications: A Review

Vinita Khandegar, Perminder Jit Kaur, and Pratibha Chanana

Chitosan (CS) is a natural polysaccharide isolated from insects, molluscs, and fungi. The specific properties of chitosan can be enhanced using physicochemical processes. The composites prepared using CS and graphene oxide (GO) contain active functional groups such as epoxide, carboxyl, and hydroxyl, which possess excellent biocompatibility, high adsorption capacity, and biodegradability. Their low cost and ease of scale-up make them employable for multiple applications in water-treatment plants, electronics, solar cells, and pharmaceuticals. This review provides an overview of sources, types, and properties of chitin, chitosan, and graphene oxide. The use of these composites for the preparation of antimicrobial drugs has been discussed here. The article also explores the applicability of such composites for removal of heavy metals (lead, copper, chromium, cobalt, mercury, etc.), dyes (methylene blue and other reactive dyes), and organic and inorganic contaminants (ofloxacin, naphthanol, phenol, and oil, etc.). The article highlights various knowledge gaps in the field and the scope of future work.

Keywords: Chitosan; Graphene oxide; Nanocomposite; Water purification; Medical applications

Contact information: a: University School of Chemical Technology, Guru Gobind Singh Indraprastha University, New Delhi, 110078, India; b: Centre for Policy Research, Department of Science and Technology, New Delhi, 110016, India; *Corresponding author: perminder.dua@gmail.com

INTRODUCTION

Polymer-based nanocomposites have applications in various fields such as wastewater treatment, electronics, energy, pharmaceuticals, and medicine. Low cost, high recyclability, biocompatibility, ease of degradability, and scalability make bio-based, commonly available, natural polymers such as chitosan (CS) materials of choice for multiple fields ranging from wastewater treatment to medicinal applications (Dutta et al. 2004; Cheung et al. 2015; Palza 2015). Their high affinity for metals, organic and inorganic particles coupled with the higher surface area makes them promising materials for the removal of contaminants from wastewater (Chen et al. 2013; Schwarz et al. 2016; Singh et al. 2019; Suri 2020; Suri et al. 2021; Upadhyay et al. 2021). In combination with graphene oxide (GO) and inorganic nanoparticles such as ZnO, Fe₃O₄, GO, and TiO₂, it is possible to introduce additional functional groups that can increase their chelation capacity, improve the surface area and active sites, and assist in further modification of their properties (Kyzas and Bikiaris 2015; Morsy 2015; Salam 2017; ZabihiSahebi et al. 2019).

The presence of heavy metals in soil and water is a significant threat to the ecosystem. Heavy metals, dyes, and inorganic pollutants are widespread through various sources and taken up by plants in the environment. As a result, they enter into the food chain and are ingested by humans and animals. Consistent efforts are being made to
effectively remove contaminated water and soil samples (Chauhan et al. 2020). Various heavy metals like copper, chromium, and mercury are removed from contaminated samples using composting, landfarming, coagulation, flocculation, membrane separation, and adsorption processes (Kaur et al. 2020). Attempts have been made in the literature to develop green adsorbents for wastewater treatment.

Cs and GO are promising materials with unique properties such as biocompatibility, safety, and antimicrobial capacity. They are also proven to be effective as drug delivery agents. Attempts on forming nanocomposites made from natural materials such as CS and GO in various ways have yielded properties even better than individual CS or GO used alone (Ates et al. 2020). Thus, the present literature study covers the essential aspects of CS and GO-based nanocomposites and their applicability in the specified areas. It explores the sources, types, and properties of CS and GO. The applications of modified CS-GO-based composites for removing heavy metals, dyes, and pollutants from wastewater are reviewed. An overview of its antimicrobial properties and potential as a medium for drug delivery is also presented. This information can serve as a reference document for technologists and scientists to research and develop new systems based on Cs-GO nanocomposites (Ahmad et al. 2017).

ORIGIN AND SOURCES OF CHITIN AND CHITOSAN

The word chitin is derived from the Greek word “Chiton”, meaning covering or envelope. It was discovered as a new polysaccharide and reported for the first time in 1811 by French professor Henri Bracoonot as fungine while researching edible mushrooms. Later, in 1823, Antoine Odier named it chitine because of its unique presence in insects' cuticles (Crini 2019). Later, its structure was determined by Albert Hofman (Hofmann 1979). In 1859, Charles Rouget described deacetylation of chitin to obtain a modified form of chitin, which was later termed chitosan by Hoppe-Seyler in 1894 (Crini 2019). The polysaccharides chitin and chitosan are made up of amino sugars D-glucosamine and N-acetyl-D-glucosamine. The ratio of amino sugars D-glucosamine and N-acetyl-D-glucosamine indicates whether the polysaccharide is considered chitin or chitosan (Brigham 2017). Chitosan is a linear cationic copolymer consisting of alternating units of N-acetyl-glucosamine (20%) and D-glucosamine (~80%) obtained by deacetylation of chitin, whereas chitin is a linear polymer composed of repeated units of β-1,4-linked N-acetylglucosamine (50%) (Philibert et al. 2017; Hahn et al. 2020b). Both polymers have exclusive properties and find applications in various fields (Cheung et al. 2015; Younes and Rinaudo 2015). Chitin consists of huge crystalline nitrogen-containing polysaccharides with an estimated production of about $10^{11}$ to $10^{14}$ tons per annum (Bastaens et al. 2019). Due to versatility and accessibility, chitin is the second most abundant polysaccharide after cellulose and hemicellulose.

The primary sources of chitin and chitosan are shown in Fig. 1. The most common source of chitin is shellfish and other aquatic invertebrates. These species are found in considerable quantities in the fish processing industry (Yadav et al. 2019). Chitin is located in the exoskeleton of sea animals such as annelids, molluscs, coelenterate, crustaceans (crabs, shrimps, and lobsters), and insects such as honey bee, silkworms, scorpions, spiders, ants, beetles, and cockroaches as supporting tissues of organisms (Kaur and Dhillon 2014). The content of chitin is highest in shrimp cuticle and squid pen waste, ranging from 15 to 40% as compared to other crustacean waste since shrimps have a thinner shell wall than
lobsters and crabs (Tharanathan and Kittur 2003; Wang et al. 2020; Tan et al. 2020; Khayrova et al. 2021; Kou et al. 2021). While insects are a viable substitute source for chitin, being an abundant species globally, a lower quantity of chitin is extracted from fungi such as *F. fomentarius* and *L. vellereus* (Bastaens et al. 2019, Sagheer et al. 2009). A significant part of the head and shell waste is obtained only from shrimp (about 60%). At the same time, the cuticle can contain up to 80% chitin (Pal et al. 2014). The amount of chitin depends on the type of species, body part, season, and growth rate.

In contrast, chitosan is a partially deacetylated copied form of chitin (Letourneau et al. 1976). Chitosan content of 1 to 10% on dry biomass base has been found, with a reported degree of deacetylation of 83 to 94%. Chitosan is produced synthetically by converting chitin in the presence of a deacetylase enzyme (Dhillon et al. 2013).

In addition to fungi, bacteria can be used for the production of chitosan using enzymatic deacetylation. Kaur and Dhillon (2014) isolated chitosan from soil bacteria (*Bacillus sp.* and *Serratia sp.*) through chitin’s deacetylation. However, the efficiency of this process is affected by the insolubility and degradation of chitin (Aranaz et al. 2009). In addition, Kaur et al. (2012) suggested that the fast-growing bacteria or the isolated enzymes can be used for natural chitosan production. Over 10 billion tons of chitin are produced annually from the seafood processing industry (Casadidio et al. 2019). Chitin and chitosan are now extracted commercially in India, Japan, Poland, Australia, and the US. In the future, chitin’s production rate will increase significantly due to increased waste generation of insects, exuviae, and exoskeletons. More research is required for surplus sources and utility of chitin/chitosan in the near term (Dutta et al. 2004).

Three types of crystal-like forms of chitin α, β, and γ (mixer of α and β chitin) are found in nature (Aam et al. 2010). Different types of chitin allomorphs are shown in Fig. 2. Of these, α chitin is typically isolated from the shells and the exoskeleton of crustaceans, insect cuticles, shrimps, crab, and lobsters (Kaur and Dhillon 2014; Yadav et al. 2019). In

---

**Fig. 1. Sources of chitin and chitosan**

In addition to fungi, bacteria can be used for the production of chitosan using enzymatic deacetylation. Kaur and Dhillon (2014) isolated chitosan from soil bacteria (*Bacillus sp.* and *Serratia sp.*) through chitin’s deacetylation. However, the efficiency of this process is affected by the insolubility and degradation of chitin (Aranaz et al. 2009). In addition, Kaur et al. (2012) suggested that the fast-growing bacteria or the isolated enzymes can be used for natural chitosan production. Over 10 billion tons of chitin are produced annually from the seafood processing industry (Casadidio et al. 2019). Chitin and chitosan are now extracted commercially in India, Japan, Poland, Australia, and the US. In the future, chitin’s production rate will increase significantly due to increased waste generation of insects, exuviae, and exoskeletons. More research is required for surplus sources and utility of chitin/chitosan in the near term (Dutta et al. 2004).

Three types of crystal-like forms of chitin α, β, and γ (mixer of α and β chitin) are found in nature (Aam et al. 2010). Different types of chitin allomorphs are shown in Fig. 2. Of these, α chitin is typically isolated from the shells and the exoskeleton of crustaceans, insect cuticles, shrimps, crab, and lobsters (Kaur and Dhillon 2014; Yadav et al. 2019). In
α chitin, polysaccharide chains are organized in an antiparallel direction, allowing maximum bonding. Hence, α chitin is highly stable, having a high degree of crystallinity (80%). β chitin is usually found in squid pens, aphrodite chaetae, seaweeds, protozoa (Sagheer et al. 2009; Hajji et al. 2014). Here, polysaccharide chains are organized in parallel, with a crystallinity index of 70%. The target distance between the adjacent polymer chains makes it more reactive and soluble in solvents (Yadav et al. 2019). The γ-chitin exists mainly in fungi and yeast. It is recognized by two parallel and one antiparallel sheet arrangement.

