Chitosan Nanocomposites-Based Electrochemical Sensors: A Review

Abstract

Chitosan nanocomposites are a unique combination of chitosan and nanomaterials, a relatively new concept gaining relevance across all fields. Their promising potentials stem from the synergistic output between chitosan and the nanomaterials' individual properties. Chitosan is a bio-derived polymeric compound with desirable features such as biocompatibility, natural availability, high film-formability, tunable functionality, and good gel-forming ability. On the other hand, nanomaterials are a class of materials that exhibit excellent properties and efficiency exceeding that of their bulky counterparts or derivatives. Chitosan's thermal, electrical, and mechanical deficiencies are compensated when engrafted with nanocomposites. Therefore, the blend of chitosan and nanomaterials has opened up a remarkable vista for numerous applications in different fields, especially as electrochemical sensors. This review provides an up-to-date compilation of the most recent advances in the application of chitosan-based nanocomposites for electrochemical sensing and highlights their tremendous significance, as well as prospects. Different chitosan-based nanocomposites are discussed including their efficient methods of preparation.

Keywords: Chitosan Nanocomposites, Electroanalytical Methods

Sensors/Biosensors, Environmental/Food monitoring, Nanomaterials, Analytical Chemistry

1.0 Introduction

Chitosan is a bio-derived polymeric compound with unique features such as biocompatibility, natural availability, high film-formability, tunable functionality, and gel-forming ability. Other properties include biodegradability, non-toxicity, biocompatibility, high adsorption capacity, solubility in weak acids, and pH sensitivity (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; Spoială 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 ß-bond (1→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 (Broquá*et al*., 2019; Vinodh *et 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 nanocomposites have also received great interest in recent times due to their ability to act as a stabilizing agent for the immobilization of biological components (such as enzymes), effectiveness in electrochemical measurements, excellent film-forming ability (Muthusankar& Ragupathy 2018, Kumar *et al.*, 2019).

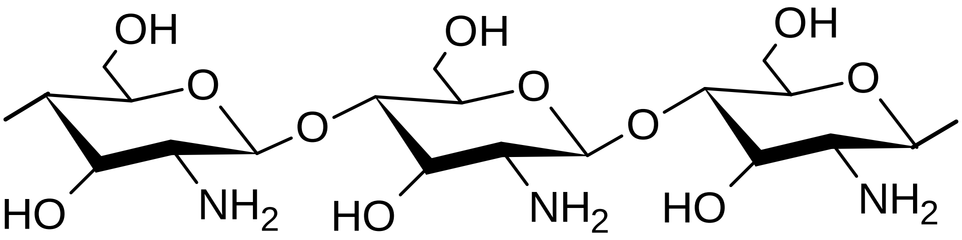

Figure 1. Chemical structure of chitosan biopolymer.

This review article captures the recent progress and advancements in the use of chitosan nanocomposites for electrochemical sensor and biosensor development within 5 years. It also presents their application for the investigation of important analytes in medical, pharmaceutical, food, beauty/cosmetics, and environmental fields, such as heavy metals, caffeine, dopamine, glucose, and hydrogen peroxide, which is one of the most studied reactive oxygen species.

2.0 Method of Chitosan synthesis

2.1 Preparation of Chitosan and Chitosan-Nanocomposites

Chitosan is the synthetic derivative of the second most abundant polysaccharide biopolymer, chitin (Negm *et al*., 2020; Zouaoui *et al*., 2020; Iñiguez-Moreno *et al*., 2021) whose structural component is based on 2-acetamido-2-deoxy-β-D-glucose linked by β-bonds (1→4). It is it's the 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. (Zouaoui *et 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 determines (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.

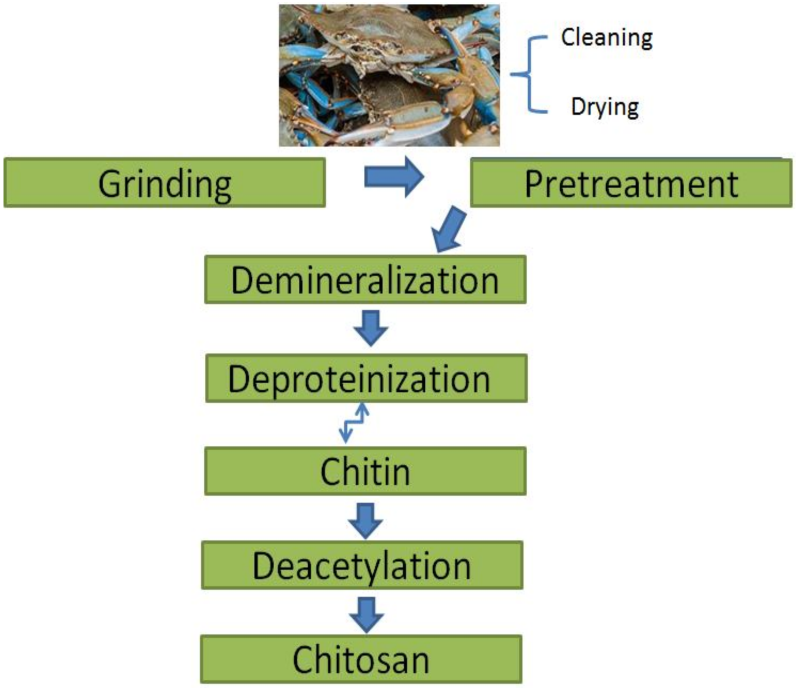

Figure 2. Preparation of Chitosan from Crabshell source.

