Malays. J. Anal. Sci. Volume 29 Number 6 (2025): 1633

MALAYSIAN JOURNAL OF ANALYTICAL SCIENCES

Journal homepage: https://mjas.analis.com.my/

Review Article

Recent advances in functionalized chitosan for water purification: From adsorption to antifouling membrane coating

Nur Aida Fatimah Mashri[1], Putri Amirah Solehin Sulizi[1], Nur Hidayah Azeman[2], Nurul Auni Zainal Abidin[3], Nadhratun Naiim Mobarak[1*]

[1]Department of Chemical Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor,Malaysia
[2]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[3]School of Chemistry and Environment, Faculty of Applied Science, Universiti Teknologi MARA (UiTM), Cawangan Negeri Sembilan, Kampus Kuala Pilah, 72000, Kuala Pilah, Negeri Sembilan, Malaysia

*Corresponding Author: nadhratunnaiim@ukm.edu.my

Received: 26 July 2025; Revised: 18 October 2025; Accepted: 1 November 2025; Published: 28 December 2025

Abstract

Chitosan, a biodegradable and renewable biopolymer, has drawn more attention recently for its potential use in water purification. However, the limited solubility at neutral pH, low mechanical stability and poor antifouling resistance of pristine chitosan limit its direct use. Recent studies have explored various chemical and physical modifications of chitosan to enhance its adsorption performance in water purification applications. In addition, the dip-coating of chitosan onto ceramic membranes has also been investigated to improve their antifouling performance. This review provides an updated overview of recent advancements in the use of functionalized chitosan for water purification, emphasizing the structure–property relationships that govern pollutant removal and fouling resistance. Looking ahead, future research should focus on enhancing the long-term stability of chitosan coatings, developing scalable and cost-effective synthesis routes, and establishing greener modification strategies. Furthermore, exploring multifunctional and hybrid chitosan-based materials, integrating computational modelling with experimental studies, and assessing real-world performance in complex water matrices will open promising directions for advancing sustainable water treatment technologies.

Keywords: functionalized chitosan, antifouling membranes, water purification, surface modification, adsorption, ceramic membranes

Introduction

Water contamination by a wide range of hazardous pollutants such as heavy metals, dyes, oils and pesticides has become a serious environmental concern, due to the cumulative negative impacts on the quality of drinking water for generations to come. Conventional water purification methods like reverse osmosis, ion exchange and activated carbon adsorption are often constrained due to their high operational cost, production of secondary waste or limited removal of pollutant [1-3]. Therefore, interest is growing in the development of more low-cost and efficient adsorbent materials made from natural polymers.

Among various biopolymers, chitosan, a natural polysaccharide obtained by partial deacetylation of chitin, has emerged as a promising candidate due to its biodegradability, biocompatibility, non-toxicity and strong chelating ability [4-6]. Chitosan contains three types of nucleophilic functional groups which are the NH_2 group at C-2, a secondary OH group at C-3, and a primary OH group at C-6, as shown in **Figure 1** [7]. The presence of these groups along its backbone enable electrostatic interaction, hydrogen bonding and formation of complexes with many types of pollutants [8-9]. These properties make chitosan an excellent adsorbent and coating material [10-11]. However, unmodified chitosan shows poor solubility at neutral pH, limited mechanical strength and susceptibility to fouling, which restrict its direct use in large-scale purification systems [12-13].

To overcome these limitations, researchers have employed both physical and chemical modifications to develop functionalized chitosan. Physical modifications including incorporation of nanoparticles, graphene oxide, quantum dots or polymer blends enhance mechanical stability, adsorption selectivity and conductivity. Meanwhile, chemical modifications like grafting or derivatization introduces electronegative or hydrophilic functional groups such as carboxymethyl (–COOH), succinyl (–CO–CH_2–CH_2–COOH), and phosphonic (–PO_3H_2) improved solubility, surface charge and resistance to fouling. The existing physicochemical properties of chitosan can be tuned through these modification in order to transform them to more versatile material for both pollutant adsorption and antifouling membrane applications.

In comparison with other conventional adsorbents, functionalized chitosan offers distinct advantages over other adsorbents like metal–organic frameworks (MOFs), zeolites and activated carbon. Those benefits include natural and renewable sources, chemical tailoring through multiple reactive sites, low cost and non-toxicity, and dual-functionality for both adsorption and membrane modification. Considering there are large number of papers discussing the chitosan-based adsorbents, there are still few reviews thoroughly discussed how diverse modification techniques affect the structure–property relationships and antifouling performance in water purification contexts.

Hence, this purpose of this review is to provide an overview of recent advancements (2018–2025) in both physical and chemical functionalization of chitosan specifically for membrane applications and pollutant adsorption, analyze the fundamental mechanisms to control adsorption and fouling resistance, and discuss major challenges and future perspectives in the development of more sustainable materials for water treatment. This comprehensive method guides the development of future chitosan-based materials for wastewater treatment technologies by providing an updated framework that connects molecular design to real-world performance.

Modifications of chitosan

Chitosan can undergo structural modifications due to its mechanical stability and the presence of large number of amino (-NH_2) and hydroxyl (-OH) groups in order to improve its physicochemical properties. These modifications can be classified into (i) physical modifications and composites, which rely on non-covalent incorporation of additional materials and (ii) chemical derivatization, which involves covalent grafting of new functional groups onto the polymer backbone. Both approaches aim to enhance chitosan's sorption capacity, stability and antifouling behaviour for water purification.

Physical modifications and composites

Physical modification refers to the addition of other elements or chemical species into the chitosan structure through hydrogen bonding, electrostatic attraction, or van der Waals interactions. Commonly added inorganic materials include metal nanoparticles [14-20], graphene oxide [21-25] and quantum dots [26-34], while organic materials include natural and synthetic polymers [35-42]. Chitosan is well known for its adsorption and antimicrobial properties, making it useful in numerous applications. However, its effectiveness in pollutant removals is often limited due to its mechanical strength, stability and selectivity toward specific analytes [43-44]. In recent years, researchers have explored the incorporation of inorganic materials such as metal nanoparticles (NPs), graphene oxide (GO), and quantum dots (QDs) into the chitosan matrix to enhance these properties. Studies have shown that these modifications significantly enhance chitosan's mechanical strength, selectivity, and adsorption efficiency, making these composites valuable especially for water treatment applications.

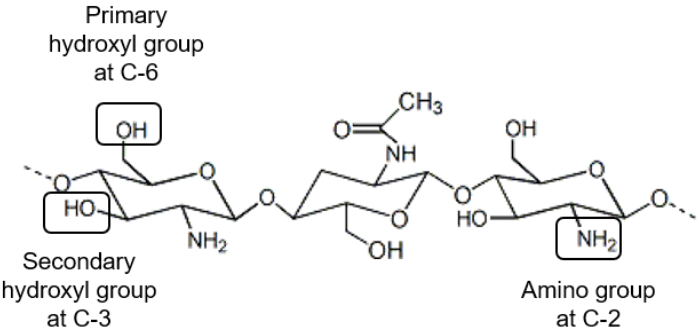


Figure 1. Chemical structure of chitosan

Metal nanoparticles

Metal nanoparticles, such as gold (AuNPs), silver (AgNPs) and platinum (PtNPs), have been introduced into chitosan structures to improve their adsorption efficiency, conductivity and antimicrobial properties [14-15]. However, despite their high reactivity, the standalone effectiveness of these nanoparticles are limited because they tend to aggregate and become unstable [16-17]. Chitosan plays a crucial role as a stabilizing agent to prevent the aggregation of nanoparticles via coordination of metal ions with its amino and hydroxyl groups, producing stable hybrid structures with larger surface areas and active binding sites [18-19]. For example, a chitosan/gold nanoparticle/graphene (CS/AuNPs/Graphene) composite has been developed by Wu et al. [20] for Cd^{2+} detection in milk and water samples. The conductivity and selectivity significantly improved with the addition of AuNPs, by increasing the binding efficiency of Cd^{2+} ions through electrostatic interactions and π–π interactions. X-ray diffraction (XRD) analysis confirmed structural changes, where a broad and weak peak at 12.8° and 20° was seen for CS alone, but with the addition of graphene, it was slightly shifted to a lower angle. This change indicates strong interactions between chitosan, AuNPs, and graphene, with a detection limit of 1.62×10^{-4} μM for Cd^{2+}. This composite shows the incorporation of AuNPs and graphene increased adsorption efficiency and conductivity. **Figure 2** depicts a schematic diagram of the preparation of CS/AuNPs/graphene for Cd^{2+} detection using an electrochemical technique.

