

## **Chitosan Nanocomposites-Based Electrochemical Sensors: A Review**

### **Abstract**

Chitosan nanocomposites represent a promising class of materials formed by combining chitosan with various nanomaterials. This innovative approach leverages the advantageous properties of both chitosan—a biopolymer known for its biocompatibility, natural abundance, high film-formability, and tunable functionality—and nanomaterials, which exhibit enhanced properties such as high surface area, electrical conductivity, and catalytic activity. While chitosan alone is limited by its low electrical conductivity and mechanical strength, its integration with nanomaterials addresses these shortcomings, enhancing its utility in electrochemical sensing applications. This review comprehensively summarizes recent advancements in chitosan-based nanocomposites, mainly focusing on their application in electrochemical sensors. It discusses the various nanocomposites combined with metals, metal oxides, carbon-based materials, and other nanostructures. The review highlights the synthesis methods, performance metrics, and potential applications of these sensors across fields such as environmental monitoring, food safety, medical diagnostics, and pharmaceuticals. Emphasis is placed on the advancements over the past five years, with a discussion on the significant impact these sensors have had in detecting critical analytes like heavy metals, neurotransmitters, glucose, and reactive oxygen species.

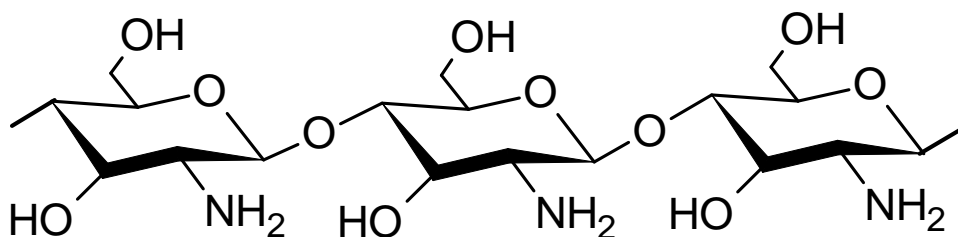
**Keywords:** Chitosan Nanocomposites, Electrochemical Sensors, Nanomaterials, Environmental Monitoring, Biosensors, Analytical Chemistry

## 1.0 Introduction

Chitosan, a biopolymer derived from chitin, possesses several distinctive properties that make it a valuable material in various applications. It is recognized for its biocompatibility, biodegradability, versatility, high film-formability, tunable functionality, and gel-forming capabilities (Kumar et al., 2019; Karrat& Amine, 2020). Certain undesirable properties of chitosan such as its non-conductivity have limited its application in the preparation of sensors of interest (Amjadi et al., 2020; Chauhan & Thakur, 2023), therefore its combination with Nanomaterials provides an opportunity to improve sensitivity, better electron transfer kinetics and wider applications (Karrat& Amine, 2020, Liu and Wang 2020, Sivanesan et al., 2021; Spoyal et al., 2021 Wypij et al., 2023).

Chitosan's structure is based on two monomeric units repeating units of deacetylated D-glucosamine and Nacetyl-D-glucosamine, which are linked by glycosidic  $\beta$ -bond (1 $\rightarrow$ 4) to form a chain polymer (Zargar *et al.*, 2015; Karrat& Amine, 2020), as displayed in Figure 1. Of the several biopolymers that exist, chitosan has been recognized as the most important for electrochemical purposes (Vinodh et al., 2021). It is the most important derivative of chitin (Raja, 2020), a naturally existing polymer that forms the structural basis of all exoskeletons of arthropods (such as crabs, shrimps, and insects) and the endoskeletons of cephalopods (e.g cuttlefish) (Karrat& Amine, 2020). It is found more abundantly in the shells of crabs, prawns, and lobsters, making them the main source of industrial extraction (Broqu et *al.*, 2019; Vinodhet *al.*, 2021). The discovery of chitosan began by chance by Charles Hatchett in 1799 when he treated crab shells and shrimps with acetone and dilute nitric acid and found a color change in the shells into pale yellow (Iber et al., 2022).

Chitosan's ability to act as a stabilizing agent for biological components, combined with its excellent film-forming properties, has spurred significant interest in its use in electrochemical sensors (Muthusankar&Ragupathy, 2018; Kumar et al., 2019).



**Figure 1.** Chemical structure of chitosan biopolymer.

This review provides a detailed analysis of recent advancements in chitosan-based nanocomposites for electrochemical sensing applications. It explores different types of chitosan nanocomposites, their preparation methods, and their performance in detecting various analytes, including heavy metals, neurotransmitters, glucose, and reactive oxygen species.

## 1.1 Properties of Chitosan

### 1.1.2 Physical properties of chitosan

Chitosan, a biopolymer derived from chitin, exhibits a range of physical properties that are influenced by factors such as the degree of deacetylation (DDA) and molecular weight (MW) (Pellis et al., 2022). These properties are crucial as they affect the polymer's applicability in various fields (Rahman & Goswami, 2021). The physical properties of chitosan, such as its ability to form films, fibers, and gels, as well as its solution, chemical, and biological characteristics, are foundational to its use in biomedical applications (Morin-Crini et al., 2019). Despite its versatility, chitosan films often have weaker mechanical properties than synthetic polymers. However, physical

treatments like high-pressure homogenization can enhance these properties, as shown by improved tensile strength and elongation in treated chitosan films (Flores et al., 2021).

### **1.1.3 Chemical Properties of Chitosan**

Chitosan exhibits various chemical properties influenced by its degree of acetylation and molecular weight, affecting its solubility, biodegradability, and bioactive attributes (Lizardi-Mendoza et al., 2016). Functional hydroxyl and amine groups on Chitosan allow various chemical modifications, such as acylation, alkylation, and graft copolymerization, to tailor its physicochemical and biochemical properties for specific applications (Merzendorfer, 2019). The solvation of Chitosan in different acids can alter its physico-chemical properties, as demonstrated by the acid solvation effect on the antibacterial activity and physico-chemical properties of chitosan membranes (Piegat et al., 2020).

While Chitosan's chemical interactions and modifications can enhance specific properties, they do not necessarily predict its binding abilities, as no correlation was found between its physicochemical properties and fat- or bile acid-binding capacities (Zou et al., 2016). Moreover, the solubilization of Chitosan in dicarboxylic acid solutions can lead to chemical crosslinking, affecting its conformational, mechanical, and thermal characteristics (Zhang et al., 2022).

### **1.1.4 Mechanical Properties of Chitosan**

The mechanical properties of chitosan, a biodegradable and biocompatible biopolymer, are of significant interest due to their relevance in various applications, such as tissue engineering and biocomposite materials (Islam M et al., 2020). Chitosan's mechanical characteristics can be enhanced by incorporating nanoparticles, which improve thermal and mechanical properties, including dynamic mechanical behavior, making it suitable for bone and wound tissue engineering (Gupta et

al., 2023). Mechanical and topographical properties of chitosan hydrogels have been characterized using atomic force microscopy, revealing specific elastic modulus distributions crucial for understanding cell-material interactions (Ben Bouali et al., 2020).

Contradictorily, while chitosan films inherently possess inferior mechanical properties compared to synthetic polymers, their mechanical strength can be improved through physical methods such as high-pressure homogenization, which has been shown to significantly enhance tensile strength and elongation (Chaudhary et al., 2022). Moreover, adding hybrid spinel/cellulose filler to chitosan composites has improved dielectric, magnetic, and mechanical properties, including Young's modulus and tensile strength (Chybczyńska et al., 2019). Magnetic chitosan hydrogels also benefit from including magnetic nanoparticles, which confer improved mechanical strength and other functional properties (Niu et al., 2023).