The preparation of chitosan nanocomposites has been carried out through different means which involve physical, mechanical, or chemical procedures. Examples of techniques that have been previously employed in the synthesis of chitosan nanocomposite include electrospinning, screen printing, ultra-sonication, phase separation, and self-assembly (Muthusankar& Ragupathy 2018). Figure 3 provides a summary of some methods for the preparation of nanomaterials before they are integrated into Chitosan to form a composite

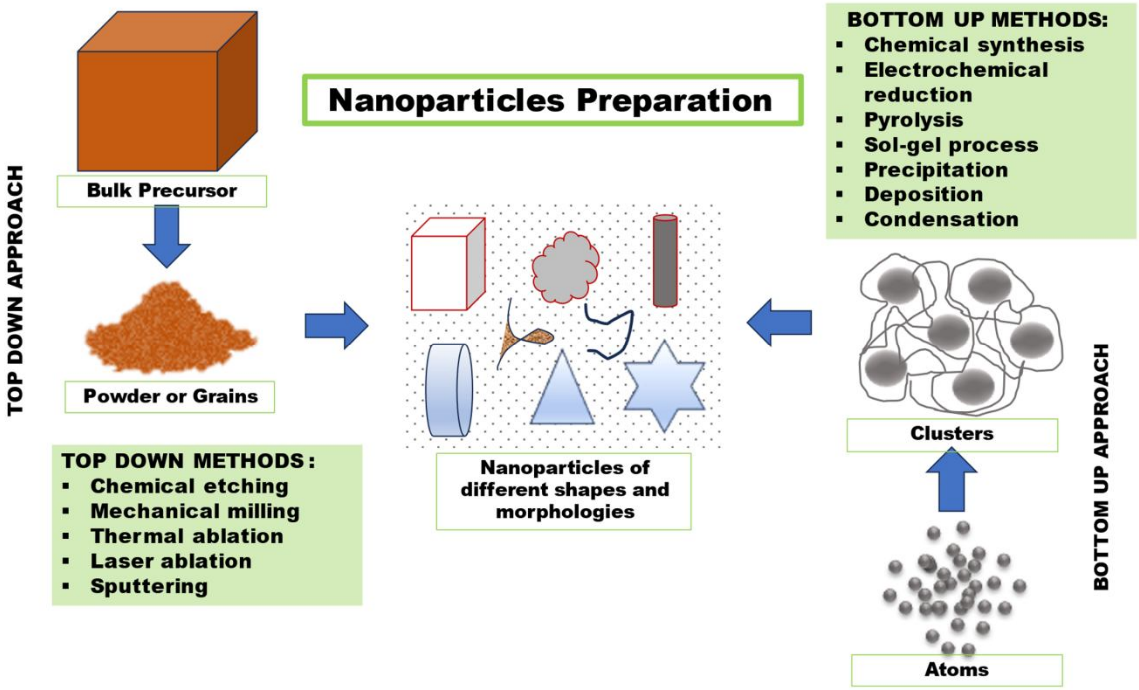

Figure 3 Methods for nanomaterials preparation

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 (Sadasivuni*et al*., 2019).

In the past five years, chitosan-silver nanocomposites have had a wide range of applications in several fields including agriculture (Shakeel *et al*., 2016, Rashed *et al*., 2022), environment (Saenchoopa*et al*., 2021, Wang *et al*., 2021), food (Sano et al., 2020, Khalaf *et 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 Nanoparticles	Nitrite	Water and ham samples	Cyclic Voltammetry (CV), Differential Pulse Voltammetry (DPV)	4.0–1000 µm	7.9×10^{-7} mol L^{-1}	Hui *et al* 2024
“Silver nanoparticles and carbon nanotubes nanocomposite”	Diazinon (DZN)	Water and food samples	“Batch injection analysis system with	0.1 to 20 µmol L^{-1}	0.35 µmol L^{-1}	Porto *et al*., 2022

			multiple pulse amperometric detection (BIA–MPA)”			
“Silver nanoparticles and carbon nanotubes nanocomposite”	Malathion (MLT)	Water and food samples	BIA–MPA	1 to 30 Mmol L^{-1}	0.89 μmol L^{-1}	Porto *et al.*, 2022
“Silver nanoparticles and carbon nanotubes nanocomposite”	Chlorpyrifos (CLPF)	Water and food samples	BIA–MPA	0.25 to 50 μmol L^{-1}	0.53 μmol L^{-1}	Porto *et al.*, 2022
“Silver/manganese oxide nanoparticles (Ag-mnoxnps/PAYR)”	2,4-dichlorophenoxyacetic acid Herbicide	Water samples	CV	22 to 11, 752 μmol L^{-1}	7.33 μmol L^{-1}	Fathi, *et al.*, 2021
“Silver/manganese oxide nanoparticles (Ag-mnoxnps/PAYR)”	2,4-dichlorophenoxyacetic acid Herbicide	Water samples	DPV	6 to 14, 308 μmol L^{-1}	2 μmol L^{-1}	Fathi *et al.*, 2021
“Multiwalled carbon nanotube chitosan-functionalized silver	Nitrite	River water sample	CV	100 nmol L^{-} to 50 μmol	30 nmol L^{-1}	Bibi *et al.*, 2019