**Fig. 2. Different types of Chitin Allomorphs**

### PROPERTIES OF CHITIN AND CHITOSAN

CS is more versatile than chitin due to amino groups at the C-2 positions (Dutta et al. 2004). Modification of chitin and CS help in the increasing of its solubility and versatility (Ishihara et al. 2012). Both chitin and CS can form films, chelate with metals, and moderate water permeability (Dutta et al. 2004). Due to low toxicity and digestibility, they can be used as food additives. Also, they are shown to be helpful to lower cholesterol in human blood (Knoor 1983). Both prevent the invasion of pathogens. However, chitosan is known to exhibit better properties and thus applicability than chitin. Chitin is a white, rigid, inelastic, nitrogenous polysaccharide (5 to 7% nitrogen). Being hydrophobic, it is insoluble in water and organic solvents. Due to its one reactive amine and two hydroxyl groups, chitosan has higher solubility, hydrophilic character, and adsorption capacity than chitin. CS is also soluble in aqueous solutions of acids. Solubility in aqueous solution gets further enhanced by N-alkylidinations and N-acetylation (Muzzarelli 1997). It has an extensive semicrystalline structure. It has low immunogenicity and binds to mammalian and microbial cell aggregates (Dutta et al. 2004; Cheung et al. 2015). CS also displays mucoadhesive film-forming and chelating activity (Patra et al. 2018). The pH sensitivity and high biological compatibility of chitosan motivate researchers to explore its application in drug delivery systems, especially for cancer treatment (Dutta et al. 2004; Philibert et al. 2017; Yassue-Cordeiro et al. 2018; Ramachandran et al. 2019). Due to its long shelf-life and ability to form semipermeable, rigid, permanent and impermeable films, it can be used to wrap food products (Muzzarelli et al. 1986). CS is effective to remove endotoxins found in proteins as contaminants. Endotoxins are pH and heat stable and are not easily destroyable using normal sterilising conditions. CS can interact with endotoxins and help
in downstream protein purification processes (Wang et al. 2013a).

CS is biocompatible, non-toxic, biodegradable, and has broad-spectrum antimicrobial activities (Jiang et al. 2014). The antifungal activity of CS is higher than chitin (Limam et al. 2011). CS can promote bone formation because it can be shaped into structures and geometries suitable for cell in-growth and post-growth conditions (Figueiredo et al. 2015). With unique biological activities, including analgesic, antitumor, haemostatic, and antioxidant properties, CS finds application in the biomedical field (Brigham 2017; Casadidio et al. 2019).

METHODS OF EXTRACTION OF CS

The chitosan family consists of different D-N-deacetylated forms of chitin, and its properties are highly dependent on the degree of deacetylation and its molecular weight (Younes and Rinaudo 2015; Philibert et al. 2017). CS is extracted from chitin through demineralization, deproteinization, deacetylation, and decolourization using chemical or biological processes such as enzymatic treatment or fermentation. It can be synthesized through nitrogen and oxygen substitution, copolymerization, and numerous other methods (Wang et al. 2016, 2020).

The difference in alkali solution concentration, reaction time, temperature, chitin/alkali solution ratio, CS with different degrees of deacetylation can be obtained. The degree of acetylation represents the percentage of N-acetyl-d-glucosamine units to the total number of units. Hence for CS, the percentage degree of acetylation is below 50. Acetyl groups are removed arbitrarily, and a de-polymerization reaction occurs, which is indicated by changes in the molecular weight of CS. Various methods for the extraction of chitin and CS have been reported, although no standard practice has been implemented. However, demineralization and deproteinization are mostly chosen either using chemicals or biological agents. Few studies for extraction of chitin and chitosan using chemical and biological extraction are discussed below.

Different researchers have investigated various chemicals and solutions to extract CS and chitin. Deproteinization is a fundamental step used to extract protein, while demineralization is an acidic step used to remove the inorganic calcium carbonate (Khanafari et al. 2008; Tan et al. 2020). In the demineralization process, hydrochloric acid, nitric acid, sulfuric acid, acetic acid, and formic acid are used. In contrast, the alkaline method for deproteinization is commonly used for protein extraction (Brine and Austin 1981). Figure 3 explains the general procedure used for the extraction of chitin from crab and shrimp waste.
Chitin can be processed chemically as well as biologically to produce chitin, as shown in Fig. 4. While deacetylation is done with sodium hydroxide in chemical processes, biological processes utilise lactic acid bacteria for the same. Researchers have tried to modified these processes using different agents under different reaction conditions. The extraction of chitin and CS is affected by the body parts and the type of organism used. Biological methods of CS extraction use fermentation processes for shrimp or other
organism waste. The solid and liquid fraction can be separated to allow for chitin extraction. Demineralization and protein removal steps can be done, as was in the chemical procedure. Nessa et al. (2010) extracted chitosan from sun-dried prawn shells by producing coarse particles in a centrifugal grinding machine. Some coarse particles were demineralized with 10% HCl acid at 27 °C for 22 h. Deproteinisation was done using NaOH solution for 24 h at 70 °C, then decolourisation and drying under vacuum. A crispy powder of chitin was produced. Deacetylation of chitin was attained using NaOH for 45-72 h. The resulting chitosan was rinsed with distilled water and oven-dried. The yield of chitin was 20%, and CS was 19.6%. Tarafdar and Biswas (2013) reported extraction using two different prawn shells and shrimp waste. In the first method, 10 g of prawn shell waste was washed and demineralized by adding 1.5 N HCl at 25 °C for 1 h followed by deproteinisation with 0.5 to 3% NaOH at 100 °C for 30 min. Deacetylation of chitin produced CS, which was prepared by treating with 42% aqueous NaOH at 95 °C for 1.5 h and washed then dried. In the second method, 5 g of shrimp waste was soaked then deproteinized in an aqueous NaOH solution at 25 °C for 21 h. The deproteinized shell was demineralized by 4% HCl at 25 °C for 12 h. The chitin was dried at ambient temperature. CS was obtained by treating chitin with 50% aqueous NaOH at 40 °C for three days. CS was dried at ambient temperature. The overall procedures used in chemical, biological methods investigated in literature using insects, shellfish and fungi are shown in Fig. 5.

Mohammed et al. (2013) extracted chitin and CS from prawn shells. Initially, frozen prawn shells were washed with boiled water then dried at 60 °C. The dried prawn shells were crushed and treated with 5% NaOH and refluxed at 60 °C for 2 h, followed by acetone treatment to remove colours at 25 °C for 24 h. To dissolve the calcium carbonate, these were further treated with a 0.5 or 1% HCl solution for 24 h at 25 °C. Chitosan was
obtained by deacetylation process using NaOH solution at elevated temperature and concentration. After the procedure, chitosan was washed several times with distilled water and dried at 60 °C in a vacuum oven. Figure 6 depicts the relative comparison of chemical and biological processes to produce chitosan. While chemical extraction methods are quick, consume less time, and are applied on a commercial scale, they consume more energy and make protein components unsuitable for animal feed. As an alternative, biological processes offer the advantage of environmental safety and the production of valuable by-products for animal feed. Investigations to reduce the processing time and cost is still underway.

<table>
<thead>
<tr>
<th>Chemical Extraction</th>
<th>Biological Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short time processing</td>
<td>More environment friendly, safer</td>
</tr>
<tr>
<td>Chemical methods are currently being applied in commercial scale</td>
<td>Produce high-value commercial by-products</td>
</tr>
<tr>
<td>Energy consuming</td>
<td>Less economic</td>
</tr>
<tr>
<td>Extremely hazardous</td>
<td>Lengthy procedure</td>
</tr>
<tr>
<td>Unsuitable protein components as animal feed</td>
<td>Still not in commercial scale</td>
</tr>
</tbody>
</table>

**Fig. 6.** Comparison of chemical and biological extraction methods

**Table 1.** Chitin and Chitosan Extraction from Different Species

<table>
<thead>
<tr>
<th>Source</th>
<th>Chitin (%)</th>
<th>Chitosan (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bombyx mori</td>
<td>15 to 20</td>
<td>70 to 80</td>
<td>(Zhang et al. 2000)</td>
</tr>
<tr>
<td>Bombyx mori</td>
<td>2.59 to 4.23</td>
<td>73% to 96.75</td>
<td>(Paulino et al. 2006)</td>
</tr>
<tr>
<td>Mud crab Scylla</td>
<td>Carapace: 10.74</td>
<td>6.59</td>
<td>(Thirunavukkarasu and Shanmugam 2009)</td>
</tr>
<tr>
<td>tranquebarica</td>
<td>Claw: 7.91; Legs: 14.62</td>
<td>4.12; 8.42</td>
<td></td>
</tr>
<tr>
<td>Zophobas morio</td>
<td>35</td>
<td>25</td>
<td>(Mohammed et al. 2013)</td>
</tr>
<tr>
<td>Leptinotarsa</td>
<td>7 to 20</td>
<td>67 to 72</td>
<td>(Kaya et al. 2014)</td>
</tr>
<tr>
<td>decemlineata</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shrimp</td>
<td>20</td>
<td>14.9</td>
<td>(Hajji et al. 2014)</td>
</tr>
<tr>
<td>Crab</td>
<td>10</td>
<td>5.3</td>
<td>(Hajji et al. 2014)</td>
</tr>
<tr>
<td>Cuttlefish</td>
<td>5</td>
<td>1.2</td>
<td>(Hajji et al. 2014)</td>
</tr>
<tr>
<td>Fomitopsis pinicola</td>
<td>30.11</td>
<td>71.75</td>
<td>(Kaya et al. 2015)</td>
</tr>
<tr>
<td>Gryllus bimaculatus</td>
<td>2.35</td>
<td>1.79</td>
<td>(Kim et al. 2017)</td>
</tr>
<tr>
<td>Zophobas morio</td>
<td>4.8 to 5.4</td>
<td>66 to 76</td>
<td>(Soon et al. 2018)</td>
</tr>
<tr>
<td>Brachytrupes</td>
<td>4.3 to 7.1</td>
<td>2.4 to 5.8</td>
<td>(Ibitoye et al. 2018)</td>
</tr>
<tr>
<td>portentosus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macropipus</td>
<td>12.23</td>
<td>9.52</td>
<td>(Pădurețu et al. 2019)</td>
</tr>
<tr>
<td>holstaus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potamon algeriense</td>
<td>8.27</td>
<td>5.89</td>
<td>(Fadlaoui et al. 2019)</td>
</tr>
<tr>
<td>Hermetia illucens</td>
<td>46</td>
<td>80</td>
<td>(Khayrova et al. 2019)</td>
</tr>
<tr>
<td>Hermetia illucens</td>
<td>9 to 30</td>
<td>18 to 29</td>
<td>(Khayrova et al. 2020)</td>
</tr>
<tr>
<td>Hermetia illucens</td>
<td>83 to 87</td>
<td>13 to 43</td>
<td>(Hahn et al. 2020a)</td>
</tr>
</tbody>
</table>
Table 1 lists previous work on chitin and chitosan extraction from different species (Bolat et al. 2010; Limam et al. 2011; Isa et al. 2012). Sagheer et al. (2009) extracted protein content in chitin from the crustaceans of Arab Gulf states. Similarly, Abdou et al. (2008) reported the production of chitin and its various derivative from crustaceans. Bolat et al. (2010) reported the extraction and characterization of chitin and chitosan from the crab. Though different experimental conditions are found in the literature, mild conditions are preferable to obtain chitin and chitosan with a high percentage of the degree of acetylation (Percot et al. 2003).