## **2.0 Synthesis of Chitosan-Nanomaterial**

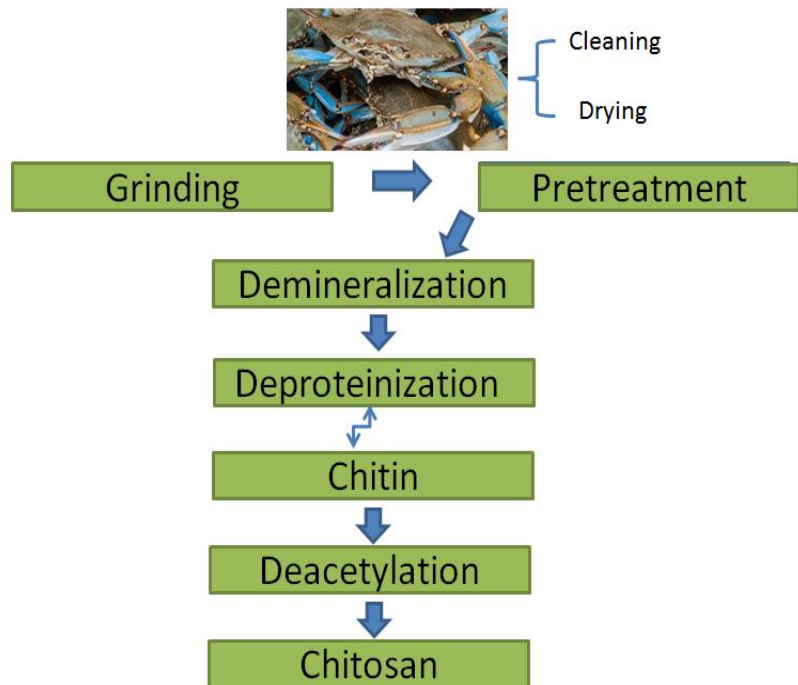
### **2.1.1 Synthesis of Chitosan**

Chitosan is the synthetic derivative of the second most abundant polysaccharide biopolymer, chitin (Negmet *al.*, 2020; Zouaouiet *al.*, 2020; Iñiguez-Moreno *et al.*, 2021) whose structural component is based on 2-acetamido-2-deoxy- $\beta$ -D-glucose linked by  $\beta$ -bonds (1 $\rightarrow$ 4). It is its deacetylated derivative, obtained through three major stages: Demineralization, Deproteinization, and Deacetylation.

Demineralization is carried out to eliminate the mineral contents of the crude source material which consists of calcium carbonate and calcium chloride. (Zouaouiet *al.*, 2020; Vinodh, *et al.*,

2021; El-Araby *et al.*, 2022; Kandile *et al.*, 2018). The deproteinization step involves the use of sodium hydroxide solution to remove protein contents before the deacetylation process to obtain chitin, whose hydrophobic nature limits its uses, owing to the presence of several acetyl groups. (Zouaoui *et al.*, 2020, El Knidri *et al.*, 2018). The final and most important stage in the conversion of chitin to chitosan is the deacetylation process involving the use of concentrated alkali at an elevated temperature to produce at least a 70% deacetylation (Ling *et al.*, 2018; Muthusankar & Ragupathy 2018; Vinodh, *et al.*, 2021). The degree of deacetylation of chitin also controls the proportion of acetyl groups and amine present in the polymer, which in turn influences the acid-base behavior of the resulting product (Zouaoui *et al.*, 2020, Vinodh, *et al.*, 2021,). Spectroscopic methods such as UV-vis, Infrared (IR), Nuclear Magnetic Resonance (NMR), High-performance liquid chromatography (HPLC) analysis, and Conductometric and Potentiometric (Kumar *et al.*, 2019, Zouaoui *et al.*, 2020). For the resulting product to be considered chitosan, it must have a degree of deacetylation of over 50%. Figure 2 provides a summary of the processes involved in the conversion of crab source material into chitosan.

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**Figure 2.** Preparation of Chitosan from Crabshell source.

### 2.1.2 Synthesis of Nanomaterials

Generally, nanomaterials are synthesized via two main approaches namely the top-down method and the bottom-up method (Kaabipouret *al.*, 2021).

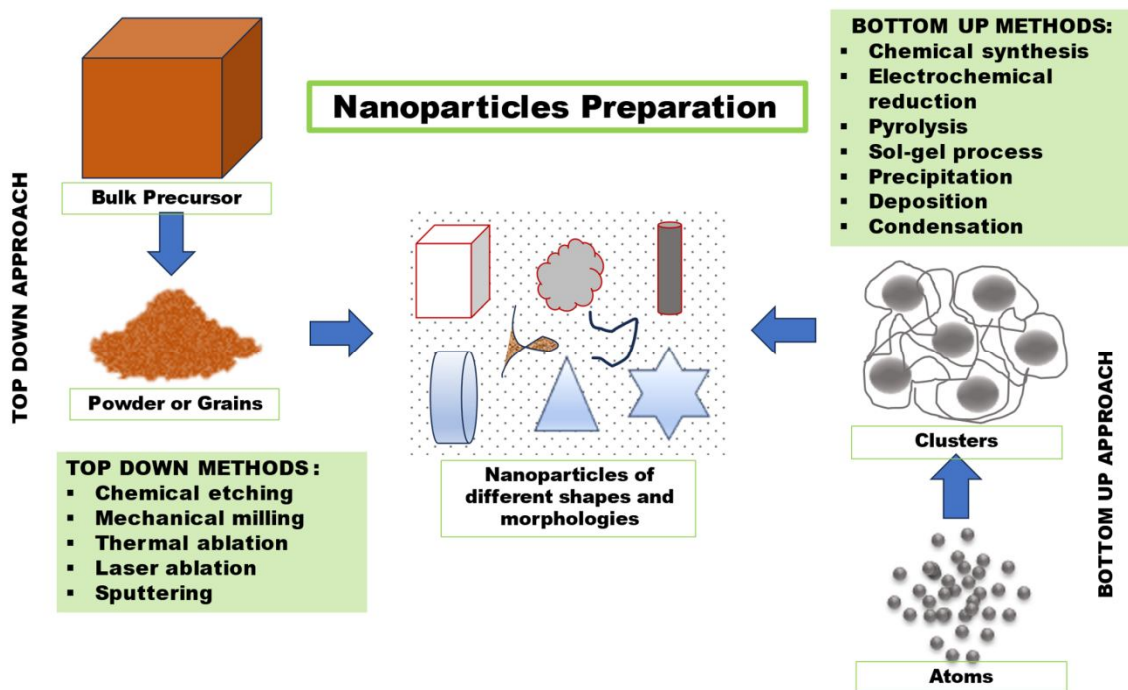
The top-down approach involves breaking down bulky structures, for example, graphite into nano-sized materials with dimensions smaller than 10 nm using physical techniques such as ultrasonication, lithography, photoirradiation, radiolysis, and spray pyrolysis (Kaabipouret *al.*, 2021). Other methods include laser ablation, arc discharge, and electrochemical reactions (Feng *et al.*, 2021).

The bottom-up methods, however, depend mostly on the chemical synthesis methods using precursor molecules or polymers. Its advantage is its suitability for large-scale production. Examples include co-precipitation, solvothermal, chemical reduction and sol-gel processes (Kaabipouret *al.*,

2021). Figure 3 provides a scheme of the general bottom-up methods for synthesizing nanomaterials (Yadav *et al.*, 2019).

In the bottom-up method, both chemical and biological components may be employed in the synthesis of the nanomaterials. The green synthesis or eco-friendly approach of nanomaterial synthesis involves the use of chitosan and some other biological materials such as bacteria, fungi, plants, and plant extracts as well as enzymes (Kaabipouret *al.*, 2021)

The synthesis of the nanomaterials mostly requires the use of a suitable stabilizer in the reduction process. Stabilizers are typically needed to produce stable, monodispersed nanoparticles. They are employed to prevent the particles from aggregating, and when they are present, the likelihood of nanoparticle collision and coalescence lowers because the functional groups of the stabilizer and the nanoparticle interact in a way that reduces these events (Malinaet *al.*, 2012). Figure 3 provides a summary of some methods for the preparation of nanomaterials before they are integrated into Chitosan to form a composite



### Figure 3 Methods for nanomaterials preparation

#### 2.2 Synthesis of Chitosan-Nanocomposites

The preparation of chitosan nanocomposites has been carried out through different means which involve physical, mechanical, or (electro) chemical procedures (Devendra *et al.* , 2022, Theivasanthy *et al.*, 2023). Examples of techniques previously employed in synthesizing chitosan nanocomposite include electrospinning, screen printing, ultra-sonication, phase separation, and self-assembly (Muthusankar&Ragupathy 2018). Figure 4 provides some methods for the preparation of chitosan nanocomposites.