Graphene-oxide (GO) composites

Graphene oxide (GO) is a carbon-based material with a large surface area and oxygen-rich functional groups (-COOH, -OH, -O-) that enhance its adsorption properties and ability to bind with pollutants [21-22]. These functional groups increase GO's hydrophilicity and pollutant affinity, allowing it to disperse more effectively within the chitosan matrix and create strong interactions with target analytes. The addition of GO into chitosan improves the composite's mechanical stability, adsorption capacity and overall efficiency in pollutant removal. Lokman and his friends [23] synthesized a chitosan/graphene oxide (CS/GO) composite for Pb^{2+} adsorption and reported that the addition of GO significantly increased the surface roughness and pollutant binding affinity. Atomic force microscopy (AFM) analysis confirmed an increase in surface area, as shown in **Figure 3**, which is attributed to the presence of additional functional groups which enhance the pollutant attachment. Surface plasmon resonance (SPR) sensor analysis also showed greater selectivity and sensitivity, confirming that GO enhances Pb^{2+}'s interactions with chitosan due to improved surface charge and hydrogen-bonding capability. Moreover, GO's incorporation into chitosan also promotes mechanical interlocking with polymer chains, which enhance membrane adhesion and pollutant adsorption [24-25]. In addition, GO reduces the crystallinity of chitosan, which indicate that these two material interact physically without altering the chemical structure [23-25]. This modification enhances the structural flexibility of the composite, making it suitable for water treatment applications.

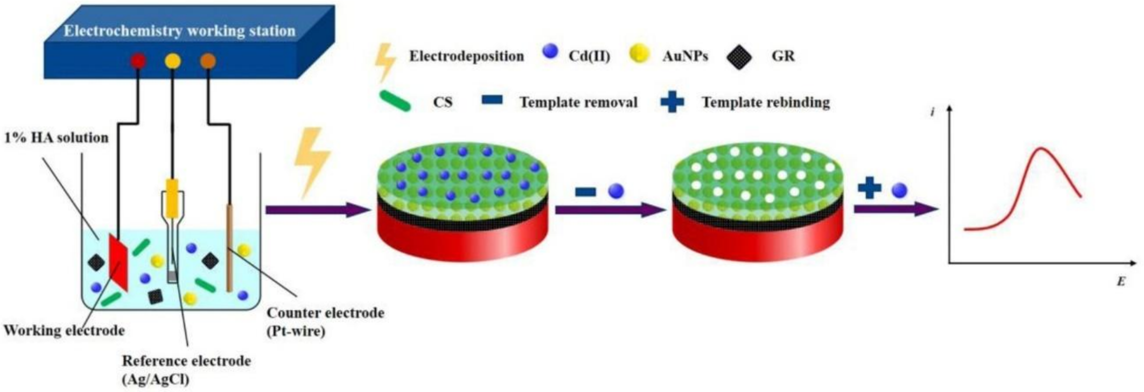


Figure 2. A schematic diagram of the preparation of CS/AuNPs/graphene for Cd^{2+} detection using the electrochemical technique (*Reproduced with permission from* [20])

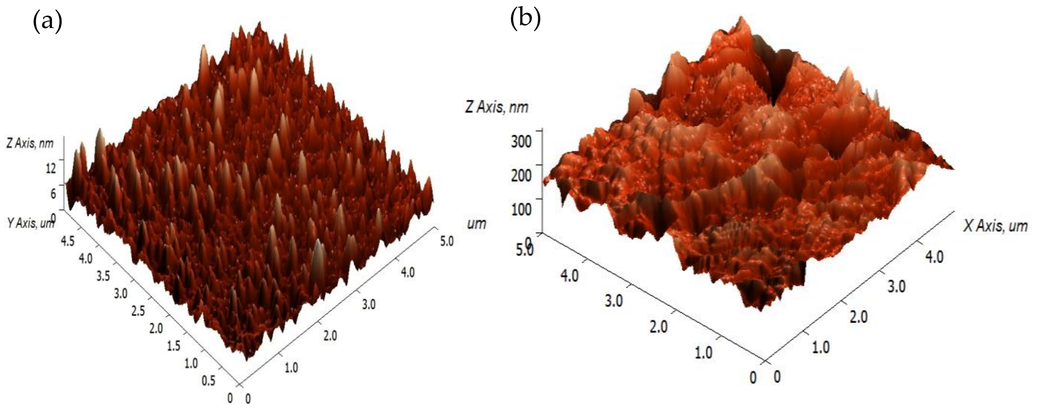


Figure 3. AFM images of (a) before, surface roughness: 1.647 nm; and (b) after the addition of GO into CS, surface roughness: 31.040 nm (*Figure adapted from [25], under the terms of the Creative Commons Attribution (CC BY) license*)

Quantum dots (QDs) composites
Quantum dots (QDs) are another class of inorganic nanomaterials that have been successfully incorporated into chitosan-based composites. QDs, such as hydroxyl-functionalized graphene QDs (OH-GQDs) and carboxyl-functionalized graphene QDs (COOH-GQDs), have attracted attention for their ability to enhance optical sensing and pollutant adsorption [26-28]. QDs possess unique photoluminescence properties, allowing them to act as fluorescent probes for the detection of heavy metals and organic pollutants [28-29]. In addition to that, functionalized QDs improved the properties of chitosan-based composite by enhancing its stability, hydrophilicity, biocompatibility and functionalization by forming form hydrogen bonds and electrostatic interactions with chitosan [29-32]. Anas et al. [33] synthesized a chitosan/OH-GQDs composite for Fe^{3+} detection and observed high selectivity toward Fe^{3+} ions and enhanced photoluminescence intensity. The incorporation of OH-GQDs improved Fe^{3+} binding affinity, due to strong electrostatic interactions and hydrogen bonding. This effect is likely due to Fe^{3+}'s high electronegativity, which increases its attraction to chitosan's functional groups. The positively charged Fe^{3+} ions interacted with the negatively charged amino (- NH_2) groups in chitosan through electron-sharing mechanisms, which resulted from the exceptional sensitivity of 0.11396° ppm^{-1} and a detection limit as low as 0.5 ppm [33]. Similarly, Ramdzan et al. [34] developed a chitosan/COOH-GQDs composite for Hg^{2+} adsorption. The composite showed improved electron transfer efficiency and high selectivity for Hg^{2+}, achieving a lower detection limit than unmodified chitosan. The presence of carboxyl (-COOH) groups in the QDs enhanced adsorption capacity, providing additional binding sites for metal ions and increasing surface reactivity [34]. **Table 1** shows a summary of chitosan-inorganic material composite together with their improved properties and target analytes.

Table 1. Summary of chitosan-inorganic material composite applications

Chitosan Composite	Improved Properties	Analyte	Ref.
CS/AuNPs/Graphene	Stability, conductivity, surface area, sensitivity	Cd^{2+}	[20]
CS/GO	Surface area, binding affinity, sensitivity, selectivity, detection accuracy, repeatability, crystallinity	Pb^{2+}	[23]
CS/OH-GQDs	Optical properties, binding affinity, sensitivity	Fe^{3+}	[33]
CS/COOH-GQDs	Optical properties, adsorption, sensitivity	Hg^{2+}	[34]

Polymer blends

Polymer blending is another approach that is useful for producing better physicochemical properties of a novel material than a single polymer [35-36]. This method is practical, simple and there are plenty of synthetic and natural polymers available for blending. Two main procedures are involved in the blending of chitosan; (i) solution blending, and (ii) melt blending. Solution blending is performed by dissolving chitosan in a solvent and followed by an evaporation process, whilst melt blending is a process in which chitosan is mixed under fusion conditions [37]. It is worth mentioning that the technique used to prepare polymer blends notably influenced their properties [38]. The characteristics of polymer blends relies upon the miscibility of the blended polymers, which is related to the distinct interactions between them. Some of the common interactions in the polymer blends include hydrogen bonding, electrostatic, π-electrons and charge-transfer complexes [37].

The choice of polymer to be blended with chitosan depends on the application and features that are yet to be improved. For instance, chitosan has been blended with natural rubber [39] and cellulose [40] to detect dyes and analyzed using the UV-visible spectrophotometric technique. By blending the aforementioned polymers, an enhancement in the sensing performance has been observed as a result of improvement in the physicochemical properties of the sensing material, particularly on the surface chemistry of the composite material. In 2011, Johns and Rao synthesized CS/natural rubber for the adsorption of methylene blue using a solution blending method. The addition of natural rubber in chitosan improved the sorption capacity for methylene blue adsorption due to the presence of additional active sites provided by chitosan. The sorption study was carried out using two isotherm models; Freundlich and Langmuir. From the reported data, the CS/natural rubber blend fit the Langmuir isotherm models at a low concentration range [39].