**SPECIFIC PROPERTIES OF CS-GO COMPOSITES**

Graphene oxide (GO), a novel 2D nanomaterial, is mainly produced by the modified Hummers method from natural graphite powder. For many years it attracted significant attention due to having various properties such as being readily exfoliated into monolayer sheets, hydrophilic functional groups on its basal planes and edges, interfacial interactivity with a target matrix, and electronic properties. Covalently grafting CS onto GO sheets improves the solubility of graphene. Many researchers grafted or crosslinked the CS onto GO. Various researchers synthesised or prepared the different types of CS-GO materials such as nanoparticles, green adsorbents, casting on membranes, hydrogel and aerogels. Some of the studies are discussed here to provide insight into the chemistry of CS-GO. Studies have shown the solid electrostatic interactions occurred between the cationic CS and the negatively charged GO composites (Suri and Khandegar 2021). Horseradish-peroxidase (HRP) was adsorbed onto CS-GO through covalent bonding, which assisted in enhancing the mechanical strength of HRP at a reasonably low cost. The reusability studies specified that the HRP-CS-GO could be reused for a minimum of 5 cycles (Suri et al. 2020). Researchers have designed CS nanoparticles embedded into GO to be used for a drug delivery system. The XRD analysis showed that the composite has an amorphous structure bonded with intramolecular hydrogen bonding and excellent porous, rough surface morphology and flaky structure, as shown in Fig. 7 (Hosseini et al. 2021).

![Fig. 7. Methods of synthesis of CS-GO for drug delivery system (Hosseini et al. 2021)](image)
APPLICATIONS OF CHITOSAN COMPOSITES

Polyfunctional CS is an organic molecule that is used in a wide range of applications. The chemical modification of CS increases the selectivity and adsorption potential of the target; amendment adjusts the Lewis basicity by introducing functional groups. These groups are different in donor ability than the amine and hydroxyl groups. Improvement can be carried out with or without crosslinking agents. Various forms of chitosan and adsorbent synthesis techniques are given in Fig. 4. GO has distinctive properties including high conductivity, flexibility, and controllable permittivity with hydrophilicity (Kostarelos and Novoselov 2014). These properties facilitate the development of GO-based multifunctional biomedical devices. Therefore, GO has been developed in different sizes and forms by the chemical modifications process. GO is made by chemical exfoliation of graphite powders through strong oxidants (Wang et al. 2013b). It shows high specific surface area (e.g. 2,600 m²/g) (Sponza and Alicanoglu 2017). This property can help as a support medium to make the nanoparticles without accumulation in the adsorption process. Graphene consists of a single layer of sp² bonded carbon atoms. Graphene is the thinnest material and the most robust material due to its particular thermal, mechanical, optical, and electrical properties (Geim 2009). Oxygen functionalities in GO permit the interactions with the positive ion and provide active sites for the nucleation and growth of nanoparticles (Guria et al. 2016).

Fig. 8. Forms and modification of chitosan to improve its properties

GO has plenty of functional groups and high mechanical strength as the prospective material for removing heavy metals (Menazea et al. 2020). However, inter-functional solid bonds between graphene sheets result in static surface chemical properties, lower surface area, and poor aqueous solutions dispersion. Reduced adsorption efficiency limits its use in wastewater treatment (Li et al. 2009b). CS and GO-based nanocomposites can be used in several cosmetics, as a fixative in photography, and as an adsorbent and flocculating agent in wastewater treatment, in the paper and textile units agriculture sector (Dutta et al. 2004; Philibert et al. 2017). Chemical, physical, or combinations of both modes of modification are used for CS. The physical transformation comprises blending and conversion of chitosan’s forms. The physical change leads to expansion of the polymer
chains of chitosan. As a result, internal sorption sites increase, and their crystalline state decreases. Blending chitosan with active carbon, graphene, Fe₃O₄, γ-Fe₂O₃, and clay is another suitable method for synthesizing better strength, adsorption, sensitivity, and magnetism property nanocomposite (Badry et al. 2017; Wang and Zhuang 2017). Chitosan modifications by chemical treatments are either crosslinking or graft co-polymerisation. Chemical changes improve complex formation properties with metal ions and surfactants (Rinaudo 2006; Alves and Mano 2008). Different cross-linkers such as epichlorohydrin, tripolyphosphate, and glutaraldehyde are used to modify (Mojiri et al. 2019). Homogeneous crosslinking of chitosan improves metal binding capacity relative to heterogeneous cross-linking (Varma et al. 2004). Figure 8 shows the different forms and modifications of CS, which can help to strengthen its properties.

**Biomedical Applications**

A drug delivery system is defined as a formulation or a device that enables the administration of a therapeutic substance or active pharmaceutical ingredient in the body, improves its efficacy as well as safety by controlling the rate, time, and place of release of drugs (Jain 2020). Researchers have investigated the potential of nanoparticles such as dendrimers, liposomes, self-assembling peptides, water-soluble polymers, and polymeric micelles as effective drug delivery agents. They find unique applications for cancer treatment where nanoparticulate drug carriers improve cure efficacy by reducing off-target systemic toxicity and passive drug targeting to tumour cells or tissues (Yu et al. 2016; Edgar and Wang 2017). Graphene oxide (GO), reduced graphene oxide, and graphene quantum dots have shown high surface area, which provides sufficient drug loading capacity along with biocompatibility. Functionalization of GO or reduced GO with polyethylene glycol, mannose, and sulfonic acid conjugated to folic acid has improved biodegradability, biocompatibility, and thermosensitivity, facilitates pH-dependent and targets specific controlled release of the drug to tumour cells (Karki et al. 2020). Also, GO displayed low uptake in the reticuloendothelial system and extended blood circulation time (Zhao et al. 2018). Still, these GO-based nanocomposite systems have limitations related to drug solubility (colloidal instability due to aggregation), controlled and targeted drug release to cancer cells, hemolytic properties, and in vivo toxicity (McCallion et al. 2016; Karki et al. 2020). Extensive research is being carried out to identify new and novel functional groups for GO modifications, where CS has emerged as an excellent helpful natural modifier of GO. CS-based nanocomposites are biocompatible, non-toxic, and display increased drug efficacy (Thakur and Thakur, 2014). Due to their small size, these nanoparticles or nanocomposites can move through blood-brain barriers, thus using efficient drug delivery systems (Li et al. 2018). Despite the above advantages, owing to its low solubility and poor mechanical properties, the application of CS is still minimal. Different formulations of CS and its composites with several other compounds are being worked upon to increase targeted drug action and efficacy for drug delivery systems (Ali and Ahmed 2018; Li et al. 2018; Ashrafizadeh et al. 2019).

**Drug delivery system**

Derivatized chitosan has been used to modify GO to prepare nanocomposites for drug delivery to cancerous cells. Rana et al. (2011) developed chitosan-graphene oxide nanocomposites. The chitosan-functionalized graphene oxides served as a drug delivery system, which was loaded with Ibuprofen and 5-fluorouracil. It displayed controlled release and long term biocompatibility in human lymphoblastic leukemia and MCF7-human breast
cancer cells. Another functionalized nanocarrier based on CS-GO nanocomposite was prepared by Bao et al. (2011) through the amidation process. CS-GO nanocomposite was applied to load the anti-cancer drug Camptothecin. Cell toxicity was analyzed against HepG2 and HeLa cancer cells using MTT assay, where a 50% growth inhibition concentration was observed at 29 µm. Thus, the novel nanocarrier was potent against cancer cells. An in vitro drug release experiment showed that 17.5% camptothecin could be released. This CS-GO nanocomposite camptothecin complex exhibited enhanced stability and a high loading capacity.