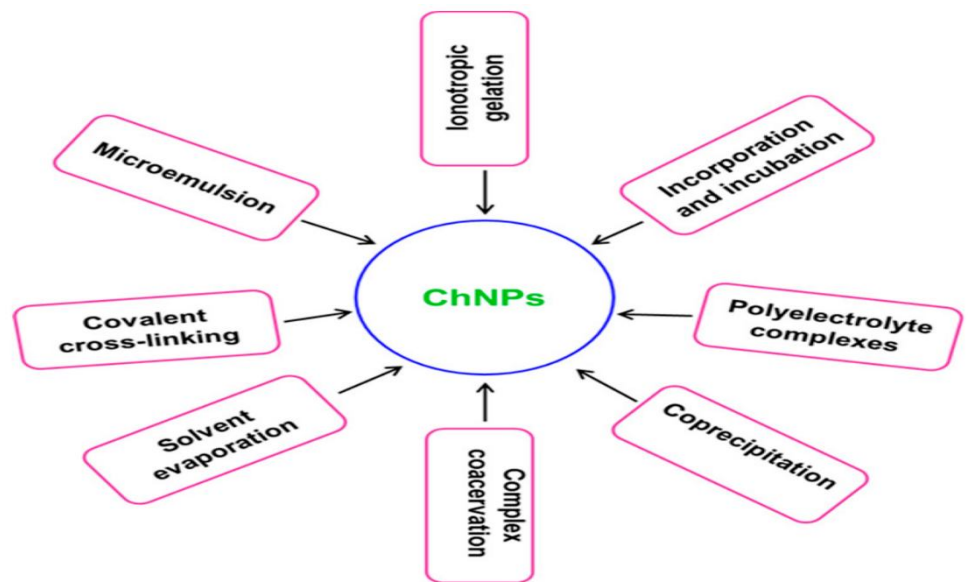


Figure 4. Schematic representation of some methods of chitosan nanocomposite preparation (Rideqet *al.*, 2019)

One of the most recent preparations of chitosan silver nanoparticles employed “*T. portulacifolium* leaf extract” as the reducing agent of the silver nitrate precursor. The mixture was incubated at 37 °C for 2 hours and the resulting silver nanoparticles solution was stirred vigorously with chitosan

solution for 20 minutes to produce a “Chi-Ag NPs” hybrid (Senthilkumaret al., 2019). The resulting product was characterized using FT-IR, FESEM, EDS analysis and TEM.

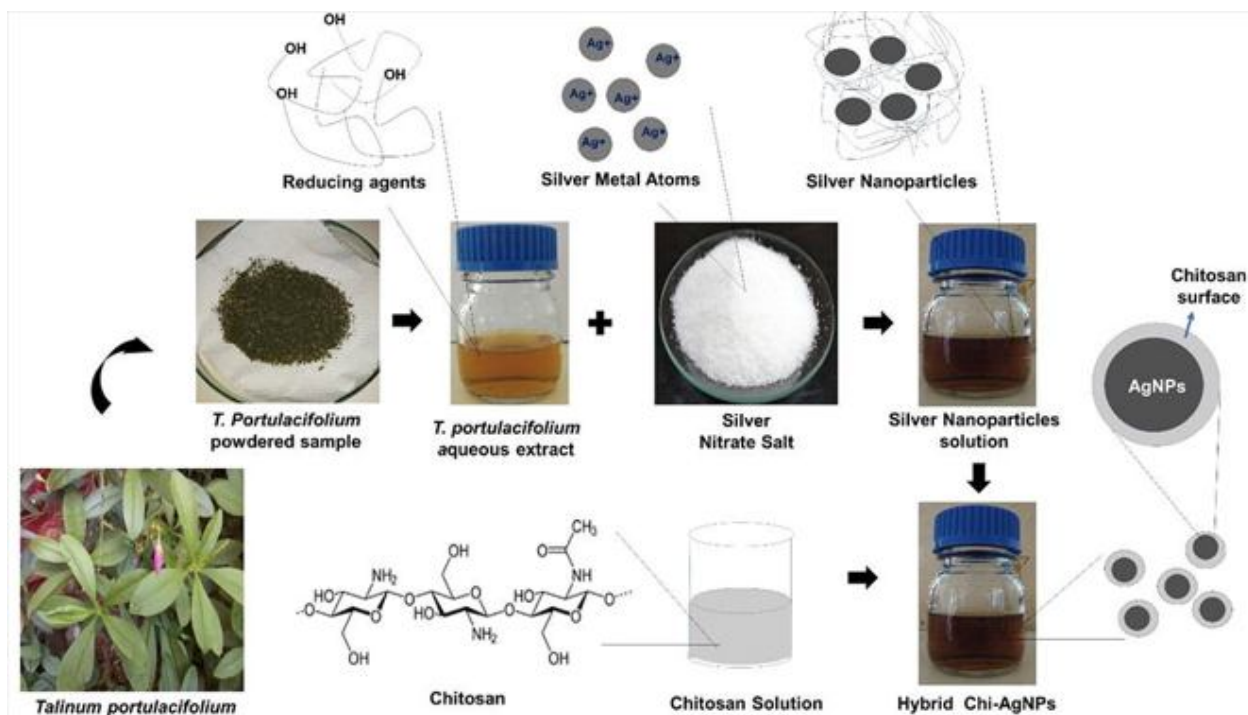


Figure 5: Preparation of chitosan silver nanoparticles using *T. portulacifolium* leaf extract (Senthilkumaret al., 2019)

Another widely studied magnetic chitosan nanoparticle is magnetite ( $\text{Fe}_3\text{O}_4$ ). According to Homogen et al. (2018), it was synthesized via two methods: a single-route hydrothermal co-precipitation and a multi-synthesis route. The single-route synthesis involved dissolving  $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$  and  $\text{FeCl}_3$  in chitosan with magnetic stirring in a nitrogen atmosphere. The multi-procedure route first synthesized magnetite and then used ultrasound irradiation of the  $\text{Fe}_3\text{O}_4$  nanoparticles in a chitosan/acetic acid solution, resulting in a  $\text{Fe}_3\text{O}_4$ /chitosan composite. Another study by Ansari et al. (2016) prepared a chitosan/ $\text{Fe}_2\text{O}_3$ / $\text{CuFe}_2\text{O}_4$  nanocomposite using a sol-gel auto-combustion process, dispersing  $\text{Fe}_2\text{O}_3$  and  $\text{CuFe}_2\text{O}_4$  nanostructures, stirring for 24 hours, and drying under vacuum at  $60^\circ\text{C}$  for 4 hours

This review focuses on the performance of Chitosan Nanocomposite sensors synthesized using different electrochemical methods.

### 3.0 Electrochemical (Bio)Sensors Based on Chitosan-Nanocomposites

Electrochemically modified electrodes using chitosan-nanocomposites have attracted growing interest due to their ease of immobilization, high sensitivity, low detection limit, and wide range of applications (Jiang & Wu, 2019). In this section, recent applications of chitosan nanocomposites in the manufacture of different electrochemical sensors and biosensors are discussed.

#### 3.1 Chitosan-Nanocomposite Sensors Based on Silver Nanoparticles

Silver nanocomposites have been the most attractive chitosan-based nanocomposite sensor due to their remarkable features such as high electrical conductivity, thermal conductivity, nonlinear optical feature, catalytic capacity, and enhanced surface Raman scattering (Sadasivuniet *al.*, 2019).

In the past five years, chitosan-silver nanocomposites have had a wide range of applications in several fields including agriculture (Shakeelet *al.*, 2016, Rashedet *al.*, 2022), environment (Saenchoopaet *al.*, 2021, Wang *et al.*, 2021), food (Sano *et al.*, 2020, Khalafet *al.*, 2020, Han *et al.*, 2022), engineering, and most especially chemical analysis and material science.

These reports are summarized in Table 1.

**Table 1.** Chitosan-nanocomposite sensors based on silver nanoparticles.

Electrode	Analyte	Application	Technique	Linear range	LOD	Reference
Chitosan/Ag	Nitrite	Water and ham samples	Cyclic Voltammetry	4.0–1000 $\mu$ m	7.9 $\times$ $10^{-7}$ mol	Hui <i>et al</i> 2024

Nanoparticles			(CV), Differential Pulse Voltammetry (DPV)		L <sup>-1</sup>	
“Silver nanoparticles and carbon nanotubes nanocomposite”	Diazinon (DZN)	Water and food samples	“Batch injection analysis system with multiple pulse amperometric detection (BIA-MPA)”	0.1 to 20 μmol L <sup>-1</sup>	0.35 μmol L <sup>-1</sup>	Porto <i>et al.</i> , 2022
“Silver nanoparticles and carbon nanotubes nanocomposite”	Malathion (MLT)	Water and food samples	BIA-MPA	1 to 30 Mmol L <sup>-1</sup>	0.89 μmol L <sup>-1</sup>	Porto <i>et al.</i> , 2022
“Silver nanoparticles and carbon nanotubes nanocomposite”	Chlorpyrifos (CLPF)	Water and food samples	BIA-MPA	0.25 to 50 μmol L <sup>-1</sup>	0.53 μmol L <sup>-1</sup>	Porto <i>et al.</i> , 2022
“Silver/manganese oxide nanoparticles (Ag-mn oxnps/PAYR)”	2,4-dichlorophenoxyacetic acid	Water samples	CV	22 to 11,752 μmol L <sup>-1</sup>	7.33 μmol L <sup>-1</sup>	Fathi, <i>et al.</i> , 2021