In another reports, Udoetok and co-workers [40] blended CS with cellulose by using self-assembled and cross-linking techniques for the adsorption of phenolic dyes. The combination of such polymer blends alter the original crystallinity and thermal stability due to the interaction that occuring in the CS/cellulose blend. This feature could be a great potential for ion uptake studies. The phenolic dyes sorption onto CS/cellulose blends followed Freundlich isotherm models. In the Freundlich model, the order of sorption affinity of phenolic dyes is as follows: phenolphthaleine (5.03×10^{-1}) > *ortho*-nitrophenyl acetic acid (2.28×10^{-1}) > *para*-nitrophenol (8.49×10^{-2}).

CS has also been blended with cellulose acetate (CA) for detection of Hg^{2+}, Cu^{2+} and Zn^{2+} using the solution blending method [41]. In their work, dithizone (DTZ) was immobilized on the surface of the CS/CA blend and used as an indicator to sense the presence of metal ions that attached to them. The CS/CA blend possesses high porosity compared to its pristine form. Based on the observation through the naked eyes, the sensing material demonstrated good stability up to 90 days [41]. In the recent work by Roshidi *et al* [42], CS was blended with poly(amidoamine) dendrimer (PAMAM) via solution blending method for detection of Pb^{2+}. The optical study showed that CS/PAMAM has an optical band gap value of 4.09 eV. The surface roughness of CS/PAMAM has smooth morphological characteristics with RMS value of 0.319 nm. After the addition of Pb^{2+}, the surface roughness increases to 1.7 nm, proving that the interaction occurs between CS/PAMAM with Pb^{2+}. Interestingly, the polysaccharide in the forms of polymer blends showed improved characteristics in terms of binding ability and binding capacity of ions [41-42]. To conclude, solution blending produce homogenous films that improve the adsorption of dyes and heavy metals via inter-polymer hydrogen bonding where it provides higher stability than pure chitosan. **Table 2** provides a summary of chitosan-organic polymer blends with improved properties and target analytes.

Table 2. Summary of chitosan-organic polymer blends applications

Chitosan-Organic Polymer	Blending Method	Improved Properties	Analyte	Ref.
CS/Natural rubber	Solution blending	Surface chemistry	Methylene blue dyes	[39]
CS/Cellulose	Solution blending	Mechanical and thermal stability, higher porosity, crystallinity, roughness and surface area	Phenolic dyes	[40]
CS/Cellulose acetate	Solution blending	Stability, binding ability and mechanical strength	Hg^{2+} Cu^{2+} Zn^{2+}	[41]
CS/PAMAM	Solution blending	Optical properties, Binding capacity	Pb^{2+}	[42]

Chemical derivatives of chitosan

Another approach that is commonly employed to improve the physicochemical properties of chitosan is through chemical modification. Chemical derivatization involves covalent grafting of functional groups onto chitosan's reactive $–NH_2$ or –OH sites to enhance the sorption capacity of chitosan, surface charge and affinity toward metal ions or organic foulants. In this modification, hydrophilic functional groups are introduced in the chitosan structure by adding or substituting carboxymethyl [45-52], succinyl [53-58], and phosphonyl [59-61] functional groups with the aim of improving the physicochemical properties of chitosan.

Carboxymethyl chitosan (CMC)

It is well-known that the solubility of chitosan is limited in acidic aqueous solutions due to its very stable crystalline structure, which resulted from strong hydrogen bonds. The addition of the carboxymethyl group in chitosan remarkably improves its solubility because the presence of an additional oxygen atom that is attached to the carboxymethyl group, henceforth leads to interaction with the water molecules via hydrogen bonding [45-46]. Not only that, the degree of carboxymethylation also plays an important role in the solubility of chitosan. Likewise, the carboxymethyl group also contributes to enhance chelation of cations and sorption characteristics of chitosan due to the presence of additional oxygen atoms in the carboxymethyl group [47].

In general, there are two methods to perform the carboxymethylation process on chitosan: (i) via reductive alkylation method and (ii) direct alkylation. The first method is carried out by reacting the $-NH_2$ group of chitosan with the carbonyl group of aldehydes, glyoxylic acid and followed by hydrogenation with reductive agents; $NaBH_4$ or $NaCNBH_3$ to produce *N*-carboxymethyl chitosan. By using this method, the carboxymethyl group is exclusively attached to the N atom of the amine group rather than the oxygen (O) atom of the hydroxyl group. The second method is the utilization of monochloroacetic acid together with sodium hydroxide to produce *N*-carboxyalkyl and *O*-carboxyalkyl chitosan in various reaction conditions. Unlike the first method, this approach is influenced by the reaction condition through pH adjustment. Under alkaline medium conditions, the carboxymethyl group is prone to selectively attach on the N atom. On the contrary, at a higher alkaline medium, the alkylation process via this approach produces a mixed *N*- and *O*-alkyl chitosan derivatives [47-49]. Past studies have showed the potential of carboxymethyl chitosan used as adsorbent to specific analytes such as Al^{3+}, Li^{+}, Cu^{2+}, Zn^{2+}, Au^{3+}, lysozyme and lectin [45-52]. The structure of carboxymethyl chitosan is as shown in **Figure 4**.

Succinyl chitosan (SC)

The succinylation of chitosan can be achieved by mixing chitosan with succinic anhydride. The addition of succinyl group into chitosan inserted many reactive functional groups such as amino group, carboxyl group, as well as primary and secondary hydroxyl groups, as shown in Figure 5, which is expected to improve the adsorption properties of chitosan [53-54]. The high hydrophilicity caused by its large number of functional groups allows this material to interact with negatively charged substances. Besides, the selectivity of sorption can be enhanced by crosslinking chitosan with a suitable crosslinker. However, the crosslinking reaction leads to a reduction in adsorption capacity due to the restriction of the polymer network and loss of the chain flexibility [54].

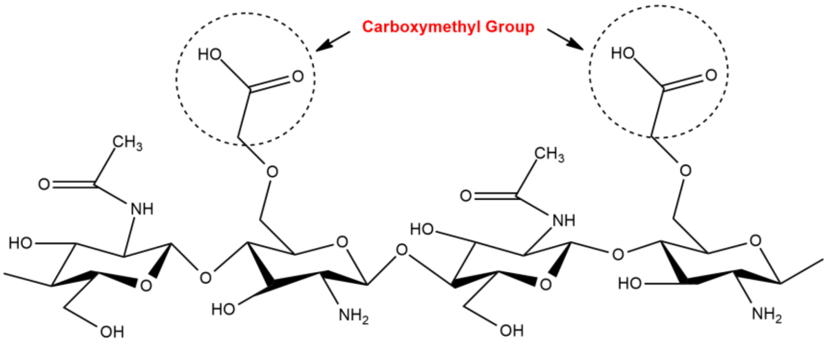


Figure 4. Structure of carboxymethyl chitosan

Sun and Wang [54] discovered the potential application of succinyl chitosan as the Pb^{2+} adsorbent. Their findings suggest that the adsorption capacity of succinyl chitosan is influenced by the substitution degree of succinyl group. The adsorption capacity of Pb^{2+} increases with the increase of substitution degree. The succinyl groups are more active than amino groups, hence making the former as the main adsorption site for Pb^{2+} binding. This conclude that adsorption capacity correlates with the substitution degree where higher substitution enhances Pb^{2+} and Cu^{2+} uptake through carboxyl-metal coordination.

Another work reported by the same group in [55] used succinyl chitosan as the adsorbent for Cu^{2+}. The selectivity towards Cu^{2+} was studied by adjusting the pH of the solution. Cu^{2+} adsorption was optimum at pH 6.2 with the maximum adsorption of 2.26 mmol/g. They further analyzed using the Langmuir adsorption isotherms model. Their findings suggest that the saturation adsorption of succinyl chitosan for Cu^{2+} is higher than that of *N, O*-carboxymethyl chitosan in their previous work of Sun and Wang (2006) [54] with 2.74 mmol/g and 2.52 mmol/g, respectively. In other reports, succinyl chitosan has also been used as an adsorbent for cationic dye [54], either by the crosslinking approach [56], or mixing with clay to form composite [57]. Based on their report, the adsorption of cationic dye was dependent on the pH and temperature during the analysis [56-58].