nanoparticles (MWCNT) nitrite (Chit-agnps)”				L^{-1}		
“Chitosan polymer complex derived nanocomposite (agnps/NSC)”	Glucose	Not stated	CV, chronoamperometry and EIS	5 µmol L^{-1} to 3 mmol L^{-1}	0.046 m mol L^{-1}	Khalaf *et al.*, 2020
“Flower-like molybdenum disulfide/Ag nanoparticle-chitosan (mos$_2$/Ag nps-CS) composite”	Butylated hydroxyanisole (BHA	Food	Molecularly imprinted electrochemical sensor	1×10^{-9} to 1×10^{-4} mol L^{-1}	7.9×10^{-9} mol L^{-1}	Han *et al.*, 2022
“Silver nanoparticles on chitosan/polyvinylpyrrolidone modified micro-needle electrode (agnps/CTS/PVP/MNE)”	Nitrate (NO_3^-)	Seawater samples	Amperometry	5 to 2000 µmol L^{-1}	1.2 µmol L^{-1}	Wang *et al.*, 2021
“Composite layer of silver nanowires,	Hg (II)	Commercial drinking water	Screen-Printed	5 to 25 µmol L^{-1}	3.94 µmol L^{-1}	Saenchoop a*et al.*,

hydroxymethyl propyl cellulose, chitosan, and urease (agnws/HPMC/CS/Urease)”		samples	Carbon Electrode (SPCE)			2021
“Silver nanoparticles using chitosan as stabilizer”	P□Nitrophenol	Surface water rice samples	DPV	1.0×10^{-6} to 1.0×10^{-4} mol L^{-1}	6.0×10^{-7} mol L^{-1}	Laghrib*et al.*, 2020
“Silver decorated chitosan nanocomposite (Ag@CTSN)”	Thiourea	Spiked samples	CV	200 to 3600 μmol L^{-1}	18 μmol L^{-1}	Rashed *et al.*, 2022
“Silver nanoparticles embedded chitosan-carbon nanotube hybrid composite (agchit-CNT)”	Clopidogrel	Urine and pharmaceutical formulations	DPV	5×10^{-8} to 12×10^{-6} M.	30 nmol L^{-1}	Satyanarayana *et al.*, .2019
“Silver nanoparticles embedded chitosan-carbon nanotube hybrid composite (agchit-CNT)”	Clopidogrel	Urine and pharmaceutical formulations	Amperometry	5×10^{-8} to 12×10^{-6} mol L^{-1}	10 nmol L^{-1}	Satyanarayana *et al.*, .2019

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 (Vasantharaj*et 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 µmol L^{-1} to10.3 mmol L^{-1}	0.390 µmol L^{-1}	Zhao *et al.*, 2020
"Copper nanoparticle/C spheres composite (Cu NPs/C)"	Azathioprine (AZP)	Environmental application	CV	0.01 to 1401 µmol L^{-1}	3.5 nmol L^{-1}	Anupriya *et al.*, 2022
"Cerium oxide-copper oxide (CeO_2-Cu_2O) /	4-Nitrophenol	Water samples	CV	74 to 375 µmol L^{-1}	2.03 µmol L^{-1}	Khan *et al.*, 2019

chitosan (CeOC-Cu_2O/CH”) nanocomposites						
“Self-assembled chitosan capped with gold nanoparticles (Cs + AuNPs)”	Acetylsalicylic acid ASA or aspirin)	Urine samples	Voltammetric electronic tongue (VE-Tongue	1 pg mL^{-1} to 1 μg mL^{-1}	0.03 pg mL^{-1}	Diouf *et al.*, 2020.
“$V_{3.6}Mo_{2.4}O_{16}$chitosan (MV-CHT) nanocomposite chitosan-molybdenum vanadate nanocomposite”	Paracetamol	Drug samples	CV	0.0019 to 194.0 μmol L^{-1}	0.224 nmol L^{-1}	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^{-1}	0.97 μmol L^{-1}	Luo *et al.*, 2021
“Pt-Pd nanoparticles/chitos	Sulfite	Drug samples	CV	8 to 600 μ mol L^{-1},	5.5 μmol L^{-1}	Luo *et al.*, 2021

an/nitrogen-doped graphene (N-Gra)" nanocomposite						
"Pt-Pd nanoparticles/chitosan/nitrogen-doped graphene (N-Gra)" nanocomposite"	Oxalic acid	Drug samples	CV	1.5 to 500 μmol L^{-1}	0.84 μmol L^{-1}	Luo *et al.*, 2021
"Chitosan/SnO$_2$-SiC"	Acrylamide	Drinking water and food samples.	CV	187 ± 12.3 ng kg^{-1} to 104 ± 8.2 μg kg^{-1}	45.9 ± 2.7 ng kg^{-1}	Wu *et al.*, 2019

3.3Chitosan-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, Ghalehno*et al.*, 2019, Diouf *et al.*, 2020, Lavanya *et 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 samples	CV	0.05–150 µm	50 nm	Hassan *et al* 2024
“Chitosan capped with gold” nanoparticles (SPCE/Cs + aunps)	Acetylsalicylic acid (ASA or aspirin	Urine, saliva and pharmaceutical	VE-Tongue	1 pg ml^{-1} and 1 µg ml^{-1}	0.03 pg ml^{-1}	Diouf *et al.*, 2020
“Chitosan/gold nanoparticles Nanocomposite Film (Chi/aunps)”	Bisphenol A (BPA)	Water samples	CV	0.4 to 20 Mmol L^{-1}	0.32 µmol L^{-1}	Almeida *et al.*, 2022
“Gold nanoparticle–chitosan/graphene paste modified carbon paste electrode	Activated protein C	APC in human serum samples	Aptasensor	0.1 ng ml^{-1} to 40 µg ml^{-1}	0.073 ng ml^{-1}	Ghalehno *et al.*, 2019.