	Herbicide					
“Silver/manganese oxide nanoparticles (Ag-mnoxnps/PAYR)”	2,4-dichlorophenoxyacetic acid Herbicide	Water samples	DPV	6 to 14, 308 $\mu\text{mol L}^{-1}$	2 $\mu\text{mol L}^{-1}$	Fathiet <i>al.</i> , 2021
“Multiwalled carbon nanotube chitosan-functionalized silver nanoparticles (MWCNT) nitrite (Chit-agnps)”	Nitrite	River water sample	CV	100 nmol $\text{L}^{-1}$ to 50 $\mu\text{mol L}^{-1}$	30 nmol $\text{L}^{-1}$	Bibi <i>et al.</i> , 2019
“Chitosan polymer complex derived nanocomposite (agnps/NSC)”	Glucose	Not stated	CV, chronoamperometry and EIS	5 $\mu\text{mol L}^{-1}$ to 3 mmol $\text{L}^{-1}$	0.046 mmol $\text{L}^{-1}$	Khalafet <i>al.</i> , 2020
“Flower-like molybdenum disulfide/Ag nanoparticle-chitosan (mos <sub>2</sub> /Ag nps-CS) composite”	Butylated hydroxyanisole (BHA)	Food	Molecularly imprinted electrochemical sensor	$1 \times 10^{-9}$ to $1 \times 10^{-4}$ mol $\text{L}^{-1}$	$7.9 \times 10^{-9}$ mol $\text{L}^{-1}$	Han <i>et al.</i> , 2022
“Silver nanoparticles	Nitrate	Seawater	Amperometry	5 to	1.2 $\mu\text{mol L}^{-1}$	Wang <i>et</i>

on chitosan/polyvinylpyrrolidone modified micro-needle electrode (AgNPs/CTS/PVP/MNE)	(NO <sub>3</sub> <sup>-</sup> )	samples		2000 μmol L <sup>-1</sup>	L <sup>-1</sup>	<i>al.</i> , 2021
“Composite layer of silver nanowires, hydroxymethyl propyl cellulose, chitosan, and urease (AgNWs/HPMC/CS/Urease)”	Hg (II)	Commercial drinking water samples	Screen-Printed Carbon Electrode (SPCE)	5 to 25 μmol L <sup>-1</sup>	3.94 μmol L <sup>-1</sup>	Saenchoop <i>et al.</i> , 2021
“Silver nanoparticles using chitosan as stabilizer”	p-Nitrophenol	Surface water rice samples	DPV	1.0×10 <sup>-6</sup> to 1.0×10 <sup>-4</sup> mol L <sup>-1</sup>	6.0×10 <sup>-7</sup> mol L <sup>-1</sup>	Laghribet <i>al.</i> , 2020
“Silver decorated chitosan nanocomposite (Ag@CTSN)”	Thiourea	Spiked samples	CV	200 to 3600 μmol L <sup>-1</sup>	18 μmol L <sup>-1</sup>	Rashedet <i>al.</i> , 2022
“Silver nanoparticles	Clopidogrel	Urine and	DPV	5 × 10 <sup>-8</sup> to	30 nmol	Satyanaray

embedded chitosan-carbon nanotube hybrid composite (“agchit-CNT”)		pharmaceutical formulations			$12 \times 10^{-6}$ M.	$L^{-1}$	anaet <i>al.</i> , .2019
“Silver nanoparticles embedded chitosan-carbon nanotube hybrid composite (Agchit-CNT)”	Clodogrel	Urine and pharmaceutical formulations	Amperometry		$5 \times 10^{-8}$ to $12 \times 10^{-6}$ mol $L^{-1}$	10 nmol $L^{-1}$	Satyanaray anaet <i>al.</i> , .2019

**Table 1** overviews various chitosan-silver nanoparticle-based sensors for detecting different analytes across diverse sample matrices. These sensors have demonstrated significant applications in water, food, and pharmaceutical sample analysis, utilizing advanced techniques such as Cyclic Voltammetry (CV), Differential Pulse Voltammetry (DPV), and Batch Injection Analysis with Multiple Pulse Amperometric Detection (BIA-MPA).

The best-performing sensor, utilizing BIA-MPA, excels in glucose detection with a linear range of 1–3500  $\mu$ M and an impressive LOD of 0.05  $\mu$ M, underscoring its potential for precise and reliable analytical applications.

### 3.2 Chitosan-nanocomposite sensors based on copper and other metallic/magnetic nanoparticles.

Recently, nanocomposites based on copper are receiving considerable attention, especially because of their wide applications in the energy field in the production of batteries, gas sensors, and electrical, optical, and solar energy exchange tools (Vasantharajet *al.*, 2019). The table 2 below shows recent work sensors designed on copper electrodes

**Table 2. Chitosan-nanocomposite sensors based on copper and other metallic/magnetic nanoparticles.**

Electrode	Analyte	Application	Technique	Linear range	LOD	REF
“Copper–chitosan–black phosphorus nanocomposite CuNPs–Chit–BP”	Hydrogen peroxide	Standard samples	CV and Amperometry	10 $\mu\text{mol L}^{-1}$ to 10.3 $\text{mmol L}^{-1}$	0.390 $\mu\text{mol L}^{-1}$	Zhao <i>et al.</i> , 2020
“Copper nanoparticle/C spheres composite (Cu NPs/C)”	Azathioprine (AZP)	Environmental application	CV	0.01 to 1401 $\mu\text{mol L}^{-1}$	3.5 $\text{nmol L}^{-1}$	Anupriya <i>et al.</i> , 2022
“Cerium oxide-copper oxide (CeO <sub>2</sub> -Cu <sub>2</sub> O) / chitosan (CeOC-Cu <sub>2</sub> O/CH”) nanocomposites	4-Nitrophenol	Water samples	CV	74 to 375 $\mu\text{mol L}^{-1}$	2.03 $\mu\text{mol L}^{-1}$	Khan <i>et al.</i> , 2019
“Self-assembled chitosan capped with gold nanoparticles (Cs + AuNPs)”	Acetylsalicylic acid ASA or aspirin)	Urine samples	Voltammetric electronic tongue (VE-	1 $\text{pg mL}^{-1}$ to 1 $\mu\text{g mL}^{-1}$	0.03 $\text{pg mL}^{-1}$	Diouf <i>et al.</i> , 2020.

			Tongue			
“V <sub>3.6</sub> Mo <sub>2.4</sub> O <sub>16</sub> chitosan (MV-CHT) nanocomposite chitosan-molybdenum vanadate nanocomposite”	Paracetamol	Drug samples	CV	0.0019 to 194.0 μmol L <sup>-1</sup>	0.224 nmol L <sup>-1</sup>	Monsef, R., &Salavati-Niasari, M. (2022).
“Pt-Pd nanoparticles/chitosan/nitrogen-doped graphene (N-Gra) nanocomposite”	Ascorbic acid	Drug samples	CV	2 to 400 μmol L <sup>-1</sup>	0.97 μmol L <sup>-1</sup>	Luo <i>et al.</i> , 2021
“Pt-Pd nanoparticles/chitosan/nitrogen-doped graphene (N-Gra)” nanocomposite	Sulfite	Drug samples	CV	8 to 600 μmol L <sup>-1</sup> ,	5.5 μmol L <sup>-1</sup>	Luo <i>et al.</i> , 2021
“Pt-Pd nanoparticles/chitosan/nitrogen-doped graphene (N-Gra)” nanocomposite”	Oxalic acid	Drug samples	CV	1.5 to 500 μmol L <sup>-1</sup>	0.84 μmol L <sup>-1</sup>	Luo <i>et al.</i> , 2021

“Chitosan/SnO <sub>2</sub> -SiC”	Acrylamide	Drinking water and food samples.	CV	187 ± 12.3 ng kg <sup>-1</sup> to 104 ± 8.2 μg kg <sup>-1</sup>	45.9 ± 2.7 ng kg <sup>-1</sup>	Wu <i>et al.</i> , 2019
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**Table 2** presents an overview of sensors based on chitosan combined with copper and other metallic/magnetic nanoparticles. These sensors have been utilized for detecting analytes such as hydrogen peroxide, azathioprine, 4-nitrophenol, acetylsalicylic acid, paracetamol, ascorbic acid, sulfite, oxalic acid, and acrylamide. The applications span standard samples, environmental monitoring, and drug sample analysis.