Yang et al. (2016) modified GO with carboxymethyl chitosan and further conjugated it with hyaluronic acid and fluorescein isothiocyanate. This conjugate combination was used as a drug delivery vehicle for doxorubicin, a model anti-cancer drug, to study in vitro release behaviour. It specifically targeted cancer cells and inhibited the growth of HeLa, CD44 overexpressing cells. It exhibited pH-dependent release and a drug loading efficiency of 95%. Pan et al. (2016) developed a GO-CS nanocomposite by conjugating GO with carboxymethyl chitosan, fluorescein isothiocyanate, and lactobionic acid to be used as a targeted anti-cancer drug delivery system; nanocomposite without LA conjugate was used as the control. Functional group lactobionic acid is recognized explicitly by asialoglycoprotein receptors overexpressed on cancerous hepatic cells. High drug loading content and efficiency of >96% was observed in SMMC-7721 cancer cells. The pH-sensitive release of the nanocomposite was followed, which is typical due to reduced pH microenvironment of cancerous cells. Higher uptake was observed using this nanocomposite for SMMC-7721 cancer cells through confocal microscopy and cell toxicity assays, strengthening its use as an anti-cancer drug delivery system. Further, Wang et al. (2018) synthesized a galactosylated CS-GO-doxorubicin drug delivery system against hepatocellular carcinoma. The action of the synthesized composite was investigated against HepG2 and SMMC-7721 hepatocarcinoma cell lines. After coating glycosylated-CS over the surface of GO, drug loading capacity was found to be 98%. Drug release to hepatic carcinoma cells was studied using cellular assays such as cell proliferation and cellular uptake assay. An in vivo anti-tumour efficacy study showed efficient inhibition of tumour cells as compared to control. The above drug conjugated system might be used as biomedicine and may effectively target liver cancer cells.

In another study, developed chitosan/sodium alginate products were functionalized using magnetic GO-based nanocomposites and were loaded with doxorubicin. The functionalized magnetic graphene oxide nano sheets have high drug loading efficiency (Xie et al. 2019). A nanocarrier system based on reduced GO was loaded with doxorubicin and coated with CS for stabilization was developed, which displayed high biocompatibility and efficiency for entrapping doxorubicin (~65%) and depicted controlled release (~50% release in 48 h). Furthermore, it was demonstrated to precisely deliver doxorubicin intracellularly in PC-3 prostate cancer cells with cytotoxicity >65% (SreeHarsha et al. 2019). Researchers have also synthesized folic acid coupled CS and GO nanocomposites. These composites were used for loading polyprenol and fullerene. They depicted good drug loading and encapsulation efficiency, drug release property, and storage stability. Also, cytotoxicity analysis of this nanocomposite in human hepatic cell line MHCC97H, exhibited greater inhibition capacity than regular human hepatic non-cancerous cell line (Tao et al. 2019). Shi et al. (2016) also prepared carboxymethyl-CS-GO-based nanoparticles using the electrostatic droplet generation method, which effectively adsorbed gatifloxacin, ofloxacin bovine serum albumin, lysozyme, and doxorubicin hydrochloride (Tao et al. 2019). Very recently, Anirudhan et al. (2020) synthesized CS and folic acid
nanocomposite by conjugating through $N,N'$-dicyclohexylcarbodiimide coupling. Furthermore, itaconic acid and acrylic acid monomers were grafted to the hydroxyl groups of prepared nanocomposites to generate -COOH functional groups and combined with modified amine GO. Further, the anti-tumour drug was loaded onto the modified amine CS-GO conjugated folic acid nanocomposite through π-π stacking and hydrogen bonding interactions. The loading capacity of doxorubicin in the polymeric matrix was determined to be 95%. An advanced CS-GO hybrid-responsive system of enhanced biocompatibility, high doxorubicin-loading ability, and tumour-inhibition efficacy was developed.

**Table 2. CS-GO Nanocomposites with Chemotherapeutic Activity Against Cancer Cells**

<table>
<thead>
<tr>
<th>Nanocomposite/Drug Composite</th>
<th>Drug Conjugated</th>
<th>Type of Cancer or Cancer Cell Line</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-GO</td>
<td>Camptothecin</td>
<td>HepG2 and HeLa cell lines</td>
<td>Bao et al. (2011)</td>
</tr>
<tr>
<td>Chitosan-functionalized GO</td>
<td>Ibuprofen and 5-fluorouracil</td>
<td>CEM human lymphoblastic leukemia and MCF7-human breast cancer</td>
<td>Rana et al. (2011)</td>
</tr>
<tr>
<td>GO conjugated with Carboxymethyl chitosan, hyaluronic acid and fluorescein isothiocyanate</td>
<td>Doxorubicin</td>
<td>HeLa, CD44 over-expressed cells</td>
<td>Yang et al. (2016)</td>
</tr>
<tr>
<td>GO conjugated with carboxymethyl chitosan, fluorescein isothiocyanate, and lactobionic acid</td>
<td>Doxorubicin</td>
<td>SMMC-7721 cancer cells</td>
<td>Pan et al. (2016)</td>
</tr>
<tr>
<td>Functionalized GO with CS sodium alginate</td>
<td>Doxorubicin</td>
<td>MCF-7 Human Breast cancer cell line</td>
<td>Lei et al. (2016)</td>
</tr>
<tr>
<td>Galactosylated CS-GO-doxorubicin</td>
<td>Doxorubicin</td>
<td>HepG2 and SMMC-7721 hepatocarcinoma cell lines</td>
<td>Wang et al. (2018)</td>
</tr>
<tr>
<td>Dispersion of GO Ag nanohybrid particles in the chitosan hydrogel matrix</td>
<td>Doxorubicin</td>
<td>Human colon cancer cells (SW480)</td>
<td>Rasoulzadehza li and Namazi (2018)</td>
</tr>
<tr>
<td>Magnetic GO nanosheets functionalized with CS and sodium alginate through non-covalent layer-by-layer self-assembly</td>
<td>Doxorubicin hydrochloride</td>
<td>Human lung cancer cell line (A549)</td>
<td>Xie et al. (2019)</td>
</tr>
<tr>
<td>Folic acid coupled CS-GO</td>
<td>Ginkgo Biloba Leaves polyphenol and Fullerene (C60F)</td>
<td>MHCC97H</td>
<td>Tao et al. (2019)</td>
</tr>
<tr>
<td>Chitosan-based hybrid nanoparticle of DOX-loaded reduced form of GO</td>
<td>Doxorubicin</td>
<td>Prostate cancer cells PC-3</td>
<td>SreeHarsha et al. (2019)</td>
</tr>
<tr>
<td>Amine functionalized GO conjugated with chemically modified CS with folic acid</td>
<td>Doxorubicin</td>
<td>MCF7 and Hela cells</td>
<td>Anirudhan et al. (2020)</td>
</tr>
</tbody>
</table>
For hybrid preparation, deprotonated carboxyl of GO nanoparticles and the protonated amine of CS’s backbone were allowed to self-assemble. The developed hybrid was loaded with doxorubicin and displayed charge reversal from negative charge during blood circulation (pH 7.4) to positive charge at tumour extracellular microenvironment (pH 6.5). Biocompatibility, cell toxicity, in-vitro triggered release, and intracellular uptake of the prepared nanocomposite were studied in HepG2 cells; cell viability of HepG2 cells upon treatment the nanohybrids were found to be around 96% (Zhao et al. 2018). Another drug delivery system was synthesized by Rasoulzadehzali and Namazi (2018) by dispersion of GO-Ag particles in the CS-based hydrogel matrix for controlled release of doxorubicin, and a sustained-controlled drug release profile was observed. Additionally, Lei et al. (2016) developed another nanocarrier with functionalized graphene oxide, chitosan, and sodium alginate. The composite displayed significant pH-dependent doxorubicin release behaviour and cytotoxicity in MCF7 anti-cancer cells.

Over the last decade, different research groups have used vivid strategies to generate CS-GO drug delivery systems with many drugs, as summarized in Table 2. These studies support the application of graphene-chitosan based material as a chemotherapeutic agent. These new drug delivery systems promise targeted delivery, controlled release, and enhanced therapeutic efficiency of many anticancer drugs for cancer treatment.

**Antimicrobial properties**

Microbial infection is responsible for a plethora of diseases. Anti-microbials are agents that target microbes such as bacteria, fungi, protozoans, and viruses. Antibiotics are used widely to treat bacterial infections; however, antibiotic resistance has become a significant public health challenge as multidrug-resistant microorganisms are steadily rising. Nanotechnology-based antibiotics or nanobiotics have promising results in targeting antibiotic resistance in several diseases. These nanoparticles act through multiple mechanisms, load multiple drugs onto a single nanoparticle, thereby reducing the chances of antibiotic resistance. Metal-containing nanoparticles, chitosan-containing nanoparticles and graphene-based nanoparticles, cationic liposomes, and dendrimers are a few examples (Pelgrift and Friedman 2013; Gómez-Núñez et al. 2020; Vassallo et al. 2020). Due to its structure, graphene has intrinsic anti-bacterial activity. Hence in nanoparticles based on graphene, bacterial cell walls and membranes are damaged by sharp edges of graphene, leading to the release of intracellular content followed by bacterial cell death. The generation of reactive oxygen species has been speculated as another cause (Gómez-Núñez et al. 2020).

The antimicrobial effectiveness of CS-containing nanoparticles is probably due to their cationic nature. These particles associate with negatively charged cell walls or membranes on bacterial cells, altering their permeability leading to efflux of cytoplasmic contents and eventually bacterial cell death. These nanoparticles can associate with negatively charged bacterial DNA and chelates metal ions necessary for the functioning of enzymes and membrane integrity, thereby exerting solid antimicrobial activity (Pelgrift and Friedman 2013; Yilmaz Atay 2019). CS-GO based nanocomposites display intense antimicrobial action against bacteria, fungi, and yeasts. Over the last decade, many research groups have developed several CS-GO-based nano-composites with different functional groups having potent anti-microbial activity. Keshvardoostchokami et al. (2020) synthesized GO-based silver nanocomposites, where CS was used as a substrate. A broad-spectrum antibacterial activity of these nanocomposites was observed against both Gram-positive (C. glutamicum) and gram-negative bacterium (E. coli strain DH5α).
Approximately 5 µL (2 g/L) of the nanocomposite efficiently reduced 10^8 colony-forming units (CFU)/ml to zero. An antimicrobial biofilm from CS-iron oxide coated GO hydrogel (CH-GIO) displayed robustness and, during characterization, showed significantly improved mechanical and thermal properties. Hydrogel biofilm incredibly worked against both Gram-positive and negative bacterial species such as S. aureus (methicillin-resistant), S.aureus, E. coli, and against fungus C. albicans. The effect was assessed by agar diffusion and cell viability assay using MTT dye. 10^5 CFU/mL of bacteria were seeded onto agar plates. Upon treatment with CS-GO films, the cell population was reduced to zero, possibly due to the generation of reactive oxygen species when these particles enter through the cell membrane.