Phosphonic chitosan (PC)

Chitosan containing phosphonic group possesses well-known strong chelating features due to the donor effect of the amine group ($-NH_2$) into the molecule as well as the presence of monodentate ligand of $-PO_3^{2-}$ contributed by phosphonic functional group that are capable of strong metal chelation. They tend to form chelates in ring form with the possibility of different conformations due to the metal ion's properties [59]. Phosphonic chitosan is prepared by reacting chitosan with phosphorus acid and formaldehyde, as in **Figure 6**. The new chitosan derivatives have improved solubility in water as well as in organic solvents compared to pristine chitosan.

Later in 2003, the same group published other reports on the applications of phosphonic chitosan as chelator for several metal ions: Ca^{2+}, Mg^{2+}, Cd^{2+}, Cu^{2+} and Fe^{2+} [60]. Their finding suggests that phosphonic chitosan possesses lower crystallinity than pristine chitosan and it is also able to chelate other divalent metal ions. Furthermore, the addition of phosphonic group counterbalances the hydrophobic moiety with the electrostatic repulsion, hence producing the amphiphilic properties of the compound. Not only that, the addition of phosphonic functional group improves the chelating ability as well [60-61]. Table 3 shows the summary of chitosan grafted with hydrophilic functional groups for analyte adsorption.

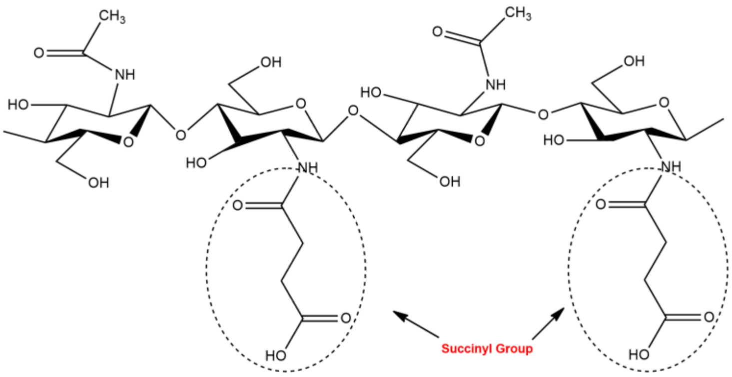


Figure 5. Structure of succinyl chitosan

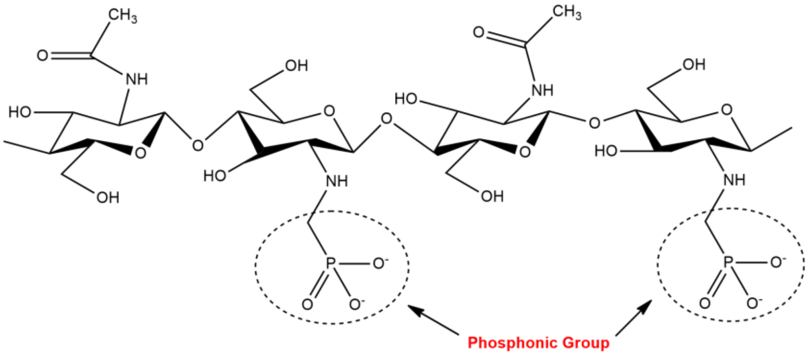
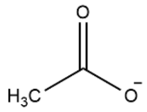
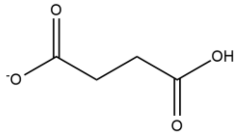
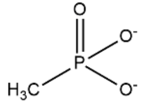


Figure 6. Structure of phosphonic chitosan

Table 3. Summary of chitosan grafted with hydrophilic functional groups for analyte adsorption

Functional Groups	Improved Properties	Analyte	Ref.
 **Carboxymethyl**	Solubility, sorption capability	Al^{3+} Li^{+} Cu^{2+} Zn^{2+} Lysozyme Au^{3+} Lectin	[45] [46] [48] [50-51] [51] [52] [49]
 **Succinyl**	Solubility, sorption capability	Zn^{2+} Cu^{2+} Pb^{2+} Cationic Dye	[53] [55] [54] [53, 56-58]
 **Phosphonic**	Solubility, crystallinity, sorption capability	Ca^{2+} Mg^{2+} Cd^{2+} Cu^{2+} Fe^{2+}	[60] [60] [60]

Applications of functionalized chitosan in water purification

Chitosan and its derivatives have been extensively studied for their diverse functional applications in water purification systems. Owing to their intrinsic antimicrobial activity, biocompatibility, and capacity to form uniform and stable coatings, they serve as promising materials for developing antifouling layers, surface modifiers, and adsorptive components in membranes used for desalination and wastewater treatment. These functionalities collectively contribute to improving membrane performance, reducing biofouling, and enhancing the overall efficiency of water treatment processes.

Antimicrobial and antifouling properties

Among these applications, one of the most significant is the antimicrobial and antifouling function of chitosan-based materials. Chitosan inherently exhibits strong antimicrobial activity against a wide range of microorganisms, including algae, bacteria, yeasts, and fungi, primarily due to its polycationic structure. The positively charged amino ($-NH_2$) groups of chitosan interact electrostatically with negatively charged microbial cell membranes, leading to cell disruption and inhibition of microbial growth [62]. This mechanism forms the foundation for its use in antifouling coatings, where microbial attachment and biofilm formation are effectively suppressed, thereby prolonging membrane lifespan and maintaining water flux stability.

Chitosan naturally exhibits notable antimicrobial properties against a range of organisms, including algae, bacteria, yeasts and fungi due to its polycationic structure. **Table 4** highlights the comparative antimicrobial analysis of native chitosan (CTS) and carboxymethyl chitosan (CMC) against negative bacteria *Escherichia coli*, *Klebsiella sp.*, *Pseudomona aeruginosa A* and *Pseudomona aeruginosa B* at concentrations of 1000 mg mL^{-1}. CMC shown strong antibacterial efficacy against *E. Coli* and *Klebsiella sp*., however it was not ineffective against *Pseudomona aeruginosa A* and *B* [57].

Studies have demonstrated that chitosan derivatives maintain or even enhance these antimicrobial effects. For instance, Abou-Zeid et al. [63] observed significant antibacterial activity of cyanoethyl chitosan against *E. coli* and *S. aureus* with MIC values of 19.5 ppm and 312 ppm, respectively, compared to 79 ppm and 625 ppm for native chitosan, while Cele et al. [64] reported that pentafluoropropionyl chitosan inhibited strong antimicrobial activity against pathogenic bacteria such as *Staphylococcus aureus* and commensal bacteria like *Streptococcus sanguinis*, both of which are commonly associated with biofilm formation. The improved performance of these derivatives is attributed to the introduction of hydrophilic and electronegative groups, which increase charge density and enhance surface hydration.

Additionally, the antimicrobial activity of chitosan derivatives are closely linked to the antifouling performance by preventing early microbial adhesion and biofilm growth on membrane surface when used as coating. Chitosan derivation can further enhances the hydrophilicity and charge repulsion where it helps to minimize the adhesion of bacteria and organic foulant on the surface. **Table 5** shows the antimicrobial activity of chitosan derivatives against wide ranges of bacteria. Carboxymethyl chitosan demonstrates excellent antimicrobial efficacy against *S. aureus* and *E. coli*, reducing viable cell counts with inhibition zone diameters of 25 mm and 30 mm, respectively [65]. Similarly, N-succinyl chitosan has shown remarkable antimicrobial activity against wide ranges of bacteria, including *S. aureus*, *Listeria*, *Salmonella*, and *E. coli*, with a minimum inhibitory concentration (MIC) value exceeding 5000 µg/mL [66]. In addition, chitosan derivatives modified with phosphorus-based compounds, such as N-methylene phosphonic chitosan (NMPC), exhibit significant antimicrobial activity against agricultural phytopathogens such as *Fusarium eumartii*, *Botrytis cinerea*, and *Phytophthora infestans*. NMPC has been shown to damage cell membranes and reduce the viability of *F. eumartii* spores [67].

Chitosan as coating materials

Chitosan is widely used as coating material specifically for filtration and desalination membranes due to its ability to form uniform and adhesive films. Chitosan-based coating improve hydrophilicity, reduce surface roughness and increase the resistance towards fouling. Studies have shown that coating membranes with chitosan significantly enhances the filtration performance. For example, Bat-Amgalan et. al [68] have reported that chitosan-coated ceramic membranes enhanced mechanical strength and the ultrafine removal of heavy metals compared to uncoated ones. The chitosan coated ceramic membrane (CCCM) demonstrated superior performance in removing Cr(VI), with a maximum removal reached of 71.25% at pH 3.