(aunps-Chi/Gr paste)”						
“Chitosan gold nanoparticles decorated molecularly imprinted polymer (Ch-aumip)”	Ciprofloxacin (CIP) antibiotic	Tap water, mineral water, milk, and pharmaceutical formulation.	MIP/CV	1 to 100 µmol L^{-1}	210 nmol L^{-1}	Surya *et al.*, 2020
“Gold nanoparticle decorated on a molybdenum disulfide/chitosan (Au@mos$_2$/Ch)”	Monosodium glutamate (MSG)	Food samples	Amperometry/ Immunosensor	0.05 to 200 µmol L^{-1}	0.03 µmol L^{-1}	Devi *et al.*, 2019
“Chitosan (CS) capped with gold nanoparticles (aunps)”	Butylated hydroxyanisole (BHA)	Food samples	MIP	0.001 µg ml^{-1}	0.01–20 µg ml^{-1}	Motia*et al.*, (2021
“Au/Carbon Nanofibers□chitosan and Reduced	Mercury (Hg^{2+})	Tap water.	Signal probe and Specific Single-	5.7 × 10^{-5} nmol L^{-1}	0.0001–460 nmol	Lv*et al.*, 2023

Graphene Oxide. (dpau/cnfs-CS)-(RGO”			Stranded DNA (ssDNA) as recognition component		L^{-1}	
“Au□W bimetallic nanoparticles decorated graphene□chitosan nanocomposite (aunps-wnps@Gr-Chi/PGE)”	Nitrite	Water, milk, and natural fruit juice samples.	CV	0.12 µmol L^{-1}	From 10 to 250 µmol L^{-1}	Lavanya *et al.*, 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 pg ml^{-1} to 50 ng ml^{-1}	0.31 pg ml^{-1} to 50 ng ml^{-1}	Zouaoui *et al.*, 2020
“Nitrogen-doped	Glucose	Standard	Amperometry	10 nmol L^{-1}	3.3 n	Ran *et*

graphene quantum dots (N-gqds Au-N-gqds were stabilized with chitosan”		samples		to 5.0 µmol L^{-1}	µmol L^{-1}	*al.*, (2019
“Chitosan (CS) biopolymer electrochemically deposited onto a gold microelectrode”	Glyphosate	River water, Soybean sprout	EIS	0.31 pg ml^{-1} to 50 ng ml^{-1}	5 fg ml^{-1}	Zouaoui *et al.*, 2020

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	Anticancer drug, nilutamide	Biological environment and pharmaceut	CV and DPV	0.005 to 20 µmol L^{-1} and 20 to 900 µmol	1.6 nmol L^{-1}	Akhter *et al.*, 2020

(CTS) with electrodeposited copper (Cu)”		ical commercial preparations		L^{-1}		
“Nano-hydroxyapatite incorporated MWCNT-chitosan scaffolds (HANPs/MWCNTCS/GCE)”	Nitrofurantoin	Tap water	CV, EIS and amperometry	0.005 to 982.1 µmol L^{-1}	1.3 nmol L^{-1}	Velmurugan, *et al.*, 2020
“Chitosan–gold nanoparticles composite cryogel on Prussian blue-coated multi-walled carbon nanotubes”	Histamine	Fish and shrimp sample	CV, SPE	2.50 to 125.0 µmol L^{-1} and 125.0 to 400.0 µmol L^{-1}	1.81 µmol L^{-1}.	Nontipich et*et al.*, 2021
“NanoAu/Poly(ABSA)-MWCNTs/GCE”	Hydroquinone	Lake water	CV , DPV	2 ~ 200 mmol L^{-1}	1.0 µmol L^{-1}	Li *et al.*, 2022
glassy carbon	Mycoba	real media	CV , DPV	1.0 × 10^{-15}–	1.53 × 1	Naghshga

electrode	cterium avium subspecies paratuberculosis (MAP)			1.0×10^{-12} mol L^{-1}	0^{-13} mol L^{-1}	r*et al.*, 2024
(chitosan/rGO/GCE)	Imatinib	Human serum samples	DPV	7.3 nM	1–300 μM	Yongzhie*t al* 2024
“Multi-walled carbon nanotubes (MWCNTs-graphene (GR)/ gold nanoparticles (AuNPs)/Nafion”	Lead (Pb^{2+})	Water and milk samples	Ion-imprinted polymers (IIPs), CV	1.0×10^{-9} to 5.0×10^{-5} mol L^{-1}	2.83×10^{-10} mol L^{-1}.	Wu, *et al.*, 2020
“Gold nanoparticle (AuNP)-decorated multiwalled carbon nanotubes (MWCNT) encapsulated in a	Catechol	Wine	CV	0 to 1 mmol L^{-1}	3.7×10^{-5} mol L^{-1}	Salvo-Comino *et al.*, 2020