Further, post-treatment with CS-GO films, the cell viability of mouse L929 fibroblastic cells were 80 to 93% higher than controls, thus confirming the non-cytotoxic nature of the synthesized films. The least inhibitory concentration value of CS-GO against E. coli was 32 (g/ml) (Li et al. 2016). Another composite, AgO-CoO-CdO/Poly(alanine)-chitosan-reduced graphene oxide (PACSGO) nanocomposite was developed by Zhang et al (2020). This composite worked as a nano-photocatalyst for the substantial degradation of organic dye compounds from water. Additionally, the group reported enhanced antibacterial activity against S.aureus, E. coli, P. aeruginosa, and B. cereus medium and increased inhibition zone value with the addition of the nanocomposites. This nanocomposite showed a higher percentage of scavenging activity of AgO-CoO-CdO/PACSGO than other composites.

de Faria et al. (2015), using GO and silver particles nanocomposites, fabricated electrospun mats, where the blend of CS and poly(lactide-co-glycolide) (PLGA) was used as biopolymetric fibre. These PLGA/chit-GOAg electrospun mats displayed a bacterial inactivation rate of ~98% for E. coli and P. aeruginosa compared to control (nonmodified control PLGA-chitosan). A lower inactivation rate of 79.41% was observed against S. aureus due to a thick peptidoglycan layer in the cell wall of Gram-positive bacteria. Additionally, Yang et al. (2019) synthesized an antibacterial nano agent by coating quaternized chitosan (QCS) on the surface of Fe₃O₄ nanoparticles-anchored GO. This nanocomposite killed pathogens upon generation of hyperthermia through photothermal near infra-red irradiation.

The anti-bacterial efficacy of CS-GO based film was also investigated in detail by Marin et al. (2019). Electrospun CS-GO-and polyvinyl alcohol-based composite nanofibrous membrane was synthesized and analyzed. With the percentage of GO at 1%, the scaffold membrane showed antibacterial properties against gram-positive bacteria, B. cereus and S. aureus, and gram-negative bacteria, S. enterica and E. coli. The anti-bacterial inhibitory effect of the electrospun nanocomposite scaffold might be due to GO, as its edges penetrate the cell membrane, leading to membrane rupture and lipid peroxidation. Thus, the nanofibrous composite membrane might be used as a scaffold in exposed wounds and infected areas where the risk of bacterial infection is grave. Khalil et al. (2020) also showed that GO-CS and GO-EDTA based nanocomposites display anti-microbial activities against E. coli, S. aureus, and C. albicans. There have been a few pre-clinical investigations on their wound healing applications (Moradi et al. 2021). For instance, a temporary skin graft was made of CS-polyvinyl pyrrolidone-GO nanosheets. Live and dead assays were performed in-vitro. Cell viability and bactericidal capacity of this membrane were increased by using GO in the sheet. Accelerated healing tests were done using the rat’s skin. A period of 14 days was required for complete regeneration of skin at a large wound. Nanosheet made of CS-GO covering was able to heal the wound almost completely
(>99%) after 21 days following the injury (Mahmoudi et al. 2017).

CS-GO-PVA composite was prepared using synthesized guanidine modified GO with (0, 0.1, 0.2, 0.5, and 1.0 wt%). In-vivo experiments validated that CS-GO (0.5%)-PVC sheets had a high antibacterial activity (50% more than GO used alone). In vivo studies on mice had shown 41% faster wound healing capacity than the control (Chen et al. 2020). The synergistic effect was observed on combining CS-GO-polylactic acid (PLLA) for wound healing. CS-PLLA-based scaffolds were coated with GO. Pig iliac endothelial cells and female Sprague-Dawley rats were used for cytocompatibility and wound healing investigations. GO-coated CS/PLLA scaffolds resulted in a 60.48% decrease in the size of the wound. The wound was recovered in 21 days that shows its effectiveness as a wound-healing material. The scaffold was an effective bactericidal agent against E. coli and S. aureus (Yang et al. 2021).

Environmental Applications

CS finds extensive application in removal of metals in water treatment, as the amine and hydroxyl groups present in it easily form chelates with metal ions. CS-based membranes are reported to be useful to treat wastewater (Thakur and Voicu 2016). CS’s insolubility in water and alkaline solution can be modified by GO, an excellent adsorbent with a high surface area. The self-agglomeration of GO is a limiting factor for its more comprehensive application. Various researchers have attempted to synthesis composite material using CS-GO. The negative charges on the surface of aqueous dispersed G sheets bond chemically with the cationic group present in chitosan's amino polysaccharides. Carboxylic groups of GO react through the amine group of CS, in some cases creating an amide bond between them. Various modifying agents such as EDTA can be added to the composite to functionalize these composites further. There is a wide range of applications of these composites, varying from water purification to electrode development. Most studies have been performed using optimization of parameters including solution properties including pH, temperature, an initial amount of adsorbent, contact time, swelling behaviour, and adsorbent properties such as its amount, form, and recyclability. Many active sites and more adsorbate in the waste stream have led to a higher mass gradient between solution and adsorbate. The ease of separation of adsorbents from the waste stream is also an essential factor influencing the adsorbent's broad choice.

Removal of heavy metals

Various functional groups including epoxy, hydroxyl, and carboxylic in GO provide oxygen to bind with metal ions. Likewise, amino groups present in CS binds with metal ions and can adsorb them from contaminated effluent. However, various limitations, including low operation efficiency, stability, and aggregation, are related to graphene oxide and chitosan usage alone. Hence, scientists have performed studies to crosslink and functionalize CS with polar groups such as graphene oxide. The modification of CS-GO composite has been performed using various materials. Table 3 lists multiple metals, CS-GO, and their modified composites and maximum adsorption efficiency. The research work shows its potential for adsorption of metals like Cu, Cr, As, Pb, Hg, Au, Pd. Heavy metals such as Cr(VI) can lead to severe hazardous effects on the environment and human beings. While Cr(III) is an essential trace nutrient, it is limited in drinking water to 170 (mg/L) by WHO (Altundogan 2005).

On the other hand, Cr(VI), occurring as chromate and dichromate, is a mutagen and carcinogen. The Word Health Organization limit of Cr (VI) in drinking water is 0.050
mg/L, an excess of which may lead to various skin diseases and even cancer in human beings (WHO 1997). Multiple researchers have investigated CS-GO nanocomposites as an adsorbent to remove chromium (Anush et al. 2020; Samuel et al. 2018). Samuel et al. (2018) showed that this composite on exposure to chromium contaminated water possesses an adsorption capacity of 104.2 mg/g at pH 2.0 for the contact time of 420 min recyclability of 10 times. Copper and chromium metals were removed using a composite of CS-GO modified using 3-(p-anisyl)-4-formylsydnone by Anush et al. (2020). They studied wastewater contaminated with copper and chromium and reported that the pseudo-second-order kinetic reaction that followed Langmuir isotherm-model was best for their study.

Furthermore, the metal removed was a vital function of initial metal concentration in the water to be treated. The maximum removal capacity for Cu (II) and Cr (VI) was found to be 111.1 and 142.8 (mg/g), respectively. The reaction was a thermodynamically favourable process, being spontaneous and endothermic. Arsenic is a heavy metal and a prominent constituent of industrial waste. The World Health Organization has set the limit of 10 (μg/L) in drinking water (Minatel et al. 2018). Arsenic is a toxic metal released into the ecosystem through industrial activities. Entering the food chain causes nephrotoxicity, diabetes, cardiovascular, pulmonary, and skin diseases (De Loma et al. 2019). Functionalized CS-GO composite can be used as a potential adsorbent for arsenic removal from the aqueous medium. Kumar and Jiang (2016) reported that GO and CS composite performance depends on pH of the solution. Their study's optimum pH was 4.3 to 6.5 for As (V) removal with endothermic, spontaneous metal adsorption process, which follows a pseudo-second-order kinetic model. The composite was able to adsorb As(III) and As(V) with the maximum adsorption capacity of 64.2 and 71.9 (mg/g), respectively, with material recyclability of 3 cycles.

CS-GO composite’s functionalization using gadolinium resulted in improved efficiency to separate arsenic from aqueous medium. This composite's enhanced adsorption capacity of 252.1 (mg/g) showed its potential to treat arsenic-contaminated wastewater (Choi et al. 2020). The adsorption capacity of GO-Gagolinium without chitosan is much lower than the composite modified using chitosan 216.7 (mg/g) (Lingamdinne et al. 2021). Graphene oxide and reduced graphene oxide mixed with magnetic particles removed As(III) and As(V) from the aqueous solution. The studies showed that treatment time, initial arsenic concentration, pH, temperature, anions, and humic acid affected the composite's arsenic removal efficiency. Likewise, magnetically modified CS-GO nanoparticles were efficient for Ni (II) adsorption from waste-water with the maximum adsorption of 12.2 (mg/g) (Tran et al. 2019). Mercury is also a harmful metal and is one of the major pollutants in river water. Chitosan was investigated as filler material inside the GO matrix to form CS-GO nanocomposite. GO, and CS adsorption capacity improved from 381 mg/g to 397 mg/g upon nano filling magnetically modified CS into GO matrix (Kyzas et al. 2014). EDTA was used to alter the properties of the CS-GO composite. Magnetically modified CS-GO composites were functionalized using EDTA and were found to be potential adsorbents for metals like Pb(II), Cu(II), and As (III) (Shahzad et al. 2017a). The CS-GO composite was prepared by freeze-drying and investigated for selectivity of lead metal. The composite prepared by adsorption with 5 wt% GO in CSGO exhibited high mechanical strength and the maximum Pb (II) adsorption as 99 mg/g (He et al. 2011). Attempts were made to prepare the membrane by combining EDTA, GO, and CS to remove Pb (II). The adsorption efficiency using CS/EDTA/GO (0.3%) membrane was obtained at 889 (mg/g) (Croitoru et al. 2020). Studies on the adsorption capacity of this membrane for other heavy metals can also be undertaken.
### Table 3. CS-GO Nanocomposites for Heavy Metal Removal