Antifouling ceramic membrane

Ceramic membranes are composed of inorganic materials commonly titania, alumina, zirconia and silica. They are often used in harsh environment such as water treatment and desalination due to their high thermal, mechanical and chemical resistance [69]. Ceramic membranes are naturally hydrophilic because of the presence of hydroxyl group (-OH) in their structure [70]. The hydrophilicity of ceramic membranes enhances its ability to attract water molecules. However, the issue of fouling is one of the major challenges in using ceramic membrane. Fouling is a phenomena where the contamination accumulated on the surface of the membranes, causing reduced filtration efficacy and increasing the need for frequent cleaning [71]. According to Li et al. [72] in his review paper, even though ceramic membranes naturally have high fouling resistance and permeability, mitigations to enhance their fouling resistance can be implemented.

One of the study to enhance antifouling properties of ceramic membrane is as demonstrated by Apriyanti et al. [73], where they have modified ceramic membrane using chitosan. The SEM images revealed that the uncoated membrane (CM) was typically rough with unselective voids, indicating that the uncoated membrane exhibits low separation performance. By contrast, the chitosan coated ceramic membrane (CCCM) exhibited smoother surface morphology, reduced pore size and increased tensile strength compared to uncoated ceramic membranes. Although the flux slightly decreased because of pore narrowing, oil rejection increased from 88% to 100%, demonstrating improved antifouling performance.

Table 4. Antimicrobial activity of CTS and CMC [57]

Organism	**Zone of Inhibition (mm)**	
	CTS	**CMC**
Escherichia coli	18.5	20.3
Klebsiella sp.	17.5	22.5
Pseudomonas aeruginosa A	8.5	–
Pseudomonas aeruginosa B	11.6	9.0

Table 5. Chitosan derivatives and its antimicrobial activity

Chitosan Derivatives	**Effect on Antimicrobial Activity**	**Ref.**
Carboxymethyl chitosan	Reduce viable cell counts of *S.aureus* and *E.coli*	[65]
N-succinyl chitosan	Exhibited antimicrobial activity against *S.aureus, Listeria, Salmonella* and *E.coli*	[66]
N-methylene phosponic chitosan	Exhibited excellent fungicidal effect on *F. eumartii, B. cinerea,* and *P. infestans*	[67]
Cyanoethyl chitosan	Enhanced antimicrobial activity *S.aureus* and *E.coli*	[63]
Pentafluoropropionyl chitosan	Exhibited antimicrobial acitivity against *S. aureus* and *S.sanguinis*	[64]

These findings aligned with Bat-Amgalan et al. [68], who stated that successful chitosan coating effectively eliminated unselective voids caused by membrane cracking. Similarly, they have reported that chitosan crosslinked with glutaraldehyde as coating material increased the resistance to fouling. The crosslinked reaction between chitosan and glutaraldehyde was confirmed by the elemental mapping. The N_2-BET showed that CCCM had a small decrease in pore size and an increase of surface area and pore volume. Comparing the CM and CCCM, the filtration performance of CCCM performed greater ultrafine filtration for the removal of Cr(VI). In addition, water absorption tests further indicated that CCCM could absorb up to 28% water for ceramic membranes sintered at 950°C, demonstrating improved hydrophilic properties which further confirming enhanced wettability and antifouling capacity. A more hydrophilic surface increases the ability to attract more water molecules rather than the contaminants due to the presence of hydration layer [74].

These studies indicate that hydrophilic modification via chitosan coating strengthens membrane–water affinity, enhances contaminant rejection and increase the resistance to fouling. **Table 6** summarizes the comparative antifouling results reported for ceramic membranes before and after chitosan coating. The porosity of CCCM decreased slightly, while their pore radius and tensile strength increased. This indicated that the chitosan coating have filled the membrane voids, and also improved its mechanical strength which enhance the integrity of the membrane. Other than that, the CCCM's performance was further assessed in terms of oil rejection, fouling resistance and permeate flux. The hydrophilic chitosan coating reduced the oil deposition on the membrane's surface, which improved the oil-water filtering. As a result, the CCCM had a lower permeate flux than uncoated CM. Cui et al. [70] provided support for these findings, stating that CM naturally reduces pore blockages and oil accumulation. From the study of Apriyanti et al. [73], it can be concluded that, the decrease of pore size after being coated with chitosan resulted in the decrease of permeate flux, proving that chitosan coating has enhanced the oil rejection rates due to the hydrophilic layer of the membrane's surface. It was also suggested that the most effective membranes for oil rejection have pore sizes in the range of 10–100 nm [73].

Dip-coating method

The surface of ceramic membranes can be modified to alter their surface properties for specific applications. These modifications are essential for improving membrane durability, fouling resistance and operational efficiency. This section provides an overview of dip-coating techniques that specifically use chitosan as the main coating substance. Physical modification methods are effective strategies to enhance ceramic membrane durability. These approaches typically involve the deposition of protective layers using polymers, nanoparticles and surfactants to improve fouling resistance and extend the operational lifespan of membranes by creating a thin protective barrier on the surface [75].

Table 6. Comparative analysis of CM and CCCM [68, 73]

Study	Parameter	CM	CCCM	Performance Observation
[68]	SEM morphology	Rough with unselective voids	Smooth, reduced voids	Reduced surface defects, improved structural integrity
	Porosity (%)	50.02	49.71	Slightly decreased due to coating layer
	Pore radius (nm)	26.41	15.84	Decrease indicates pore narrowing
	Tensile strength (MPa)	84.72	112.47	Mechanical strength increased
	Permeate flux ($Lm^{-2}h^{-1}$, 60 min)	55	20	Flux decreased slightly due to denser surface
	Oil rejection (%)	88	100	Complete rejection achieved
[73]	Surface area (m^2g^{-1})	11.3	12.1	Surface area increased
	Pore volume (cm^3g^{-1})	0.0478	0.0494	Increased hydrophilicity and adsorption capacity
	Average pore size (nm)	16.9	16.2	Reduced pore diameter
	Cr(VI) removal (%)	2.23	71.25	Significantly improved contaminant removal
	Water absorption (%)	—	28	Increased hydrophilicity

Dip-coating is one of the most practical and widely used methods for depositing chitosan layers onto ceramic membranes. This technique is low-cost, flexible and able to produce uniform coatings with controllable thickness. This statement is corroborated by Xia [76], who claims that the dip coating technique is perfect for modifying ceramic membranes since it is flexible and simple to use. In this approach, a dry substrate is dipped in a coating or suspension and then removed. Upon drying, the chitosan forms a thin hydrophilic film that adheres strongly to the ceramic surface through hydrogen bonding and electrostatic interactions with surface hydroxyl groups. According to Chen et al. [77], this procedure enables the membrane surface to absorb the suspended layer via capillary forces, enabling the formation of a compact interfacial layer.

Recent studies have shown that the dip-coating technique effectively improves the hydrophilicity, mechanical strength and antifouling performance of ceramic membranes. For instance, Apriyanti et al. prepared chitosan-coated fly-ash/kaolin membranes that exhibited a reduction in average pore size from 26.41 to 15.84 nm and an increase in tensile strength from 84.72 to 112.47 MPa. Bat-Amgalan et al. [68] also demonstrated that dip-coated chitosan layers produced an ultrafine and hydrophilic surface structure, effectively filling surface voids and narrowing pores. Furthermore, Jana et al. reported that increasing the chitosan concentration and dipping time further reduced pore size and achieved nearly 100% removal of mercury and arsenic from wastewater [78]. To conclude, the dip-coating method is a reliable and scalable approach to fabricate hydrophilic, smoother and more durable chitosan-based coatings that enhance the performance of ceramic membranes in water purification and desalination processes.

Challenges and future perspective

Although there are significant advancements in developing chitosan for water purification, several challenges remain before these materials can be effectively used in industrial and real-world scales. One of the major concerns is to ensure the durability and operational stability of chitosan-based coating under real purification conditions, which typically involve variable pH environments, high pressures and exposure to foulants and contaminants [79-81]. Although numerous studies have proven enhanced hydrophilicity and antifouling performance, the long-term stability of these coatings remains insufficiently investigated, as most assessments are confined to short-term filtration cycles [82]. Future research should therefore emphasize improving coating adhesion and chemical robustness to maintain both structural stability and biodegradability. Moreover, the requirement for uniform synthesis and testing procedures is another crucial element. Accurate comparisons between research are currently hindered by variations in preparation processes, characterization methods and antifouling evaluation approaches. It will be possible to create replicable standards for various research by standardizing characteristics like coating technique, coating thickness and contact angle. Both toxicological and environmental factors are equally important for future development, where certain chemical modification methods use solvents or crosslinkers that could be harmful to the environment or human health if released to the environment. Thus, to improve the environmental compatibility of chitosan derivatives, greener synthesis techniques should be investigated to guarantee environmental safety during large-scale implementation. Looking ahead, the integration of chitosan-based coatings in advanced water treatment technologies could offer promising impact to the future. The combination of functionalized chitosan layers with nanofiltration membranes, catalytic interfaces or even AI-assisted monitoring platforms could enable real-time fouling detection, self-cleaning functionality or adaptive process optimization. In summary, overcoming these challenges will be crucial for converting chitosan-based coatings from promising material into more flexible and robust solutions for water purification.