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

		urine samples				
“FC/Chi-MWCNT”	Xanthine	Human serum and urine samples	DPV	1 to 191.3 μmol L^{-1}	7.3 nmol L^{-1}	Li et al., 2019
“FC/Chi-MWCNT”	Caffeine	Human serum and urine samples	DPV	10 to 2.4 μmol L^{-1}	2.2 μmol 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

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 µmol L^{-1}	15.99 µmol L^{-1}	Elugoke*et al.*, 2023
“Carbon quantum dots (cqds) synthesized from candle soot”	Insulin detection	Human blood serum	Differential-Pulse Adsorptive Anodic Stripping Voltammetry (DPAdASV)	0.5 nmol L^{-1} to 10 nmol L^{-1}	106.8 p mol L^{-1}	Abazar &Noorbakhsh, 2020
“Nitrogen-doped carbon quantum dots (N-CQDS)”	Fluorescent sensor	Fe^{3+} ions in water samples	Fluorescent sensor	Not stated	0.15 lµmol L^{-1}	Zhao *et al.*, 2019
“Graphene quantum dots, chitosan, and	Diazinon	Cucumber and tomato samples	CV	0.1 to 330 µmolµmol L^{-1}	30 nmol L^{-1}	Eddin *et al.*, 2021

nickel molybdate ($NiMoO_4$)”						
“Cu-doped carbon dots (Cu-CDS) with chitosan”	H_2O_2	Human serum samples spiked with glucose.	Colorimetry	0.625 to 40 µM	0.12 µM	Tummala *et al.*, 2022
“Cross-linked chitosan/thiolated graphene quantum dots modified by gold nanoparticle (Au-NSS/GQDS-CS/Cysteamine	Ractopamine	Biological samples	DPV	0.0044 fmol L^{-1} to 19.55 µmolµmol L^{-1} L	0.0044 fmol L^{-1}	Mirzaie *et al.*, 2019
Polypyrrole-chitosan/graphene quantum dots nanocomposite	Glucose detection	Biological samples	Surface plasmon resonance sensor	Not stated	1 ppm	Sadrolhosseini*et al.*, 2019

layer deposited on gold-coated glass”						
“Nitrogen-doped graphene quantum dots	Triclocarban	Personal care Products	CV	0.05 to 8.0 µmol L^{-1}	17.0 nmol L^{-1},	Santana,*et al.*, 2021
“Γ-Cyclodextrin-graphene quantum dots-chitosan modified SPE	Fluoroquinolones	Animal source products e.g. broths, bouillon cubes and milkshakes	CV and DPV	4 to 250 µmol L^{-1}	1.2 µmol L^{-1}	Bartolomé *et al.*, 2023
“Integrated chitosan, poly(diallyldimethylammonium chloride)-functioned multi-walled carbon nanotubes and	Glucose	Human serum samples	Closed bipolar electrochemiluminescence (C-BP-ECL)	0.1 to 5000 µmo lµmol L^{-1} L	64 nmol L^{-1}	Wang *et al.*, 2019

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 µmol L−1	6.6 nmol L^{-1}	Santos *et al.*, 2019
“Graphene quantum dots, chitosan, and nickel molybdate nanocomposites”	Diazinon	Cucumber and tomato samples.	DPV	0.1 to 330 µmol µmol L^{-1} L	30 nmol L^{-1}	Eddin *et al.*, 2021
“Gold -Nitrogen-doped graphene quantum dots	Glucose	Standard samples	Electrochemiluminescence (ECL)	10 nmol L^{-1} to 5.0 µmolµ	3.3 nmol L^{-1}	Ran *et al.*, 2019

(Au-N-GQDS) stabilized with chitosan”				mol L^{-1} L		
“Graphene quantum dots”	Epinephrine	Human serum	CV	0.36 to 380 μmol μmol L^{-1} L	0.3 nmol L^{-1}	Tashkhouri an*et al*., 2018

Table 6. Chitosan-Nanocomposite Sensors Based on Graphene.

Electrode	**Analyte**	**Application**	**Technique**	**Linear range**	**LOD**	**REF**
glassy carbon electrode/gold nanoparticle/gold nanodendrites/chitosan-reduced graphene oxide/Anti-CEA antibody	carcinoembryonic antigen	Human serum	Electrochemical Impedance Spectroscopy (EIS) and Linear Sweep Voltammetry (LSV)	1×10^{-13} to 1×10^{-8} g/mL	2.23 (±0.03) x 10^{-14} g/mL	Buddhadev *et al* 2024
glass carbon electrode (GCE)	Aflatoxin B_1	CV, DPV, and Electrochemical Impedance Spectroscopy		0.05 to 25 ng/mL	0.021 ng/mL	Zhang *et al* 2024