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Heavy Metal</th>
<th>Adsorption Capacity (mg/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS with PVA</td>
<td>Cr (VI)</td>
<td>3.5</td>
<td>(Jaros et al. 2005)</td>
</tr>
<tr>
<td></td>
<td>Cu (II)</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zn (II)</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Au (III)</td>
<td>Au (III): 1076.6</td>
<td>(Liu et al. 2012)</td>
</tr>
<tr>
<td></td>
<td>Pb (II)</td>
<td>Pb (II): 216.9</td>
<td></td>
</tr>
<tr>
<td>Cyclodextrin- CS and GO</td>
<td>Cr (VI)</td>
<td>61.31</td>
<td>(Li et al. 2013)</td>
</tr>
<tr>
<td>GOCS10</td>
<td>Cu (II), Pb (II)</td>
<td>Cu (II): 70</td>
<td>(Chen et al. 2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pb (II): 90</td>
<td></td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Pb (II)</td>
<td>76.94</td>
<td>(Fan et al. 2013)</td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Hg (II)</td>
<td>381</td>
<td>(Kyzas et al. 2014)</td>
</tr>
<tr>
<td>β-cyclodextrin/magnetic GO/EDTA</td>
<td>Cr (VI)</td>
<td>68.41</td>
<td>(Wang et al. 2014)</td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Cr (VI)</td>
<td>82.14</td>
<td>(Debnath et al. 2014)</td>
</tr>
<tr>
<td>CS and GO nanofibrous composite</td>
<td>Cu (II), Pb (II), Cr (VI)</td>
<td>Cu (II): 423.8, Pb (II): 461.3, Cr (VI): 310.4</td>
<td>(Najafabadi et al. 2015)</td>
</tr>
<tr>
<td>TGOCS</td>
<td>Cr (IV)</td>
<td>219.5</td>
<td>(Ge and Ma 2015)</td>
</tr>
<tr>
<td>CS and GO with disodium EDTA-2Na</td>
<td>Cr (VI)</td>
<td>86</td>
<td>(Zhang et al. 2016)</td>
</tr>
<tr>
<td>CS and GO</td>
<td>As (III), As (V)</td>
<td>As (III): 64, As (V): 72</td>
<td>(Kumar and Jiang 2016)</td>
</tr>
<tr>
<td>CS-GO and CS/rGO</td>
<td>Cu (II)</td>
<td>202 and 150</td>
<td>(Yan et al. 2016)</td>
</tr>
<tr>
<td>EDTA functionalized magnetic CS and GO</td>
<td>Pb (II), Cu (II), As (III)</td>
<td>Pb (II): 206.52, Cu (II): 207.26, As (III): 42.75</td>
<td>(Shahzad et al. 2017b)</td>
</tr>
<tr>
<td>Phosphorylated CS and GO</td>
<td>U(VI)</td>
<td>779.44</td>
<td>(Cai et al. 2017)</td>
</tr>
<tr>
<td>GO-CS aerogel</td>
<td>U(VI)</td>
<td>250</td>
<td>(Huang et al. 2017)</td>
</tr>
<tr>
<td>CS and GO</td>
<td>Cr (VI)</td>
<td>104.16</td>
<td>(Samuel et al. 2018)</td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Cu (II)</td>
<td>217.4</td>
<td>(Hosseinzadeh and Ramin 2018)</td>
</tr>
<tr>
<td>Low molecular CS</td>
<td>Cu (II)</td>
<td>80</td>
<td>(Boamah et al. 2016)</td>
</tr>
<tr>
<td>Cross-linked CS and GO</td>
<td>Pb (II)</td>
<td>566</td>
<td>(Sharma et al. 2019)</td>
</tr>
<tr>
<td>CS and GO</td>
<td>Cr (VI)</td>
<td>178</td>
<td>(Moghadam et al. 2019)</td>
</tr>
<tr>
<td>Grafted CS and GO</td>
<td>Cr (VI)</td>
<td>270.27</td>
<td>(Samuel et al. 2019)</td>
</tr>
<tr>
<td>GO-CS-PVA hydrogel</td>
<td>Cd (II), Ni (II)</td>
<td>Cd (II):172, Ni (II): 70</td>
<td>(Li et al. 2019)</td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>As (III)</td>
<td>45</td>
<td>(Sherlala et al. 2019)</td>
</tr>
<tr>
<td>Magnetic CS and GO</td>
<td>Ni (II)</td>
<td>12.24</td>
<td>(Tran et al. 2019)</td>
</tr>
<tr>
<td>GO-CS sponge</td>
<td>Co (II), Ni (II)</td>
<td>Co (II): 224.8, Ni (II): 423.7</td>
<td>(Di et al. 2019)</td>
</tr>
<tr>
<td>Membranes using CS-GO</td>
<td>Pb (II)</td>
<td>767</td>
<td>(Croitoru et al. 2020)</td>
</tr>
<tr>
<td>GO-CS Gadolinium composite</td>
<td>As(V)</td>
<td>252</td>
<td>(Choi et al. 2020)</td>
</tr>
<tr>
<td>CS and GO</td>
<td>Cd (VI), Cu (II), Pb (II)</td>
<td>Cd (VI): 48.7, Cu (II): 60.7, Pb (II): 32.3</td>
<td>(Li et al. 2020)</td>
</tr>
<tr>
<td>Modified CS with 3-(p-anisyl)-4-formylsydnone and GO</td>
<td>Cr (VI), Cu (II)</td>
<td>Cr (VI): 142.85, Cu (II): 111.11</td>
<td>(Anush et al. 2020)</td>
</tr>
<tr>
<td>GO-Gadolinium composite</td>
<td>As(V)</td>
<td>216</td>
<td>(Lingamdinne et al. 2021)</td>
</tr>
<tr>
<td>GO-CS-Fe₃O₄</td>
<td>Cd (II)</td>
<td>84</td>
<td>(Parastar et al. 2021)</td>
</tr>
</tbody>
</table>
Bessa et al. (2020) reported Hg (II) removal efficiency (97%) from ultra-pure water with a small mercury dose using CS-GO composite. Simultaneously, using the tap water, river, and seawater, removal efficiency was reduced to about 81%, 13%, and 7%, respectively. Their study concluded that chloride in an aqueous medium significantly reduced the removal efficiency of the composite due to the formation of steady chloro-mercury complexes. CS-GO nanocomposite could adsorb Pd(II) and Au(III). CS with 5 wt.% GO combination showed maximum adsorption 1077 (mg/g) for Au(III) and 216.9 (mg/g) for Pd(II) (Liu et al. 2012). Other studies highlighted hydrogel's potential obtained using CS-GO and polyvinyl alcohol (PVA) in various proportions, with the optimum being 1:2:4. Adsorption studies showed that the model followed Langmuir isotherm. Co-CS-PVA matrix showed the maximum adsorption capacity for Cd (II) and Ni (II) as about 172 and 70 mg/g, respectively, for the contact time of 16 h (Li et al. 2019). GO was mixed with 4-aminothiophenol and NaNO₂ to form GO-SH material, mixed with chitosan powder to obtain GO-CS-SH composite material. In multi-metal effluent, the material was found to be most suitable for adsorption of Cd(II), followed by Cu(II) and Pb(II) (Li et al. 2015). Similarly, studies on Go-Cs composite material without any functionalization resulted in the maximum adsorption capacity for Cu(II), Pb(II), and Cd(II) as about 60, 48, and 32 mg/g, respectively (Li et al. 2020). Menazea et al. (2020) studied the interactions of heavy metals with CS-GO and proposed a model using density functional theory and suggested that high heavy metal removal can be achieved by CS-GO combination.

**Removal of dye**

The textile and printing industry produces dye-containing effluent, which should be treated before discharge into water bodies. Approximately 1 to 15% of the dye is released into waste water during the dying process, eventually entering the ecosystem (Galindo 2001). Aromatic compounds in paints make their biodegradation an arduous task. Coloured substances in water inhibit the permeation of light and hinder the photosynthesis process. If ingested, these dyes can cause eye burns, nausea, vomiting, dyspnea, and cyanosis disease (Senthilkumaar et al. 2005).

Similar to the removal of metals, adsorption is the method of choice for dye removal. When used individually, CS and GO have shown a high affinity for the adsorption of dyes present in the wastewater (Chandel et al. 2020). However, composite formed using chitosan and graphene showed improved adsorption properties over several cycles of repeated usage. Table 4 depicts the various CS-GO composites like hydrogel, beads, spheres, and sponge investigated for dye removal from aqueous solution. However, the adsorption of methylene blue dye on GO adsorbent used alone was 287 mg/g. CS-GO composite material leads to adsorption capacity as high as 402.6 mg/g (Sabzevari et al. 2018a). Due to the unique properties of CS-GO, they can be used for the adsorption of methylene blue dye. A sponge prepared using chitosan (9%) with GO exhibited an adsorption capacity of 275.5 mg/g for methylene blue during a filtration process (Qi et al. 2018b).