Conclusion

Chitosan and its derivatives have proven to be remarkable materials in the ongoing efforts to mitigate the effects of water pollution, effectively removing heavy metals, dyes, oil and organic contaminants from water sources by offering tunable surface chemistry, excellent biocompatibility and potential for dual applications in adsorption and antifouling membrane coating [45, 70-71]. By leveraging both physical and chemical modifications, researchers have significantly enhanced chitosan's solubility, charge density and surface hydrophilicity, resulting in improved pollutant adsorption, fouling resistance and mechanical durability. chitosan's adsorption capacity, mechanical strength, and resistance to fouling, particularly through the introduction of electronegative and hydrophilic groups such as carboxymethyl, succinyl and phosphonic moieties, together with physical reinforcement via graphene oxide and polymer blends. It has provided valuable insight into the structure–property–performance relationships that govern adsorption efficiency and membrane stability. The development of chitosan-coated ceramic membranes (CCCMs) has further revolutionized water purification by improving membrane durability and permeability, making them a promising material in modern filtration systems [83-84]. With these efforts, chitosan-based materials are poised to play a crucial role in shaping a cleaner, more sustainable future for global water management [85,86]. Dip-coating has proven to be a particularly practical and scalable route for fabricating defect-free, hydrophilic and uniform chitosan films on ceramic supports. Despite these advancements, several challenges persist in converting laboratory-scale findings into real-world systems. The long-term durability of chitosan-based coatings under variable pH and high-pressure conditions remains inadequately assessed, while inconsistent synthesis and testing protocols hinder direct comparison between studies. Environmental and toxicological concerns arising from solvent use and crosslinking chemistry also need to be addressed to ensure safe and sustainable implementation. Future progress will depend on the development of standardized methodologies, greener modification strategies and scalable fabrication processes as well as the integration in advanced water treatment technologies towards more sustainable purification systems.

Acknowledgement

The authors would like to thank the Ministry of Science, Technology and Innovation (MOSTI), Malaysia, for funding this project under the Fundamental Research Grant Scheme (FRGS), FRGS/1/2024/STG04/UKM/02/5.

References

1. Crini, G., Lichtfouse, E., Wilson, L. D., and Morin-Crini, N. (2019). Conventional and non-conventional adsorbents for wastewater treatment. *Environmental Chemistry Letters*, 17(1), 195–213.
2. Riegel, M., Haist-Gulde, B., and Sacher, F. (2023). Sorptive removal of short-chain perfluoroalkyl substances (PFAS) during drinking water treatment using activated carbon and anion exchanger. *Environmental Sciences Europe*, 35(1), 12.
3. Yaqub, M., Nguyen, M. N., and Lee, W. (2022). Treating reverse osmosis concentrate to address scaling and fouling problems in zero-liquid discharge systems: A scientometric review of global trends. *Science of The Total Environment*, 844, 157081.
4. Latańska, I., Rosiak, P., Paul, P., Sujka, W., and Kolesińska, B. (2021). Modulating the physicochemical properties of chitin and chitosan as a method of obtaining new biological properties of biodegradable materials. In *Chitin and Chitosan - Physicochemical Properties and Industrial Applications*. IntechOpen.
5. Patel, A. K. (2015). Chitosan: Emergence as potent candidate for green adhesive market. *Biochemical Engineering Journal*, *102*, 74–81.
6. Pradines, B., Bories, C., Vauthier, C., Ponchel, G., Loiseau, P. M., and Bouchemal, K. (2015). Drug-free chitosan coated poly(isobutylcyanoacrylate) nanoparticles are active against trichomonas vaginalis and non-toxic towards pig *Vaginal mucosa*. *Pharmaceutical Research*, 32(4), 1229–1236.
7. Bradić, B., Bajec, D., Pohar, A., Novak, U., and Likozar, B. (2018). A reaction–diffusion kinetic model for the heterogeneous N-deacetylation step in chitin material conversion to chitosan in catalytic alkaline solutions. *Reaction Chemistry and Engineering*, 3(6), 920–929.
8. Benettayeb, A., Seihoub, F. Z., Pal, P., Ghosh, S., Usman, M., Chia, C. H., Usman, M., and Sillanpää, M. (2023). Chitosan nanoparticles as potential nano-sorbent for removal of toxic environmental pollutants. *Nanomaterials*, 13(3), 447.
9. Kyzas, G., and Bikiaris, D. (2015). Recent modifications of chitosan for adsorption applications: A critical and systematic review. *Marine Drugs*, 13(1), 312–337.
10. Aranaz, I., Alcántara, A. R., Civera, M. C., Arias, C., Elorza, B., Caballero, A. H., and Acosta, N. (2021). Chitosan: An overview of its properties and applications. *Polymers*, 13(19), 3256.
11. Wu, Q.-X., Lin, D.-Q., and Yao, S.-J. (2014). Design of chitosan and its water soluble derivatives-based drug carriers with polyelectrolyte complexes. *Marine Drugs*, 12(12), 6236–6253.
12. Ahmed, M. J., Hameed, B. H., and Hummadi, E. H. (2020). Review on recent progress in chitosan/chitin-carbonaceous material composites for the adsorption of water pollutants. *Carbohydrate Polymers*, 247, 116690.
13. Hsu, C.-Y., Ajaj, Y., Mahmoud, Z. H., Kamil Ghadir, G., Khalid Alani, Z., Hussein, M. M., Abed Hussein, S., Morad Karim, M., Al-khalidi, A., Abbas, J. K., Hussein Kareem, A., and kianfar, E. (2024). Adsorption of heavy metal ions use chitosan/graphene nanocomposites: A review study. *Results in Chemistry*, 7, 101332.
14. M. Fathil, M. A., Faris Taufeq, F. Y., Suleman Ismail Abdalla, S., and Katas, H. (2022). Roles of chitosan in synthesis, antibacterial and anti-biofilm properties of bionano silver and gold. *RSC Advances*, 12(30), 19297–19312.
15. Ren, W., Tang, Q., Cao, H., Wang, L., and Zheng, X. (2023). Biological preparation of chitosan-loaded silver nanoparticles: Study of methylene blue adsorption as well as antibacterial properties under light. *ACS Omega*, 8(25), 22998–23007.