		(EIS)				
“Chitosan-reduced graphene oxide (CS-rGO) Fe-hemin-MOFs/CS-rGO”	H_2O_2	Human serum samples	Amperometry	1 to 61 lμmol L^{-1}	0.57 μmol L^{-1}	Zhao *et al.*, 2020
“Reduced graphene oxide-chitosan-ferrocene carboxylic acid/platinum nanoparticle (RGO-CS-Fc/Pt NPs)”	H_2O_2	Clinical serum samples	Amperometry	0.5 to 4.0 mg mL^{-1}	5.70 μg mL^{-1}	Li *et al.*, 2019.
“Ion-imprinted chitosan-graphene nanocomposites (IIP-S)”	Cr(VI)	Tap water and river water	CV, EIS and DPV	1.0×10^{-9} to 1.0×10^{-5} mol/L	6.4×10^{-1} mol/L	Wu *et al.*, 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^{-1}	5.70 μg mL^{-1}	Li *et al.*, 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−1 to 5.0 μmolμ mol L^{-1} L	3.3 nmol L−1	Ran *et al.*, 2019
“Reduced graphene oxide (RGO) and carbon black (CB) in Chitosan” (rGO-CB-CS)	Dopamine	Urine samples	Square Wave Voltammetry (SWV)	3.2×10^{-6} to 3.2×10^{-5} mol L^{-1}	2.0×10^{-7} mol L^{-1}	Baccarin *et al.*, 2017

RGO-CB-CS	Paracetamol	Urine samples	SWV	2.8×10^{-6} to 1.9×10^{-5} mol L^{-1}	5.3×10^{-8} mol L^{-1}	Baccarin *et al.*, 2017
“Graphene nanoplatelets (GNPs)-multiwalled carbon nanotube (MWCNTs) and chitosan (CS) (GNPs-MWCNTs-CS)”	Bisphenol A , BPA	Milk samples	DPV	0.1 to 100 µmol L^{-1}	0.05 nmol L^{-1}	Zou *et al.*, 2019
“Sulfur-doped reduced graphene oxide (S-rGO)”	Mercury (Hg^{2+})	Fish muscle	DPAdASV	0.125 to 6 µmol L^{-1}	1.6 nmol L^{-1}	Ran *et al.*, 2022
“Functionalized Graphene (f-graphene) doped chitosan (CS)”	Ochratoxin A (OTA)	Grape juice samples	DPV	1 µgmL^{-1} to 1 fg mL^{-1}	1 fg mL^{-1}	Kaur *et al.*, 2019
“Graphene, and titanium dioxide	Lead (Pb^{2+})	Food sample	CV	1 ng L^{-1} to 1000 ng	0.33 ng L^{-1}	Wang *et al.*, 2022

(CS/RGO/TiO_2)”		s		L^{-1}		
“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 µmolµ mol L^{-1} L.	1.62 × 10^{-4}µmolµ mol L^{-1} L	Wu *et al.*, 2020).
“Chitosan–Graphene Glassy Carbon Modified Electrode”	Hydroxyflavonoid Morin	Food samples.	CV	0.30 µmol $L^{-1}$to 1.0 µmol L^{-1}	0.30 µmol L^{-1}	Nagles*et al.*, 2022
“Ag-reduced graphene oxide (rGO) and chitosan (CS)”	Carbaryl pesticide	Pesticide residues	CV	1.0 × 10^{-8} to 1.0 µg mL^{-1}	1.0 × 10^{-9}µg mL^{-1}.	Mashuni*et al.*, 2022
"Chitosan-graphene oxide composites polymer	Cu (II)	Tap and river water	DPAdASV	0.5 to 100 µmol L^{-1}	0.15 µmol L^{-1}	Wei *et al.*, 2019

modified glassy carbon electrode (CS/GO-IIP)”		samples				
“Graphene oxide-chitosan composite (GO-chit)”	Phorate	Fresh vegetables	DPV	0.1 to 800 nmol L^{-1}	0.1 nmol L^{-1}	Fu *et al.*, 2020
“GO-chit”	Isocarbophos	Fresh vegetables	DPV	0.01 to 1000 nmol L^{-1}	0.01 nmol L^{-1}	Fu *et al.*, 2020
“GO-chit”	Omethoate	Fresh vegetables	DPV	0.1– 100 nmol L^{-1}	0.1 nmol L^{-1}	Fu *et al.*, 2020

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	Dopamine (DA) Epinephrine (EP)	Blood serum, urine and pharmaceutical	DPAdASV	DA- 0.115 to 5.909 ng mL^{-1}	“Dopamine: 28 pg mL^{-1} (Water), 28 pg mL^{-1} (Serum), 61 pg mL^{-1}	Fatma *et al.*, 2019

composite polymer (aGO/CBOMNiDIP/SPE)”		samples		EP- 0.079 to 1.307 ng mL^{-1}	(Urine) and 29 pg mL^{-1} (Pharmaceutical sample) Epinephrine: 17 pg mL^{-1} (Water), 18 pg mL^{-1} (Serum), 19 pg mL^{-1} (Urine) and 20 pg mL^{-1} (Pharmaceutical sample)”	
“Carbon black and CdTe quantum dots in a chitosan film”	Norfloxacin	Urine and spiked serum.	SWAdASV	0.2 to 7.4 μmol L^{-1}	6.6 nmol L^{-1}	Santos *et al.*, 2019
“Carbon black - chitosan-stabilized platinum nanoparticles (CB-Ch-PtNP)”	H_2O_2	Natural water samples	Chronoamperometry		10 μmol L^{-1}.	Silva *et al.*, 2023
“Carbon black -	Bisphenol	Natural	DPAdASV		7.9 nmol L^{-1}	Silva *et*