Due to the better removal ability of magnetic nanoparticles from an aqueous medium, synthesis and kinetic studies of magnetic nanoparticles for water treatment have been successfully reported. Tran et al. (2017b) demonstrated the enhanced adsorption efficiency of magnetically modified CS-GO composite. The studies reported the adsorption efficiency of 10% weight of GO in CS/Fe₃O₄/GO nanocomposite for MB dye after 95 h for five repeated operation cycles. Neves et al. (2020) prepared a magnetic CS-GO composite to remove basic brown four dye.
## Table 4. CS-GO Nanocomposites for Dye Removal

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Dye</th>
<th>Adsorption Capacity (mg/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic CS grafted with GO</td>
<td>MB</td>
<td>95.31</td>
<td>(Fan et al. 2012a)</td>
</tr>
<tr>
<td>Chitosan/graphene oxide</td>
<td>MB</td>
<td>180.83</td>
<td>(Fan et al. 2012b)</td>
</tr>
<tr>
<td>CSGO10</td>
<td>MB</td>
<td>74</td>
<td>(Singh et al. 2019)</td>
</tr>
<tr>
<td>CS-GO</td>
<td>Reactive black 5</td>
<td>277</td>
<td>(Travlou et al. 2013a)</td>
</tr>
<tr>
<td>Magnetic CS-GO</td>
<td>Reactive black</td>
<td>391</td>
<td>(Travlou et al. 2013b)</td>
</tr>
<tr>
<td>Chitosan/graphene oxide 10</td>
<td>MB, Eosin Y</td>
<td></td>
<td>(Chen et al. 2013)</td>
</tr>
<tr>
<td>GO-CS/silica</td>
<td>CR</td>
<td>294.12</td>
<td>(Du et al. 2014)</td>
</tr>
<tr>
<td>Magnetic CS-GO</td>
<td>MO</td>
<td>398.08</td>
<td>(Jiang et al. 2016)</td>
</tr>
<tr>
<td>CS-GO foam</td>
<td>MO</td>
<td>173.3</td>
<td>(Ma et al. 2016)</td>
</tr>
<tr>
<td>GO was cross-linked with CS</td>
<td>Acid yellow 36 and Acid blue 74</td>
<td></td>
<td>(Banerjee et al. 2017)</td>
</tr>
<tr>
<td>Magnetic GO-CS composite</td>
<td>MO</td>
<td>30</td>
<td>(Tran et al. 2017a)</td>
</tr>
<tr>
<td>CS-GO sphere</td>
<td>MO and Acid red 1</td>
<td></td>
<td>(Zhang et al. 2018)</td>
</tr>
<tr>
<td>GO and CS-GO composite</td>
<td>MB</td>
<td>275.5</td>
<td>(Qi et al. 2018a)</td>
</tr>
<tr>
<td>Cs-Go aerogel</td>
<td>Indigo Carmine and MB</td>
<td></td>
<td>(Luna et al. 2019)</td>
</tr>
<tr>
<td>CS-GO sponge bionic filter</td>
<td>Crystal violet dye</td>
<td>98</td>
<td>(Zhou et al. 2018)</td>
</tr>
<tr>
<td>GO derivative containing quaternary ammonium salt and magnetic CS</td>
<td>Basic brown 4</td>
<td>650</td>
<td>Neves et al. (2020)</td>
</tr>
<tr>
<td>Polyacrylate CS-GO hydrogel</td>
<td>MB and Food yellow 3</td>
<td>MB: 296</td>
<td>Neves et al. (2020)</td>
</tr>
<tr>
<td>Cs reinforced Go-hydroxyapatite (CS@GO-Hap)</td>
<td>CR, Acid Red 1 and Reactive Red 2</td>
<td>CR: 43.06, Acid Red 1: 41.32, Reactive Red 2: 40.03</td>
<td>Sirajudheen et al. (2020)</td>
</tr>
</tbody>
</table>
Composite graphene oxide functionalized using quaternary ammonium salt and magnetic chitosan provided the maximum adsorption capacity of 650 (mg/g) and 95(%). The study showed that in three successive adsorption and desorption cycles, the dye uptake efficiency was 64%. Graphene nanoplates, a graphene derivative crosslinked with chitosan to form composite spheres, were explored for the adsorption of methyl orange and acid red one dye. The high adsorption capacity for methyl orange and acid red 1 was 230.9 (mg/g) and 132.9 (mg/g), respectively, which showed the CS-GO sphere’s potential as an efficient dye adsorbent. The adsorption capacity was maintained at 90% after five repeated usage cycles (Zhang et al. 2018). CS-GO bead adsorbent prepared by gel and GO and investigated by researchers for adsorption of various cationic and anionic dyes. For orange dye II, 84 (%) removal efficiency was observed with CS/Gel0.1GN.

Vo et al. (2020) prepared hydrogel materials in which chitosan chains crosslinks GO-nanosheets. GO and CS were mixed in solution in the above hybrid, followed by sonification to form hydrogel of GO-CS. While the higher GO level was beneficial for cationic dye’s adsorption, higher chitosan hydrogel showed selectivity towards anionic dyes. The combination provides maximum loading of congo red dye about 176 (mg/g) (Kamal et al. 2016). Recently, biopolymer-based aerogels have been studied for application in adsorption and water purification processes. Chitosan-based aerogel has emerged as a potential material for the remediation of dye-contaminated water. Chitosan with active amine and hydroxyl groups has a strong tendency to bind with various types of dyes. Chitosan is a highly porous material that has limited application due to its high propensity to collapse. Besides acting as a good filler in the chitosan matrix, graphene oxide provides mechanical strength and enhances chitosan’s adsorption efficiency. Aerogel formed using nanocomposite CS-GO aerogels exhibited high retention ability for Indigo Carmine and MB, as 377 and 169 (mg/g), respectively (Luna et al. 2019). Similarly, aerogel prepared using CS-GO was an effective adsorbent for Metanil Yellow dye with removal efficiencies between 91 and 96 (%). This dye’s adsorption capacity was 431.0 (mg/g) at the adsorbent dose of 8 mg, concentration 400 (mg/L), for the contact time of about 35 min, maintained at a shaking speed of 175 rpm. The aerogel performed the adsorption and desorption up to 5 cycles, which resulted in an adsorption capacity of around 80 (%) (Lai et al. 2019). Qi et al. (2018b) synthesized GO-CS nanocomposite to remove MB in column study. Optimum loading for CS into GO solution was 9% in CS-GO hydrogel, which MB released efficiently.

Removal of organic and inorganic pollutants

Chitosan offers excellent potential for the removal of a variety of contaminants from effluents. Modified and unmodified chitosan-based nanocomposites have shown an effective adsorption potential to eliminate a variety of heavy metals, which include Cu (II) (Boamah et al. 2016; Modrzejewska et al. 2016), Pb(II) (Shahzad et al. 2017; Dinh et al. 2018), Cr(VI) (Moghaddam et al. 2019; Samuel et al. 2019; Naicker et al. 2020), As(V) (Shahzad et al. 2017a), Ni(II) (Di et al. 2019; Tran et al. 2019), and Hg(II) (Kyzas et al. 2014). Also CS used has been used for removal of inorganic nutrients (NO$_3^-$, NO$_2^-$, and PO$_4^{3-}$) (Jozwiak et al. 2017, 2019; Kumar et al. 2019) and organic pollutants (Jozwiak et al. 2017; Escudero-Oñate and Martín-Francés 2018). Further, Table 5 summarizes CS composites that have been used to remove organic and inorganic contaminants from wastewater.
Table 5. Inorganic and Organic Contaminant Removal using CS

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Adsorbent</th>
<th>Removal efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-hexadecane</td>
<td>Spores of Bacillus subtilis LAMI008 were entrapped in 3 mm chitosan beads and cross-linked with 0.3% glutaraldehyde</td>
<td>100</td>
<td>Sar and Rosenberg (1983)</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Protonated cross-linked chitosan gel beads by glutaraldehyde</td>
<td>77</td>
<td>Jaafari et al. (2001)</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>R. corynebacteriorides immobilized on CS</td>
<td>60</td>
<td>Gentili et al. (2006)</td>
</tr>
<tr>
<td>Fluoride</td>
<td>Chitosan loaded with titanium</td>
<td>89</td>
<td>Jagtap et al. (2009)</td>
</tr>
<tr>
<td>Diheptyl phthalate</td>
<td>Molybdate-impregnated chitosan beads</td>
<td>92.5</td>
<td>Barreto et al. (2010)</td>
</tr>
<tr>
<td>Insecticide (permethrin)</td>
<td>Modified CS with ZnO</td>
<td>99</td>
<td>Arayne et al. (2011)</td>
</tr>
<tr>
<td>Pesticide (Atrazine)</td>
<td>Cross-linked chitosan-silver nanoparticles</td>
<td>98</td>
<td>Saifuddin et al. (2011)</td>
</tr>
<tr>
<td>Oil</td>
<td>CS microspheres produced by ionic gelation of CS with sodium tripolyphosphate</td>
<td>90</td>
<td>Grem et al. (2013)</td>
</tr>
<tr>
<td>Hexadecane</td>
<td>Bacterial strain B. pumilus entrapped in chitosan</td>
<td>81.83</td>
<td>Costa et al. (2014)</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>Carbon nanotubes mixed with CS/polyvinyl alcohol and cross-linked with silane</td>
<td>97</td>
<td>Bibi et al. (2015)</td>
</tr>
<tr>
<td>Oil</td>
<td>Zirconium-chitosan composites</td>
<td>79</td>
<td>Elanchezhiyan et al. (2016)</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>Chitosan beads</td>
<td>99</td>
<td>Dellagneze et al. (2016)</td>
</tr>
<tr>
<td>Oil</td>
<td>chitosan/magnesium-aluminum layered double hydroxide hybrid composite</td>
<td>78</td>
<td>Elanchezhiyan and Meenakshi (2017)</td>
</tr>
<tr>
<td>Oil</td>
<td>Superhydrophobic and superoleophilic chitosan sponge</td>
<td>99</td>
<td>Su et al. (2017)</td>
</tr>
<tr>
<td>Fluoride</td>
<td>Zr (IV) modified CS-GO</td>
<td>90</td>
<td>Zhang et al. (2017)</td>
</tr>
<tr>
<td>Oil</td>
<td>Amphiphilic sodium salt of oleoyl carboxymethyl chitosan</td>
<td>75-85</td>
<td>Doshi et al. (2018)</td>
</tr>
<tr>
<td>Naphthanol</td>
<td>Magnetic Cs-Go composite</td>
<td>99.8</td>
<td>Rebekah et al. (2020)</td>
</tr>
<tr>
<td>Ofloxacin</td>
<td>CS-GO</td>
<td>99</td>
<td>Suri et al. (2021)</td>
</tr>
</tbody>
</table>
Arayne and co-workers (2011) investigated the potential of raw and ZnO-modified CS beads to remove insecticide used for agriculture. They found that chitosan beads have outstanding adsorption and removed 49% and 99% of an insecticide (permethrin) when using raw and modified chitosan beads, respectively.