16. Sharma, A. R., Lee, Y.-H., Bat-Ulzii, A., Bhattacharya, M., Chakraborty, C., and Lee, S.-S. (2022). Recent advances of metal-based nanoparticles in nucleic acid delivery for therapeutic applications. *Journal of Nanobiotechnology*, 20(1), 501.
17. Xu, W., Yang, T., Liu, S., Du, L., Chen, Q., Li, X., Dong, J., Zhang, Z., Lu, S., Gong, Y., Zhou, L., Liu, Y., and Tan, X. (2022). Insights into the Synthesis, types and application of iron Nanoparticles: The overlooked significance of environmental effects. *Environment International*, 158, 106980.
18. Collado-González, M., Montalbán, M. G., Peña-García, J., Pérez-Sánchez, H., Víllora, G., and Díaz Baños, F. G. (2017). Chitosan as stabilizing agent for negatively charged nanoparticles. *Carbohydrate Polymers*, 161, 63–70.
19. Franconetti, A., Carnerero, J. M., Prado-Gotor, R., Cabrera-Escribano, F., and Jaime, C. (2019). Chitosan as a capping agent: Insights on the stabilization of gold nanoparticles. *Carbohydrate Polymers*, 207, 806–814.
20. Wu, S., Li, K., Dai, X., Zhang, Z., Ding, F., and Li, S. (2020). An ultrasensitive electrochemical platform based on imprinted chitosan/gold nanoparticles/graphene nanocomposite for sensing cadmium (II) ions. *Microchemical Journal*, 155, 104710.
21. Ghulam, A. N., dos Santos, O. A. L., Hazeem, L., Pizzorno Backx, B., Bououdina, M., and Bellucci, S. (2022). Graphene oxide (GO) materials—applications and toxicity on living organisms and environment. *Journal of Functional Biomaterials*, 13(2), 77.
22. Rana, K., Kaur, H., Singh, N., Sithole, T., and Siwal, S. S. (2024). Graphene-based materials: Unravelling its impact in wastewater treatment for sustainable environments. *Next Materials*, 3, 100107.
23. Lokman, N. F., Bakar, A. A. A., Suja, F., Abdullah, H., Rahman, W. B. W. A., Huang, N.-M., and Yaacob, M. H. (2014). Highly sensitive SPR response of Au/chitosan/graphene oxide nanostructured thin films toward Pb (II) ions. *Sensors and Actuators B: Chemical*, 195, 459–466.
24. Alves, D. C. da S., Healy, B., Yu, T., and Breslin, C. B. (2021). Graphene-based materials immobilized within chitosan: Applications as adsorbents for the removal of aquatic pollutants. *Materials*, 14(13), 3655.
25. Lokman, N. F., Azeman, N. H., Suja, F., Arsad, N., and Bakar, A. A. A. (2019). Sensitivity enhancement of Pb(II) ion detection in rivers using SPR-based Ag metallic layer coated with chitosan–graphene oxide nanocomposite. *Sensors*, 19(23), 5159.
26. Lesiak, A., Drzozga, K., Cabaj, J., Bański, M., Malecha, K., and Podhorodecki, A. (2019). optical sensors based on II-VI quantum dots. *Nanomaterials*, 9(2), 192.
27. Şahin, S., Ergüder, Ö., Trabzon, L., and Ünlü, C. (2023). Quantum dots for sensing applications. In *Fundamentals of Sensor Technology* (pp. 443–473). Elsevier.
28. Tshangana, C. S., Muleja, A. A., Kuvarega, A. T., Malefetse, T. J., and Mamba, B. B. (2021). The applications of graphene oxide quantum dots in the removal of emerging pollutants in water: An overview. *Journal of Water Process Engineering*, 43, 102249.
29. Mahmoud, M. E., Amira, M. F., Daniele, S., El Nemr, A., Abouelanwar, M. E., and Morcos, B. M. (2023). Recovery of silver and gold quantum dots from wastewater via coagulative adsorption onto $CoFe_2O_4$ based magnetic covalent-organic framework to generate efficient nanocatalysts for degradation of doxorubicin drug. *Journal of Water Process Engineering*, 51, 103409.
30. Marpu, S. B., and Benton, E. N. (2018). Shining light on chitosan: A review on the usage of chitosan for photonics and nanomaterials research. *International Journal of Molecular Sciences*, 19(6), 1795.
31. Nie, Q., Tan, W. B., and Zhang, Y. (2006). Synthesis and characterization of monodisperse chitosan nanoparticles with embedded quantum dots. *Nanotechnology*, 17(1), 140–144.
32. Yuan, Q., Hein, S., and Misra, R. D. K. (2010). New generation of chitosan-encapsulated ZnO quantum dots loaded with drug: Synthesis, characterization and in vitro drug delivery response. *Acta Biomaterialia*, 6(7), 2732–2739.
33. Anas, N. A. A., Fen, Y. W., Omar, N. A. S., Ramdzan, N. S. M., Daniyal, W. M. E. M. M., Saleviter, S., and Zainudin, A. A. (2019). Optical properties of chitosan/hydroxyl-functionalized graphene quantum dots thin film for potential optical detection of ferric (III) ion. *Optics and Laser Technology*, 120, 105724.
34. Ramdzan, N. S. M., Fen, Y. W., Omar, N. A. S., Anas, N. A. A., Daniyal, W. M. E. M. M., Saleviter, S., and Zainudin, A. A. (2019). Optical and surface plasmon resonance sensing properties for chitosan/carboxyl-functionalized graphene quantum dots thin film. *Optik*, 178, 802–812.
35. Johns, J., and Rao, V. (2011). Adsorption of methylene blue onto natural rubber/chitosan blends. *International Journal of Polymeric Materials*, 60(10), 766–775.
36. Markovic, G., and Visakh, P. M. (2017). Polymer blends. In *Recent Developments in Polymer Macro, Micro and Nano Blends* (pp. 1–15). Elsevier.

37. Elhefian, E. A., El-Hefian, E. A., Nasef, M. M., and Yahaya, A. H. (2014). Chitosan-based polymer blends: current status and applications. *Journal Chemical Society Pakistan,* 36, 1.
38. Albadarin, A. B., Collins, M. N., Naushad, M., Shirazian, S., Walker, G., and Mangwandi, C. (2017). Activated lignin-chitosan extruded blends for efficient adsorption of methylene blue. *Chemical Engineering Journal*, 307, 264–272.
39. Rao, V., and Johns, J. (2008). Mechanical properties of thermoplastic elastomeric blends of chitosan and natural rubber latex. *Journal of Applied Polymer Science*, 107(4), 2217–2223.
40. Udoetok, I. A., Wilson, L. D., and Headley, J. V. (2016). Self-Assembled and Cross-linked animal and plant-based polysaccharides: Chitosan–cellulose composites and their anion uptake properties. *ACS Applied Materials and Interfaces*, 8(48), 33197–33209.
41. Azmi, N. A., and Low, S. C. (2017). Investigating film structure of membrane-based colorimetric sensor for heavy metal detection. *Journal of Water Process Engineering*, 15, 37–42.
42. Roshidi, M. D. A., Fen, Y. W., Daniyal, W. M. E. M. M., Omar, N. A. S., and Zulholinda, M. (2019). Structural and optical properties of chitosan–poly(amidoamine) dendrimer composite thin film for potential sensing Pb^{2+} using an optical spectroscopy. *Optik*, 185, 351–358.
43. Wang, J., and Zhuang, S. (2017). Removal of various pollutants from water and wastewater by modified chitosan adsorbents. *Critical Reviews in Environmental Science and Technology*, 47(23), 2331–2386.
44. Syeda, S. E. Z., Khan, M. S., and Skwierawska, A. M. (2024). Chitosan-based modalities with multifunctional attributes for adsorptive mitigation of hazardous metal contaminants from wastewater. *Desalination and Water Treatment*, 320, 100679.
45. Bai, R., Zhang, X., Yong, H., Wang, X., Liu, Y., and Liu, J. (2019). Development and characterization of antioxidant active packaging and intelligent Al^{3+}-sensing films based on carboxymethyl chitosan and quercetin. *International Journal of Biological Macromolecules*, 126, 1074–1084.
46. Mobarak, N. N., Jantan, F. N., Dzulkurnain, N. A., Ahmad, A., and Abdullah, M. P. (2018). Kesan garam litium nitrat terhadap sifat elektrokimia karboksimetil kitosan. *Sains Malaysiana*, 47(9), 2091–2098.
47. Mourya, V. K., Inamdara, N., and Ashutosh T. N. (2010). Carboxymethyl chitosan and its applications. *Advanced Materials Letters*, 1(1), 11–33.
48. Chen, S., Ding, R., Ma, X., Xue, L., Lin, X., Fan, X., and Luo, Z. (2016). Preparation of highly dispersed reduced graphene oxide modified with carboxymethyl chitosan for highly sensitive detection of trace Cu(II) in water. *Polymers*, 8(4), 78.
49. Liu, Z., Liu, H., Wang, L., and Su, X. (2016). A label-free fluorescence biosensor for highly sensitive detection of lectin based on carboxymethyl chitosan-quantum dots and gold nanoparticles. *Analytica Chimica Acta*, 932, 88–97.
50. Ma, Q., Lin, Z.-H., Yang, N., Li, Y., and Su, X.-G. (2014). A novel carboxymethyl chitosan–quantum dot-based intracellular probe for Zn^{2+} ion sensing in prostate cancer cells. *Acta Biomaterialia*, 10(2), 868–874.
51. Song, Y., Li, Y., Liu, Z., Liu, L., Wang, X., Su, X., and Ma, Q. (2014). A novel ultrasensitive carboxymethyl chitosan-quantum dot-based fluorescence "turn on–off" nanosensor for lysozyme detection. *Biosensors and Bioelectronics*, 61, 9–13.
52. Wan Ngah, W. S., and Liang, K. H. (1999). Adsorption of gold(III) ions onto chitosan and *n* -carboxymethyl chitosan: Equilibrium studies. *Industrial and Engineering Chemistry Research*, 38(4), 1411–1414.
53. Kyzas, G. Z., Siafaka, P. I., Pavlidou, E. G., Chrissafis, K. J., and Bikiaris, D. N. (2015). Synthesis and adsorption application of succinyl-grafted chitosan for the simultaneous removal of zinc and cationic dye from binary hazardous mixtures. *Chemical Engineering Journal*, 259, 438–448.
54. Sun, S., and Wang, A. (2006). Adsorption properties of N-succinyl-chitosan and cross-linked N-succinyl-chitosan resin with Pb(II) as template ions. *Separation and Purification Technology*, 51(3), 409–415.
55. Sun, S., Wang, Q., and Wang, A. (2007). Adsorption properties of Cu(II) ions onto N-succinyl-chitosan and crosslinked N-succinyl-chitosan template resin. *Biochemical Engineering Journal*, 36(2), 131–138.
56. Li, Q., Zhao, Y., Wang, L., and Aiqin, W. (2011). Adsorption characteristics of methylene blue onto the N-succinyl-chitosan-g-polyacrylamide/attapulgite composite. *Korean Journal of Chemical Engineering*, 28(8), 1658–1664.
57. Olanipekun, E. O., Ayodele, O., Olatunde, O. C., and Olusegun, S. J. (2021). Comparative studies of chitosan and carboxymethyl chitosan doped with nickel and copper: Characterization and

antibacterial potential. *International Journal of Biological Macromolecules*, 183, 1971–1977.