chitosan-stabilized platinum nanoparticles (CB-Ch-PtNP)”	A (BPA).	water samples				*al.*, 2023
“Super P carbon black particles and chitosan”	Macrolide antibiotics, environmental samples	Water and pharmaceutical samples	CV	1.0–190.0 µmol	Not stated	Veloso *et al.*, 2022
Carbon paste						
“Gold nanoparticle–chitosan/graphene paste modified carbon paste electrode. AuNPs-CS/Gr/CPE electrode”	Activated protein C (APC)	Human serum samples	CV, DPV & EIS	0.1 ng·mL^{-1} - 40 µg·mL^{-1}	0.073 ng·mL^{-1}	Ghalehno*et al.*, 2019
“A carbon paste electrode, modified with chitosan-based magnetic molecularly	Lactic acid	Milk samples	CV and DPV	0.01–10.0 µM and 10.0–	0.005 µm	Mahmoudi *et al.*, 2022

imprinted Polymer (CS-MIP)”				500.0 µM		
“Poly (chitosan) (P (CS))”	Riboflavin	Commercial multivitamins	CV, DPV, and SWV	24.6 to 176µM	24.6µM	Hassanpour *et al.*, 2020
“Sn/Cs/PGE”	Riboflavin	Food samples.	CV and EIS	10 to 1200 nmol L^{-1}	5.56 nmol L^{-1}	Nagarajan & Vairamuthu (2021).
“Mung bean-derived porous carbon@ chitosan (MBC@CTS) composite”	Carbendazim	Juices	CV	0.1 to 20 lµmol L^{-1}	20 nmol L^{-1}	Liu *et al.*, 2022
“Carbon paste electrode, modified with chitosan-based magnetic molecularly imprinted polymer	Lactic acid	In real milk samples	CV and DPV	0.01–10.0 µmol L^{-1} and 10.0–	0.005 µmol L^{-1}	Mahmoudi *et al.*, 2022

(CS-MIP)"				500.0 μmol L^{-1}		
"Pentoxide (V_2O_5) into the carbon paste electrode (CPE)"	H_2O_2	Cosmetic and personal care products.	EIS	5.0 to 1400.0 μmol L^{-1}	2.5 μmol L^{-1}	Ghanei-Motlagh *et al.*, 2019
"Hemoglobin–Iron Magnetic Nanoparticle–Chitosan Modified Carbon Paste Electrode"	Acrylamide	French fries	CV	10 to 171 nmol L^{-1}	0.06 nmol L^{-1}	Navarro *et al.*, 2020
"Three-dimensional hierarchical porous carbon coupled with chitosan"	Niclosamide	Food samples	CV	0.01 to 10 μmol L^{-1}	6.7 nmol L^{-1}	Li *et al.*, 2022
"$V_{3.6}Mo_{2.4}O_{16}$-chitosan (MV-CHT) nanocomposite"	Paracetamol	Drug samples	CV	0.0019 to 194.0 μmol 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 lµmol L^{-1}	0.97 µmol L^{-1}	Luo *et al.*, 2021
Pt-Pd-CS-N-Gra	Sulfite	Drug samples	CV	8 to 600 µmol L^{-1}	5.5 µmol L^{-1}	Luo *et al.*, 2021
Pt-Pd-CS-N-Gra	Oxalic acid	Drug samples	CV	1.5 to 500 lµmol L^{-1}	0.84 µmol L^{-1}	Luo *et al.*, 2021
“Chitosan/SnO_2-SiC”	Acrylamide	Drinking water and food samples.	Immunosensor	187 ± 12.3 ng kg^{-1} to 104 ± 8.2 µg kg^{-1}	45.9 ± 2.7 ng kg^{-1}	Wu *et al.*, 2019

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.

References

1. Amjadi, S., Nazari, M., Alizadeh, S. A., &Hamishehkar, H. (2020). Multifunctional betanin nanoliposomes-incorporated gelatin/chitosan nanofiber/ZnO nanoparticles nanocomposite film for fresh beef preservation. *Meat Science*, *167*, 108161.

2. Broquá, J., Zanin, B. G., Flach, A. M., Mallmann, C., Taborda, F. G. D., Machado, L. E. L., ... & Dias, R. J. S. P. (2019). Methods of chitin production a short review. *Am J Biomed Sci & Res*, 307-314.

3. Chauhan, S., & Thakur, A. (2023). Chitosan-based biosensors-A Comprehensive Review. *Materials Today: Proceedings*.
4. Devi, R., Gogoi, S., Barua, S., Dutta, H. S., Bordoloi, M., & Khan, R. (2019). Electrochemical detection of monosodium glutamate in foodstuffs based on Au@ MoS2/chitosan modified glassy carbon electrode. *Food chemistry*, *276*, 350-357.

5. Diouf, A., Moufid, M., Bouyahya, D., Österlund, L., El Bari, N., & Bouchikhi, B. (2020). An electrochemical sensor based on chitosan capped with gold nanoparticles combined with a voltammetric electronic tongue for quantitative aspirin detection in human physiological fluids and tablets. *Materials Science and Engineering: C*, *110*, 110665.

6. El Knidri, H., Belaabed, R., Addaou, A., Laajeb, A., &Lahsini, A. (2018). Extraction, chemical modification and characterization of chitin and chitosan. *International Journal of biological macromolecules*, *120*, 1181-1189

7. El-Araby, A., El Ghadraoui, L., &Errachidi, F. (2022). Physicochemical properties and functional characteristics of ecologically extracted shrimp chitosans with different organic acids during demineralization step. *Molecules*, *27*(23), 8285.