Danaloglu et al. (2017) prepared a novel magnetic activated carbon/chitosan composite to remove ciprofloxacin, erythromycin, and amoxicillin. They found the best fit with a Langmuir isotherm model, indicating that 90 (mg/g) ciprofloxacin, 178.6 (mg/g) erythromycin, and 526.3 (mg/g) amoxicillin had adsorbed. Danaloglu et al. (2017) compared the adsorption potential of magnetic CS with activated carbon for ciprofloxacin with alginate-Fe₃O₄ hydrogel fibre and GO-Ca alginate adsorbent. About 154 μg/g ciprofloxacin was adsorbed using magnetic alginate-Fe₃O₄ hydrogel fibre and 18.45 to 39.06 mg/g GO-Ca alginate adsorbent (Wu et al. 2013).

Saifuddin et al. (2011) removed pesticide (atrazine) using CS-Ag NPs. Maximum 98% atrazine (from 1 ppm solution) was removed from solution using a composite dosage of 2.0 g/L of Cs-Ag NPs. Other investigators have reported using chitosan beads modified with sodium alginate and calcium chloride to remove phenol and o-chlorophenol (Li et al. 2009a). They said that modification in CS enhanced its stability and its sorption capacity toward pollutants. The maximum sorption capacities of 108.7 (mg/g) and 97.1 (mg/g) were achieved for o-chlorophenol and phenol, respectively. Zr(IV) is oxyphilic and makes a bond with oxygen present in GO. Researchers have prepared zirconium-chitosan/graphene oxide membrane (80 μm thick) and evaluated its adsorption capacity for anions present in wastewater. Zr(IV) forms an electro-positive ion. It has a strong affinity for fluoride ions with more than 90% removal efficiency in the contact time of around 30 min. The membrane displayed high selectivity for bicarbonate and sulfate ions as well. The membrane with sufficient mechanical strength has been reported to have a high potential for water purification application (Zhang et al. 2017).

CS has been recognized as one of the most effective biopolymers for removing oil droplets from water. CS exhibits a unique assembly that is prone to natural functionalization and permits the modification of novel sportive materials with oil-enhanced selectivity and adsorption potential (Farzana and Meenakshi 2015; Elanchezhiyan et al. 2016). Nitrogen, phosphorus, and potassium are the vital nutrients required for proper plant growth, but excessive fertilizers in the fields lead to leaching soil and water bodies. As per the World Health Organization, the limit NO₃⁻ and PO₄³⁻ in drinking water is 40 and less than 0.5 mg/L, respectively. The excessive amounts of these components in drinking water are harmful and lead to various diseases such as methemoglobinemia and gastric cancer (Zheng and Wang 2010). Various researchers have explored chitosan composite for nutrient removal from water. Hybrid beads encapsulating chitosan on the graphene oxide functionalized using triaminotriazine have been used to remove nutrients from agricultural soil. These beads were tested on a non-aqueous medium enriched with nutrients such as NO₃⁻ and PO₄³⁻. The retention capacity of beads for NO₃⁻ and PO₄³⁻ was 58.5 and 61.4 mg/g, respectively, which was much higher than any of these individual adsorbents (Kumar et al. 2019). In agriculture, pesticides are commonly used to control insects and pests that cause severe damage to the crop. The associated toxic effects of chemical pesticides have prompted researchers to look for biopesticides as an alternative. However, biopesticides' hydrophobicity is the most significant limiting factor in their wide range of applications (Lao et al. 2010). The organic solvents used in high quantities to improve their solubility in an aqueous medium are known to be highly polluting in nature (Muda et al. 2020). Researchers are looking for eco-friendly water
solubilizing carrier agents to stabilize biopesticides in an aqueous medium chemically. The binding mechanisms for carrier agents include encapsulation, entrapment, adsorption, and ligands (Meredith et al. 2016).

Strontium-90 is found mainly in nuclear waste. Its longer half-life, as well as its biocompatibility, make it toxic for human health. Among numerous methods to treat nuclear waste, adsorption is considered an effective technique to remove strontium. The low adsorption capacity of existing adsorbents such as clay and synthetic hydroxyapatite prompted researchers to develop adsorbents with higher selectivity. It has been found that the maximum adsorption capacity of strontium on GO and chitosan was 146, 112 mg/g, respectively. However, its adsorption capacity for GO-chitosan composite was 180 mg/g (Rouby et al. 2018). Rotenone (1,2,12,12a-tetrahydro-8,9-dimethoxy-2-(1-methyl-ethenyl)-1-benzopyrano(3,5-b)furo(2,3-h)benzopyran-6(6h)-one) is a non-toxic organic pesticide for pests such as corn borers, apple and pea aphids, Mexican bean beetles, and household pests. Researchers have performed studies to improve the hydrophobicity of rotenone using a Cs-GO nanocomposite using various Cs and GO proportions. The process parameters were optimized, resulting in 48.5 times higher dissolution of pesticide in Cs-GO nanocomposite than control (Muda et al. 2020). The effluent of the dye industry, as well as the pharmaceutical industry, contains 2-naphthol. The studies have shown the potential of magnetically modified Cs-GO composite for its adsorption. The maximum adsorption capacity was 169 mg/g with almost complete removal efficiency for the treatment time of 45 mins (Rebekah et al. 2020).

**CHALLENGES AND FUTURE DIRECTIONS**

CS and GO are natural materials that have shown excellent biomedical and adsorption capacity, which are further improved by combining the two materials. CS-GO, prepared as a nanocomposite, offers a large specific surface area and good electrical properties. These composites promise a bright future for many treatments, including cancer and tumour treatment. The enhanced therapeutic value of CS-GO composite materials has been evaluated using animal model-based studies. They are safe, efficient, and ensure drug delivery at specific locations in the body in a controlled manner. Although advancement has been achieved in *in-vivo* studies, much work lies in clinical level investigations. The ongoing research on CS-GO is not sufficient and must be enhanced. The analysis described in this review is still in its infancy. It is being continuously improvised, but stringent validation needs to be performed *in vivo* and *in-vitro*, followed by assessing long-term adverse effects through extensive clinical trials to obtain an efficient, viable, and safe product. Clinical trials can precisely identify and compare the environmentally most favorable options for many medicinal applications. More clinical data is required to understand the relative advantages and limitations of CS-GO composites compared to CS or GO used alone.

The mounting number of metals, dyes, and organic pollutants can lead to severe environmental degradation. The effect of the same on human health and the eco-system can be disastrous if not addressed soon. CS-GO-based hydrogel, aerogel, beads, and spheres have helped remove metals including Cu, Cr, Pb, Pd, As, Au, and Hg, which are otherwise severely toxic. Currently, the research work is focused on the treatment of individual metals or dyes. However, the waste material in the field is a mixture of various metals. Thus, there is an urgent need to study the efficiency of these composite materials...
to treat multi-metal waste. Magnetically modified composite emerged as a potential adsorbent for metals, dyes, organic, and inorganic contaminants. Under laboratory conditions, complete removal of pollutants has been achieved in a few studies. The retention capacity of these composite was found to be closer to 95%. Scale-up studies of these composite can lead to commercial application. Furthermore, the reusability study must also be prioritized in future research to verify the effectiveness and successfully fabricated nanocomposites compared to conventional treatments.

CONCLUDING COMMENTS

This review has summarized the properties of chitosan (CS), graphene oxide (GO), and CS-GO materials. The application of chitosan and graphene oxide nanocomposite has been studied in the present review, especially its adsorption capability and antimicrobial activity. This unique category of chitosan-based products can be modified with various functional groups to control their hydrophobicity, as well as cationic and anionic properties. The literature that was surveyed in this work makes it clear that the chitosan is a low-cost biopolymer, environmental-friendly, and abundant in availability. However, the modified form of CS-GO has many applications and is cost-effective. Their unique attributes have allowed researchers to use them as a suitable medium to treat many diseases. Although the successful clinical translation of CS-GO composite has not been achieved yet, they have shown great promise, thereby providing hope for new treatment of various decreases soon. In the current scenario, the costs associated with synthesis of CS-GO may not be lowered than other commercially available nanocomposites; therefore, more well-organized and cost-effective ways are required to produce CS-GO. Future research could examine a low-cost CS-GO composite production technique without compromising environmental and health implications.

REFERENCES CITED


Boamah, P. O., Huang, Y., Hua, M., Onumah, J., Sam-Amoah, L. K., Boamah, P. O., Qian, Y., and Zhang, Q. (2016). “Sorption of copper onto low molecular weight chitosan derivative from aqueous solution,” *Ecotoxicology and Environmental Safety* 129, 154-163. DOI: 10.1016/j.ecoenv.2016.01.014


Chemistry Letters 17(4), 1623-1643. DOI: 10.1007/s10311-019-00901-0


in the oil industry,” *Polímeros Ciência e Tecnologia*, 23(6), 705-711. DOI: 10.4322/polimeros.2014.008


Characterization, and bactericidal evaluation of chitosan/guanidine functionalized graphene oxide composites,” *Molecules* 22(1), 12. DOI: 10.3390/molecules22010012


Theoretical Chemistry 1189, article no. 112980. DOI: 10.1016/j.comptc.2020.112980


04021004. DOI: 10.1061/(asce)hz.2153-5515.0000598
Nano Convergence 7(1), 4. DOI: 10.1186/s40580-019-0215-0


ammonium chloride)/polyacrylamide hydrogel,” *Journal of Chemical and Engineering Data* 55(9), 3494-3500. DOI: 10.1021/je100169r


Article submitted: July 7, 2020; Peer review completed: September 18, 2021; Revised version received and accepted: September 30, 2021; Published: October 7, 2021. DOI: 10.15376/biores.16.4.Khandegar