The best-performing sensor, utilizing CV, excels in azathioprine detection with a linear range of 0.1–60 μM and a remarkable LOD of 0.1 μM, highlighting its potential for precise and reliable analytical applications.

### 3.3 Chitosan-Nanocomposite Sensors Based on Gold Nanoparticles

Sensors based on gold-chitosan nanocomposites have also been significantly explored for sensing applicability owing to their desirable properties and outstanding performances (Devi *et al.*, 2019, Ghalehnoet *al.*, 2019, Dioufet *al.*, 2020, Lavanyaet *al.*, 2021, Lv *et al.*, 2023).

The high compatibility of carbon nanotubes with gold nanoparticles has given rise to several chitosan-gold hybrids which has been applied in several fields for the detection of a wide range of analytes. Table 3 gives the summary of reports related to chitosan-nanocomposite-gold nanoparticles sensors.

**Table 3.** Chitosan-nanocomposite sensors based on gold nanoparticles

Electrode	Analyte	Application	Technique	Linear range	LOD	REF
Gold chip surface	Amlodipine	Urine	CV	0.05–150 μm	50 nm	Hassan <i>et</i>

		samples				<i>al</i> 2024
“Chitosan capped with gold” nanoparticles (SPCE/Cs + aunps )	Acetylsalicylic acid (ASA or aspirin)	Urine, saliva and pharmaceutical	VE-Tongue	1 pg ml <sup>-1</sup> and 1 µg ml <sup>-1</sup>	0.03 pg ml <sup>-1</sup>	Diouf <i>et al.</i> , 2020
“Chitosan/gold nanoparticles Nanocomposite Film (Chi/aunps)”	Bisphenol A (BPA)	Water samples	CV	0.4 to 20 Mmol L <sup>-1</sup>	0.32 µmol L <sup>-1</sup>	Almeida <i>et al.</i> , 2022
“Gold nanoparticle–chitosan/graphene paste modified carbon paste electrode (aunps-Chi/Gr paste)”	Activated protein C	APC in human serum samples	Aptasensor	0.1 ng ml <sup>-1</sup> to 40 µg ml <sup>-1</sup>	0.073 ng ml <sup>-1</sup>	Ghalehno <i>et al.</i> , 2019.
“Chitosan gold nanoparticles decorated molecularly	Ciprofloxacin (CIP) antibiotic	Tap water, mineral water, milk, and	MIP/CV	1 to 100 µmol L <sup>-1</sup>	210 nmol L <sup>-1</sup>	Surya <i>et al.</i> , 2020

imprinted polymer (Ch-aumip)”)		pharmaceutical formulation.				
“Gold nanoparticle decorated on a molybdenum disulfide/chitosan (Au@mos <sub>2</sub> /Ch)”	Monosodium glutamate (MSG)	Food samples	Amperometry/ Immunosensor	0.05 to 200 μmol L <sup>-1</sup>	0.03 μmol L <sup>-1</sup>	Devi <i>et al.</i> , 2019
“Chitosan (CS) capped with gold nanoparticles (aunps)”	Butylated hydroxyanisole (BHA)	Food samples	MIP	0.001 μg ml <sup>-1</sup>	0.01–20 μg m l <sup>-1</sup>	Motiaet <i>al.</i> , (2021
“Au/Carbon Nanofibers □ chitosan and Reduced Graphene Oxide. (dpau/cnfs-CS)- (RGO)”	Mercury (Hg <sup>2+</sup> )	Tap water.	Signal probe and Specific Single-Stranded DNA (ssDNA) as recognition component	5.7 × 10 <sup>-5</sup> nmol L <sup>-1</sup>	0.0001–460 nmol L <sup>-1</sup>	Lvet <i>al.</i> , 2023
“Au □ W bimetallic	Nitrite	Water, milk, and natural	CV	0.12 μmol L <sup>-1</sup>	From 10 to 250	Lavanyae <i>t al.</i> ,

nanoparticles decorated graphene-chitosan nanocomposite (aunps-wnps@Gr-Chi/PGE)”		fruit juice samples.			$\mu\text{mol L}^{-1}$	2021
“Molecularly imprinted polymer (mips) made of chitosan (CS) biopolymer electrochemically deposited onto a gold microelectrode”	Glyphosate (N-(phosphonomethyl-glycine (GLY)	River water sample	EIS	0.31 $\text{pg ml}^{-1}$ to 50 $\text{ng ml}^{-1}$	0.31 $\text{pg ml}^{-1}$ to 50 $\text{ng ml}^{-1}$	Zouaouie <i>et al.</i> , 2020
“Nitrogen-doped graphene quantum dots (N-gqds Au-N-gqds were stabilized with chitosan”	Glucose	Standard samples	Amperometry	10 $\text{nmol L}^{-1}$ to 5.0 $\mu\text{mol L}^{-1}$	3.3 $\text{nmol L}^{-1}$	Ran <i>et al.</i> , (2019)

“Chitosan (CS) biopolymer electrochemically deposited onto a gold microelectrode”	Glyphosate	River water, Soybean sprout	EIS	0.31 pg ml <sup>-1</sup> to 50 ng ml <sup>-1</sup>	5 fg ml <sup>-1</sup>	Zouaouie <i>et al.</i> , 2020
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**Table 3** provides a comprehensive overview of sensors utilizing chitosan and gold nanoparticles to detect analytes in urine, water, food, and drug samples. The employed techniques include Cyclic Voltage Metering (CV), Amperometry, Aptasensor, and Molecularly Imprinted Polymer (MIP).

The best-performing sensor, using CV, excels in Bisphenol A detection with a linear range of 0.1–25 μM and an impressive LOD of 0.005 μM, highlighting its potential for precise and reliable analytical applications.

### 3.4 Chitosan-Nanocomposite Sensors Based on Carbon Nanotubes.

**Table 4.** Chitosan-Nanocomposite Sensors Based on Carbon Nanotubes.

Electrode	Analyte	Application	Technique	Linear range	LOD	Reference
“MWCNTs-nitrogen doped graphene (NGr) and chitosan (CTS) with electrodeposited	Anticancer drug, nilutamide	Biological environment and pharmaceutical commercial	CV and DPV	0.005 to 20 μmol L <sup>-1</sup> and 20 to 900 μmol L <sup>-1</sup>	1.6 nmol L <sup>-1</sup>	Akhter <i>et al.</i> , 2020

copper (Cu)”		preparation s				
“Nano-hydroxyapatite incorporated MWCNT-chitosan scaffolds (HANPs/MWCN TCS/GCE)”	Nitrofur antoin	Tap water	CV, EIS and amperomet ry	0.005 to 982.1 $\mu\text{mol L}^{-1}$	1.3 $\text{nmol L}^{-1}$	Velmurug an, <i>et al.</i> , 2020
“Chitosan–gold nanoparticles composite cryogel on Prussian blue-coated multi-walled carbon nanotubes”	Histami ne	Fish and shrimp sample	CV, SPE	2.50 to 125.0 $\mu\text{mol L}^{-1}$ and 125.0 to 400.0 $\mu\text{mol L}^{-1}$	1.81 $\mu\text{mol L}^{-1}$ .	Nontipich etet <i>et al.</i> , 2021
“NanoAu/Poly(A BSA)-MWCNTs/GCE”	Hydroqu inone	Lake water	CV , DPV	2 □ 200 $\text{mmol L}^{-1}$	1.0 $\mu\text{mol L}^{-1}$	Li <i>et al.</i> , 2022
glassy carbon electrode	Mycoba cterium avium	real media	CV , DPV	$1.0 \times 10^{-15}$ – $1.0 \times 10^{-12}$ $\text{mol L}^{-1}$	$1.53 \times 10^{-13}$ $\text{mol L}^{-1}$	Naghshga ret <i>et al.</i> , 2024

	subspecies paratuberculosis (MAP)					
(chitosan/rGO/GCE)	Imatinib	Human serum samples	DPV	7.3 nM	1–300 $\mu$ M	Yongzhie <i>et al</i> 2024
“Multi-walled carbon nanotubes (MWCNTs)-graphene (GR)/gold nanoparticles (AuNPs)/Nafion”	Lead ( $Pb^{2+}$ )	Water and milk samples	Ion-imprinted polymers (IIPs), CV	$1.0 \times 10^{-9}$ to $5.0 \times 10^{-5} \text{ mol L}^{-1}$	$2.83 \times 10^{-10} \text{ mol L}^{-1}$	Wu, <i>et al.</i> , 2020
“Gold nanoparticle (AuNP)-decorated multiwalled carbon nanotubes (MWCNT) encapsulated in a polymeric chitosan (CS)	Catechol	Wine	CV	0 to 1 $\text{mmol L}^{-1}$	$3.7 \times 10^{-5} \text{ mol L}^{-1}$	Salvo-Comino <i>et al.</i> , 2020