58. Huang, X.-Y., Bu, H.-T., Jiang, G.-B., and Zeng, M.-H. (2011). Cross-linked succinyl chitosan as an adsorbent for the removal of Methylene Blue from aqueous solution. *International Journal of Biological Macromolecules*, *49*(4), 643–651.
59. Ramos, V. M., Rodríguez, M. S., Agulló, E., Rodríguez, N. M., and Heras, A. (2002). Chitosan with phosphonic and carboxylic group: New multidentate ligands. *International Journal of Polymeric Materials*, 51(8), 711–720.
60. Ramos, V. M., Rodríguez, N. M., Díaz, M. F., Rodríguez, M. S., Heras, A., and Agulló, E. (2003). N-methylene phosphonic chitosan. Effect of preparation methods on its properties. *Carbohydrate Polymers*, 52(1), 39–46.
61. Heras, A. (2001). N-methylene phosphonic chitosan: A novel soluble derivative. *Carbohydrate Polymers*, 44(1), 1–8.
62. Yilmaz Atay, H. (2020). Antibacterial activity of chitosan-based systems. *Functional Chitosan*, 2020, 457.
63. Abou-Zeid, N. Y., Waly, A. I., Kandile, N. G., Rushdy, A. A., El-Sheikh, M. A., and Ibrahim, H. M. (2011). Preparation, characterization and antibacterial properties of cyanoethylchitosan/ cellulose acetate polymer blended films. *Carbohydrate Polymers*, 84(1), 223–230.
64. Cele, Z. E. D., Somboro, A. M., Amoako, D. G., Ndlandla, L. F., and Balogun, M. O. (2020). Fluorinated quaternary chitosan derivatives: Synthesis, characterization, antibacterial activity, and killing kinetics. *ACS Omega*, *5*(46), 29657.
65. Farag, R., and Mohamed, R. (2012). Synthesis and characterization of carboxymethyl chitosan nanogels for swelling studies and antimicrobial activity. *Molecules*, 18(1), 190–203.
66. Niu, X., Zhu, L., Xi, L., Guo, L., and Wang, H. (2020). An antimicrobial agent prepared by N-succinyl chitosan immobilized lysozyme and its application in strawberry preservation. *Food Control*, 108, 106829.
67. Mesas, F. A., Terrile, M. C., Silveyra, M. X., Zuñiga, A., Rodriguez, M. S., Casalongué, C. A., and Mendieta, J. R. (2021). The water-soluble chitosan derivative, n-methylene phosphonic chitosan, is an effective fungicide against the phytopathogen *Fusarium eumartii*. *The Plant Pathology Journal*, 37(6), 533–542.
68. Bat-Amgalan, M., Miyamoto, N., Kano, N., Yunden, G., and Kim, H. J. (2022). Preparation and characterization of low-cost ceramic membrane coated with chitosan: Application to the ultrafine filtration of Cr(VI). *Membranes*, 12(9), 835.
69. He, Z., Lyu, Z., Gu, Q., Zhang, L., and Wang, J. (2019). Ceramic-based membranes for water and wastewater treatment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *578*, 123513.
70. Cui, Q., Shang, Y., Fei, Z., Tu, T., and Yan, S. (2022). Hydrophobic-hydrophilic janus ceramic membrane for enhancing the waste heat recovery from the stripped gas in the carbon capture process. *ACS Sustainable Chemistry and Engineering*, 10(12), 3817–3828.
71. Jiang, S., Li, Y., and Ladewig, B. P. (2017). A review of reverse osmosis membrane fouling and control strategies. *Science of the Total Environment*, 595, 567–583.
72. Li, C., Sun, W., Lu, Z., Ao, X., and Li, S. (2020). Ceramic nanocomposite membranes and membrane fouling: A review. *Water Research*, 175, 115674.
73. Apriyanti, E., Susanto, H., and Widiasa, I. N. (2023). Chitosan-modified fly-ash/kaolin ceramic membrane for enhancing FOG-water separation performance. *Reaktor*, 1(1), 26–36.
74. Gul, A., Hruza, J., and Yalcinkaya, F. (2021). Fouling and chemical cleaning of microfiltration membranes: A mini-review. *Polymers*, 13(6), 846.
75. Ewis, D., Ismail, N. A., Hafiz, M. A., Benamor, A., and Hawari, A. H. (2021). Nanoparticles functionalized ceramic membranes: fabrication, surface modification, and performance. *Environmental Science and Pollution Research International*, 28(10), 12256–12281.
76. Xia, C. (2000). Preparation of yttria stabilized zirconia membranes on porous substrates by a dip-coating process. *Solid State Ionics*, 133(3–4), 287–294.
77. Chen, M., Heijman, S. G. J., and Rietveld, L. C. (2021). State-of-the-art ceramic membranes for oily wastewater treatment: Modification and application. *Membranes,* 11(11), 888.
78. Changmai, M., and Purkait, M. K. (2018). Detailed study of temperature-responsive composite membranes prepared by dip coating poly (2-ethyl-2-oxazoline) onto a ceramic membrane. *Ceramics International*, 44(1), 959–968.
79. Cai, Y.-H., Yang, X. J., and Schäfer, A. I. (2020). Removal of naturally occurring strontium by nanofiltration/reverse osmosis from groundwater. *Membranes*, 10(11), 321.
80. Ezaier, Y., Hader, A., Latif, A., Khan, M. E., Ali, W., Ali, S. K., Khan, A. U., Bashiri, A. H., Zakri, W., Yusuf, M., Rajamohan, N., and Ibrahim, H. (2024). Solving the fouling mechanisms in composite membranes for water purification: An advance approach. *Environmental Research*, 250, 118487.

81. Liu, X.-Y., Chen, Y.-B., Fu, J., Zhu, X., Lv, L.-Y., Sun, L., Zhang, G.-M., and Ren, Z.-J. (2024). A review of combined fouling on high-pressure membranes in municipal wastewater reuse: Behaviors, mechanisms, and pretreatment mitigation strategies. *Chemical Engineering Journal*, 485, 150135.
82. Yue, Y., Hou, K., Chen, J., Cheng, W., Wu, Q., Han, J., and Jiang, J. (2022). Ag/AgBr/$AgVO_3$ photocatalyst-embedded polyacrylonitrile/poly amide/chitosan nanofiltration membrane for integrated filtration and degradation of RhB. *ACS Applied Materials and Interfaces*, 14(21), 24708–24719.
83. Bellich, B., D'Agostino, I., Semeraro, S., Gamini, A., and Cesàro, A. (2016). "The good, the bad and the ugly" of chitosans. *Marine Drugs*, 14(5), 99.
84. Sagheer, F. A. Al, Al-Sughayer, M. A., Muslim, S., and Elsabee, M. Z. (2009). Extraction and characterization of chitin and chitosan from marine sources in Arabian Gulf. *Carbohydrate Polymers*, 77(2), 410–419.
85. Mironenko, A., Modin, E., Sergeev, A., Voznesenskiy, S., and Bratskaya, S. (2014). Fabrication and optical properties of chitosan/Ag nanoparticles thin film composites. *Chemical Engineering Journal*, 244, 457–463.
86. Omar, N., Fen, Y., Saleviter, S., Daniyal, W., Anas, N., Ramdzan, N., and Roshidi, M. (2019). Development of a graphene-based surface plasmon resonance optical sensor chip for potential biomedical application. *Materials*, 12(12),1928.