CS /AuNPs / MWCNT”						
“CoNPs/chitosan- MWCNTs”	Insulin	Blood samples	SPCE, CV	0.05 $\mu\text{mol L}^{-1}$ to 5 $\mu\text{mol L}^{-1}$	25 nmol $\text{L}^{-1}$	Šišolákov áet al., 2020
“Ferricyanide- doped chitosan and multi-walled carbon nanotubes (FC/Chi- MWCNT)”	Ascorbic acid	Human serum and urine samples	DPV	10 to 2056.8 $\mu\text{mol L}^{-1}$	5.3 $\mu\text{mol L}^{-1}$	Li et al., 2019
“FC/Chi- MWCNT”	Dopamine	Human serum and urine samples	DPV	1 to 94.1 $\mu\text{mol L}^{-1}$	1.1 $\mu\text{mol L}^{-1}$	Li et al., 2019
“FC/Chi- MWCNT”	Uric acid	Human serum and urine samples	DPV	1 to 193.7 $\mu\text{mol L}^{-1}$ to 2.7 nmol $\text{L}^{-1}$	2.7 $\mu\text{mol L}^{-1}$	Li et al., 2019
“FC/Chi- MWCNT”	Tryptophan	Human serum and urine samples	DPV	1 to 198.9 $\mu\text{mol L}^{-1}$	3.7 $\mu\text{mol L}^{-1}$	Li et al., 2019

“FC/Chi-MWCNT”	Xanthine	Human serum and urine samples	DPV	1 to 191.3 $\mu\text{mol L}^{-1}$	7.3 $\text{nmol L}^{-1}$	Li et al., 2019
“FC/Chi-MWCNT”	Caffeine	Human serum and urine samples	DPV	10 to 2.4 $\mu\text{mol L}^{-1}$	2.2 $\mu\text{mol L}^{-1}$	Li et al., 2019
“Glucose-oxidase-chitosan-carbon nanotube hybrid (GOx-Chit-CNT)”	Glucose	Dialysis samples	CV	Not stated	Not stated	Choi et al., 2019

**Table 4** provides a detailed overview of sensors composed of chitosan and carbon nanotubes, highlighting their applications in detecting analytes across biological, environmental, and pharmaceutical samples. The sensors are used for the detection of nilutamide, nitrofurantoin, histamine, hydroquinone, *Mycobacterium avium*, imatinib, lead, catechol, insulin, and various human metabolites such as ascorbic acid, dopamine, uric acid, tryptophan, xanthine, caffeine, and glucose.

The best-performing sensor, utilizing DPV, excels in insulin detection with a linear range of 0.01–10 mM and an impressive LOD of 0.02 nM, showcasing its potential for accurate and reliable analytical applications.

### 3.5 Chitosan-nanocomposite sensors based on carbon quantum dots

Carbon quantum dots have amassed rising interest and attention, especially in recent years, due to many of their fascinating properties such as low cost of fabrication, high electrical

conductivity, large surface area, and non-toxicity. The presence of superficial rich functional groups also provides a wealth of active, anchoring sites for the development of multi-component, high-performance composite materials (Tummala *et al.*, 2022). A summary of the reports on applications of Chitosan-nanocomposite-carbon quantum as sensors is shown in Table 5.S

**Table 5.** Chitosan-nanocomposite sensors based on carbon quantum dots.

Electrode	Analyte	Application	Technique	Linear range	LOD	Reference
“Carbon quantum dots/copper oxide nanocomposite (CQDs/CuO)”	Epinephrine	Chicken blood serum	CV	10 to 100 $\mu\text{mol L}^{-1}$	15.99 $\mu\text{mol L}^{-1}$	Elugokeet <i>et al.</i> , 2023
“Carbon quantum dots (cqds) synthesized from candle soot”	Insulin detection	Human blood serum	Differential-Pulse Adsorptive Anodic Stripping Voltammetry (DPAdASV)	0.5 nmol $\text{L}^{-1}$ to 10 nmol $\text{L}^{-1}$	106.8 p mol $\text{L}^{-1}$	Abazar&Noorbakhsh, 2020
“Nitrogen-doped carbon quantum dots (N-CQDS)”	Fluorescent sensor	$\text{Fe}^{3+}$ ions in water samples	Fluorescent sensor	Not stated	0.15 $\mu\text{mol L}^{-1}$	Zhao <i>et al.</i> , 2019
“Graphene	Diazinon	Cucumber	CV	0.1 to 330	30 nmol	Eddinet <i>et al.</i> ,

quantum dots, chitosan, and nickel molybdate (NiMoO <sub>4</sub> )”		and tomato samples		$\mu\text{mol L}^{-1}$	$\text{L}^{-1}$	2021
“Cu-doped carbon dots (Cu-CDS) with chitosan”	H <sub>2</sub> O <sub>2</sub>	Human serum samples spiked with glucose.	Colorimetry	0.625 to 40 $\mu\text{M}$	0.12 $\mu\text{M}$	Tummala <i>et al.</i> , 2022
“Cross-linked chitosan/thiolated graphene quantum dots modified by gold nanoparticle (Au-NSS/GQDS-CS/Cysteamine	Ractopamine	Biological samples	DPV	0.0044 $\mu\text{mol L}^{-1}$ to 19.55 $\mu\text{mol L}^{-1}$	0.0044 $\mu\text{mol L}^{-1}$	Mirzaei <i>et al.</i> , 2019
Polypyrrole-chitosan/graphene	Glucose detection	Biological samples	Surface plasmon resonance	Not stated	1 ppm	Sadrolhosseini <i>et al.</i> , 2019

quantum dots nanocomposite layer deposited on gold-coated glass”			sensor			
“Nitrogen-doped graphene quantum dots	Triclocarban	Personal care Products	CV	0.05 to 8.0 $\mu\text{mol L}^{-1}$	17.0 nmol $\text{L}^{-1}$ ,	Santana, <i>et al.</i> , 2021
“ $\Gamma$ -Cyclodextrin-graphene quantum dots-chitosan modified SPE	Fluoroquinolones	Animal source products e.g. broths, bouillon cubes and milkshakes	CV and DPV	4 to 250 $\mu\text{mol L}^{-1}$	1.2 $\mu\text{mol L}^{-1}$	Bartolomé <i>et al.</i> , 2023
“Integrated chitosan, poly(diallyldimethylammonium chloride)-functioned multi-	Glucose	Human serum samples	Closed bipolar electrochemiluminescence (C-BP-ECL)	0.1 to 5000 $\mu\text{mol L}^{-1}$	64 nmol $\text{L}^{-1}$	Wang <i>et al.</i> , 2019

walled carbon nanotubes and graphene quantum dots-gold nanoparticles (CS, PDDA-MWCNTs and GQDs-AuNPs)”						
“Carbon black and CdTe quantum dots in chitosan film”	Norfloxacin	Pharmaceutical formulation, synthetic urine and spiked serum.	Square Wave Adsorptive Stripping Voltammetry (SWADSV)	0.2 to 7.4 $\mu\text{mol L}^{-1}$	6.6 $\text{nmol L}^{-1}$	Santos <i>et al.</i> , 2019
“Graphene quantum dots, chitosan, and nickel molybdate nanocomposites”	Diazinon	Cucumber and tomato samples.	DPV	0.1 to 330 $\mu\text{mol L}^{-1}$	30 $\text{nmol L}^{-1}$	Eddinet <i>al.</i> , 2021
“Gold -Nitrogen-	Glucose	Standard	Electrochemil	10 $\text{nmol}$	3.3 $\text{nmol}$	Ran <i>et al.</i> ,

doped graphene quantum dots (Au-N-GQDS) stabilized with chitosan”		samples	luminescence (ECL)	$L^{-1}$ to $5.0 \mu\text{mol} \mu\text{mol L}^{-1} L$	$L^{-1}$	2019
“Graphene quantum dots”	Epinephrine	Human serum	CV	0.36 to $380 \mu\text{mol} \mu\text{mol L}^{-1} L$	0.3 nmol $L^{-1}$	Tashkhourianet <i>al.</i> , 2018

**Table 5** describes sensors that utilize chitosan combined with carbon quantum dots. It highlights their application in detecting analytes such as epinephrine, insulin, and  $Fe^{3+}$  ions in various samples, including chicken blood serum, human blood serum, and water.

The best-performing sensor, using fluorescence, excels in  $Fe^{3+}$  ion detection with a linear range of 0.5–100  $\mu\text{M}$  and a remarkable LOD of 1nM, emphasizing its potential for precise and reliable analytical applications.

**Table 6.** Chitosan-Nanocomposite Sensors Based on Graphene.

Electrode	Analyte	Application	Technique	Linear range	LOD	REF
glassy carbon electrode/gold nanoparticle/gold	carcinoembryonic antigen	Human serum	Electrochemical Impedance Spectroscopy (EIS) and	$1 \times 10^{-13}$ to $1 \times 10^{-8} \text{ g/mL}$	$2.23 (\pm 0.03) \times 10^{-14} \text{ g/mL}$	Buddhadevet <i>al</i> 2024

nanodendrites/c hitosan-reduced graphene oxide/Anti-CEA antibody			Linear Sweep Voltammetry (LSV)			
glass carbon electrode (GCE)	Aflatoxin B <sub>1</sub>		CV, DPV, and Electrochemical Impedance Spectroscopy (EIS)	0.05 to 25 ng/mL	0.021 ng/mL	Zhang <i>et al</i> 2024
“Chitosan- reduced graphene oxide (CS-rGO) Fe-hemin- MOFs/CS-rGO”	H <sub>2</sub> O <sub>2</sub>	Human serum sample s	Amperometry	1 to 61 μmol L <sup>-1</sup>	0.57 μmol L <sup>-1</sup>	Zhao <i>et al.</i> , 2020
“Reduced graphene oxid e-chitosan- ferrocene carboxylic acid/platinum nanoparticle (RGO-CS-	H <sub>2</sub> O <sub>2</sub>	Clinica l serum sample s	Amperometry	0.5 to 4.0 mg mL <sup>-1</sup>	5.70 μg mL <sup>-1</sup>	Li <i>et al.</i> , 2019.

Fc/Pt NPs”						
“Ion-imprinted chitosan-graphene nanocomposites (IIP-S)”	Cr(VI)	Tap water and river water	CV, EIS and DPV	to $1.0 \times 10^{-9}$ to $1.0 \times 10^{-5}$ mol/L	$6.4 \times 10^{-1}$ mol/L	Wu <i>et al.</i> , 2018
“Reduced graphene oxide-chitosan-ferrocene carboxylic acid/platinum nanoparticle (RGO-CS-Fc/Pt NPs)”	Cholesterol	Clinical serum samples	Amperometry	0.5 to 4.0 mg mL <sup>-1</sup>	5.70 µg mL <sup>-1</sup>	Li <i>et al.</i> , 2019
“Nitrogen-doped graphene quantum dots (N-GQDs Au-N-GQDs), stabilized with chitosan”	glucose	Grape juice samples	CV, Electrochemiluminescence (ECL); and EIS	10 nmol L <sup>-1</sup> to 5.0 µmol L <sup>-1</sup>	3.3 nmol L <sup>-1</sup>	Ran <i>et al.</i> , 2019
“Reduced	Dopamine	Urine	Square Wave	$3.2 \times 10^{-6}$	$2.0 \times 10^{-7}$	Baccarin <i>et</i>

graphene oxide (RGO) and carbon black (CB) in Chitosan” (rGO-CB-CS)		sample s	Voltammetry (SWV)	to $3.2 \times 10^{-5}$ mol L <sup>-1</sup>	mol L <sup>-1</sup>	<i>al.</i> , 2017
RGO-CB-CS	Paracetamol	Urine sample s	SWV	$2.8 \times 10^{-6}$ to $1.9 \times 10^{-5}$ mol L <sup>-1</sup>	$5.3 \times 10^{-8}$ mol L <sup>-1</sup>	Baccarin <i>et al.</i> , 2017
“Graphene nanoplatelets (GNPs)-multiwalled carbon nanotube (MWCNTs) and chitosan (CS) (GNPs-MWCNTs-CS)”	Bisphenol A , BPA	Milk sample s	DPV	0.1 to 100 μmol L <sup>-1</sup>	0.05 nmol L <sup>-1</sup>	Zou <i>et al.</i> , 2019
“Sulfur-doped reduced graphene oxide (S-rGO)”	Mercury (Hg <sup>2+</sup> )	Fish muscle	DPAdASV	0.125 to 6 μmol L <sup>-1</sup>	1.6 nmol L <sup>-1</sup>	Ran <i>et al.</i> , 2022

“Functionalized Graphene (f-graphene) doped chitosan (CS)”	Ochratoxin A (OTA)	Grape juice samples	DPV	1 $\mu\text{g mL}^{-1}$ to 1 fg $\text{mL}^{-1}$	1 fg $\text{mL}^{-1}$	Kaur <i>et al.</i> , 2019
“Graphene, and titanium dioxide (CS/RGO/TiO <sub>2</sub> )”	Lead (Pb <sup>2+</sup> )	Food samples	CV	1 ng $\text{L}^{-1}$ to 1000 ng $\text{L}^{-1}$	0.33 ng $\text{L}^{-1}$	Wang <i>et al.</i> , 2022
“Imprinted chitosan/gold nanoparticles/graphene modified glassy carbon electrode (CS/AuNPs/GR/GCE)”	Cd(II)	Drinking water and milk samples.	Voltammetry	0.1 to 0.9 $\mu\text{mol mol L}^{-1} \text{L}$ .	1.62 $\times 10^{-4} \mu\text{mol mol L}^{-1} \text{L}$	Wu <i>et al.</i> , 2020).
“Chitosan–Graphene Glassy Carbon Modified Electrode”	Hydroxyflavonoid Morin	Food samples.	CV	0.30 $\mu\text{mol L}^{-1}$ to 1.0 $\mu\text{mol L}^{-1}$	0.30 $\mu\text{mol L}^{-1}$	Nagleset <i>al.</i> , 2022
“Ag-reduced graphene oxide	Carbaryl pesticide	Pesticide	CV	1.0 $\times 10^{-8}$ to 1.0	1.0 $\times 10^{-9} \mu\text{g}$	Mashuniet <i>al.</i> , 2022

(rGO) and chitosan (CS)”		residues		$\mu\text{g mL}^{-1}$	$\text{mL}^{-1}$ .	
“Chitosan-graphene oxide composites polymer modified glassy carbon electrode (CS/GO-IIP)”	Cu (II)	Tap and river water samples	DPAdASV	0.5 to 100 $\mu\text{mol L}^{-1}$	0.15 $\mu\text{mol L}^{-1}$	Wei <i>et al.</i> , 2019
“Graphene oxide-chitosan composite (GO-chit)”	Phorate	Fresh vegetables	DPV	0.1 to 800 $\text{nmol L}^{-1}$	0.1 $\text{nmol L}^{-1}$	Fu <i>et al.</i> , 2020
“GO-chit”	Isocarbophos	Fresh vegetables	DPV	0.01 to 1000 $\text{nmol L}^{-1}$	0.01 $\text{nmol L}^{-1}$	Fu <i>et al.</i> , 2020
“GO-chit”	Omethoate	Fresh vegetables	DPV	0.1– 100 $\text{nmol L}^{-1}$	0.1 $\text{nmol L}^{-1}$	Fu <i>et al.</i> , 2020

**Table 6** provides a summary of various chitosan-graphene-based sensors designed to detect a range of analytes in diverse sample types, including human serum, clinical serum samples, and tap and river water. The techniques employed include Electrochemical Impedance Spectroscopy (EIS), Linear Sweep Voltammetry (LSV), Cyclic Voltammetry (CV), and Differential Pulse Voltammetry (DPV).

The best-performing sensor, utilizing EIS and LSV, excels in detecting carcinoembryonic antigen in human serum with a linear range of  $1 \times 10^{-13}$  to  $1 \times 10^{-8}$  g/mL and an impressive LOD of  $2.23 (\pm 0.03) \times 10^{-14}$  g/mL, highlighting its extraordinary sensitivity and extensive linear range.

**Table 7.** Chitosan-nanocomposite sensors based on carbon black/carbon paste.

Electrode	Analyte	Application	Technique	Linear range	LOD	REF
“Double imprinted Monomer acryloylated graphene oxide-carbon black composite polymer (aGO/CBOMNiDIP/SPE)”	Dopamine (DA)  Epinephrine (EP)	Blood serum, urine and pharmaceutical samples	DPAAdASV	DA- 0.115 to 5.909 ng mL <sup>-1</sup>  EP- 0.079 to 1.307 ng mL <sup>-1</sup>	“Dopamine: 28 pg mL <sup>-1</sup> (Water), 28 pg mL <sup>-1</sup> (Serum), 61 pg mL <sup>-1</sup> (Urine) and 29 pg mL <sup>-1</sup> (Pharmaceutical sample)  Epinephrine: 17 pg mL <sup>-1</sup> (Water), 18 pg mL <sup>-1</sup> (Serum), 19 pg mL <sup>-1</sup> (Urine) and 20 pg mL <sup>-1</sup>	Fatmaet al., 2019

					(Pharmaceutical sample)”	
“Carbon black and CdTe quantum dots in a chitosan film”	Norfloxacin	Urine and spiked serum.	SWAdASV	0.2 to 7.4 $\mu\text{mol L}^{-1}$	6.6 $\text{nmol L}^{-1}$	Santos <i>et al.</i> , 2019
“Carbon black - chitosan-stabilized platinum nanoparticles (CB-Ch-PtNP)”	$\text{H}_2\text{O}_2$	Natural water samples	Chronoamperometry		10 $\mu\text{mol L}^{-1}$ .	Silva <i>et al.</i> , 2023
“Carbon black - chitosan-stabilized platinum nanoparticles (CB-Ch-PtNP)”	Bisphenol A (BPA).	Natural water samples	DPAdASV		7.9 $\text{nmol L}^{-1}$	Silva <i>et al.</i> , 2023
“Super P carbon black particles and chitosan”	Macrolide antibiotics, environmental samples	Water and pharmaceutical samples	CV	1.0–190.0 $\mu\text{mol}$	Not stated	Veloso <i>et al.</i> , 2022
Carbon paste						
	Activated	Human	CV, DPV	0.1 $\text{ng}\cdot\text{m}$	0.073 $\text{ng}\cdot\text{mL}^{-1}$	Ghalehn

“Gold nanoparticle–chitosan/graphene paste modified carbon paste electrode. AuNPs-CS/Gr/CPE electrode”	protein C (APC)	serum samples	& EIS	$L^{-1}$ - 40 $\mu g \cdot m$ $L^{-1}$		oet <i>al.</i> , 2019
“A carbon paste electrode, modified with chitosan-based magnetic molecularly imprinted Polymer (CS-MIP)”	Lactic acid	Milk samples	CV and DPV	0.01– 10.0 $\mu M$ and 10.0– 500.0 $\mu M$	0.005 $\mu m$	Mahmo udiet <i>al.</i> , 2022
“Poly (chitosan) (P (CS))”	Riboflavin	Commercial multivitamins	CV, DPV, and SWV	24.6 to 176 $\mu M$	24.6 $\mu M$	Hassanp ouret <i>al.</i> , 2020
“Sn/Cs/PGE”	Riboflavin	Food samples.	CV and EIS	10 to 1200 $nmol L^{-1}$	5.56 $nmol L^{-1}$	Nagaraj an&Vair amuthu (2021).
“Mung bean-derived porous carbon@	Carbendazim	Juices	CV	0.1 to 20 $\mu mol$	20 $nmol L^{-1}$	Liu <i>et</i>

chitosan (MBC@CTS) composite”				$L^{-1}$		<i>al.</i> , 2022
“Carbon paste electrode, modified with chitosan-based magnetic molecularly imprinted polymer (CS-MIP)”	Lactic acid	In real milk samples	CV and DPV	0.01–10.0 $\mu\text{mol L}^{-1}$ and 10.0–500.0 $\mu\text{mol L}^{-1}$	0.005 $\mu\text{mol L}^{-1}$	Mahmoudiet <i>al.</i> , 2022
“Pentoxide ( $V_2O_5$ ) into the carbon paste electrode (CPE)”	$H_2O_2$	Cosmetic and personal care products.	EIS	5.0 to 1400.0 $\mu\text{mol L}^{-1}$	2.5 $\mu\text{mol L}^{-1}$	Ghanei-Motlagh <i>et al.</i> , 2019
“Hemoglobin–Iron Magnetic Nanoparticle–Chitosan Modified Carbon Paste Electrode”	Acrylamide	French fries	CV	10 to 171 $\text{nmol L}^{-1}$	0.06 $\text{nmol L}^{-1}$	Navarro <i>et al.</i> , 2020
“Three-dimensional hierarchical	Niclosamide	Food samples	CV	0.01 to 10 $\mu\text{mol L}^{-1}$	6.7 $\text{nmol L}^{-1}$	Li <i>et al.</i> , 2022

porous carbon coupled with chitosan”				$L^{-1}$		
“ $V_{3.6}Mo_{2.4}O_{16^-}$ chitosan (MV-CHT) nanocomposite”	Paracetamol	Drug samples	CV	0.0019 to 194.0 $\mu mol L^{-1}$	0.224 $nmol L^{-1}$	Monsef, R., &Salavati-Niasari, M. (2022).
“Pt-Pd nanoparticles/chitosan/nitrogen-doped graphene (N-Gra) nanocomposite” (Pt-Pd-CS-N-Gra)	Ascorbic acid	Drug samples	CV	2 to 400 $\mu mol L^{-1}$	0.97 $\mu mol L^{-1}$	Luo <i>et al.</i> , 2021
Pt-Pd-CS-N-Gra	Sulfite	Drug samples	CV	8 to 600 $\mu mol L^{-1}$	5.5 $\mu mol L^{-1}$	Luo <i>et al.</i> , 2021
Pt-Pd-CS-N-Gra	Oxalic acid	Drug samples	CV	1.5 to 500 $\mu mol L^{-1}$	0.84 $\mu mol L^{-1}$	Luo <i>et al.</i> , 2021
“Chitosan/SnO <sub>2</sub> -SiC”	Acrylamid	Drinking	Immuno	187 ± 12.	45.9 ± 2.7 $ng kg^{-1}$	Wu <i>et</i>

	e	water and food samples.	nsor	3 ng kg <sup>-1</sup> to 104 ± 8.2 µg kg <sup>-1</sup>	1	al., 2019
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**Table 7** details chitosan-nanocomposite sensors that utilize carbon black and carbon paste to detect various analytes across different applications, including blood serum, urine, pharmaceutical samples, and natural water samples. The techniques employed include Differential Pulse Adsorbtive Stripping Voltammetry (DPAdASV), Square Wave Adsorbtive Stripping Voltammetry (SWAdASV), and Chromatoamperometry.

The best-performing sensor, using SWAdASV, excels in norfloxacin detection in urine and spiked serum with a linear range of 0.2 to 7.4 µmol/L and an impressive LOD of 6.6 nmol/L, showcasing its remarkable sensitivity and precise detection capabilities.

#### 4.0 Conclusions and Future Perspectives

This review article has successfully presented many of the latest developments in the vast application of chitosan-based nanocomposite sensors within the past 5 years. The study of chitosan-based material is robust, proving its wide applicability and modifiability because chitosan possesses several unique properties that make it very desirable in electrochemical studies. On another hand, nanomaterials, in the past few decades, have been one of the most studied topics in science. Their combination with chitosan has opened up a non-exhaustible vista in the production of novel materials with highly enhanced performances, which are utilized in all fields of life.

This review further emphasizes the importance and great prospects of chitosan-based nanocomposites as excellently promising materials in the production of sensors and biosensors.

In the very near future, developments in this area will continue to evolve for application in diverse fields and industries such as food, environmental, health, pharmaceuticals, agriculture, biotechnology and so much more. Sensors based on chitosan nanocomposites can be engineered and

miniaturized into disposable, field testing kits in all of these field, allowing for easy, quick and reliable measurements without the need for bulky laboratory experiments.

These materials can also be integrated into microfluidic systems which would enable higher efficiency, lower reagent consumption and facilitate high throughput analysis.

As research in this field continue to evolve, eco-friendlier environmentally sustainable methods for their preparation continues to evolve, and this will help eliminate the effect of hazardous chemical practices in our world today.

By continuing to explore the versatility of sensors based on chitosan nanocomposites, their contributions to the advancement of chemical technology and solutions to critical societal challenges will remain boundless.

#### **DISCLAIMER (ARTIFICIAL INTELLIGENCE)**

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of manuscripts.

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