8. Ghalehno, M. H., Mirzaei, M., &Torkzadeh-Mahani, M. (2019). Electrochemical aptasensor for activated protein C using a gold nanoparticle–chitosan/graphene paste modified carbon paste electrode. *Bioelectrochemistry*, *130*, 107322.

9. Hatchett C (1800b) Experiments and obfervations on shell and bone (concluded). In: Nicholson W(ed) Journal of natural philosophy, chemistry, and the arts, London. March 1800, volume III, article II, pp 529–534

10. Han, B., Wen, X., Wang, J., & Sun, Y. (2022). A Novel Nanocomposite of Zn (II)-Protoporphyrin-Chitosan-Multi Walled Carbon Nanotubes and the Application to Caffeic Acid Sensing. *Nanomaterials*, *12*(19), 3412.

11. Hui Hu, Feng Hu, Xiaohui Wang, Xiaowen Shi, Paper-based sensor with electro-modified chitosan/silver nanoparticles for rapid and sensitive nitrite detection, Journal of Environmental Chemical Engineering, Volume 12, Issue 3, 2024, 112858, ISSN 2213-3437, https://doi.org/10.1016/j.jece.2024.112858.

12. Iber, B.T., Kasan, N.A., Torsabo, D., Omuwa, J.W. (2022). A review of various sources of chitin and chitosan in nature. *Journal of Renewable Materials*, *10(4)*, 1097-1123. https://doi.org/10.32604/jrm.2022.018142

13. Iñiguez-Moreno, M., Ragazzo-Sánchez, J. A., & Calderón-Santoyo, M. (2021). An extensive review of natural polymers used as coatings for postharvest shelf-life extension: Trends and challenges. *Polymers*, *13*(19), 3271.

14. Jiang, Y., & Wu, J. (2019). Recent development in chitosan nanocomposites for surface-based biosensor applications. *Electrophoresis*, *40*(16-17), 2084-2097.

15. Kandile, N. G., Zaky, H. T., Mohamed, M. I., Nasr, A. S., & Ali, Y. G. (2018). Extraction and characterization of chitosan from shrimp shells. *Open Journal of Organic Polymer Materials*, *8*(3), 33-42.

16. Karrat, A., & Amine, A. (2020). Recent advances in chitosan-based electrochemical sensors and biosensors. *Arab. J. Chem. Environ. Res*, *7*(2), 66-93.

17. Khalaf, N., Ahamad, T., Naushad, M., Al-Hokbany, N., Al-Saeedi, S. I., Almotairi, S., & Alshehri, S. M. (2020). Chitosan polymer complex derived nanocomposite (AgNPs/NSC) for electrochemical non-enzymatic glucose sensor. *International journal of biological macromolecules*, *146*, 763-772.

18. Kumar, S., Ye, F., Dobretsov, S., & Dutta, J. (2019). Chitosan nanocomposite coatings for food, paints, and water treatment applications. *Applied Sciences*, *9*(12), 2409.

19. Lavanya, A. L., Kumari, K. G. B., Prasad, K. R. S., & Brahman, P. K. (2021). Development of pen-type portable electrochemical sensor based on Au-W bimetallic nanoparticles decorated graphene-chitosan nanocomposite film for the detection of nitrite in water, milk and fruit juices. *Electroanalysis*, *33*(4), 1096-1106.

20. Ling, S., Chen, W., Fan, Y., Zheng, K., Jin, K., Yu, H., ...& Kaplan, D. L. (2018). Biopolymer nanofibrils: Structure, modeling, preparation, and applications. *Progress in Polymer Science*, *85,* 1-56.

21. Liu, Q., & Wang, X. (2020). Polyoxometalate clusters: Sub-nanometer building blocks for construction of advanced materials. *Matter*, *2*(4), 816-841. DOI:https://doi.org/10.1016/j.matt.2020.01.020

22. Lv, Z., Zhang, M., Jin, H., & Wei, M. (2023). An Ultrasensitive DNA Sensor for Hg2+ Assay Based on Electrodeposited Au/Carbon Nanofibers-chitosan and Reduced Graphene Oxide. *Electroanalysis*, *35*(2), e202200152.

23. Muthusankar, E., & Ragupathy, D. (2018). Chitosan based nanocomposite biosensors: A recent review. *Sensor Letters*, *16*(2), 81-91.

24. Negm, N. A., Hefni, H. H., Abd-Elaal, A. A., Badr, E. A., & Abou Kana, M. T. (2020). Advancement on modification of chitosan biopolymer and its potential applications. *International journal of biological macromolecules*, *152*, 681-702.

25. Raja, A. N. (2020). Recent development in chitosan-based electrochemical sensors and its sensing application. *International Journal of Biological Macromolecules*, *164*, 4231-4244.

26. Rashed, M. A., Ahmed, J., Faisal, M., Alsareii, S. A., Jalalah, M., &Harraz, F. A. (2022). Highly sensitive and selective thiourea electrochemical sensor based on novel silver nanoparticles/chitosan nanocomposite. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *644*, 128879.

27. Rizeq, B. R., Younes, N. N., Rasool, K., & Nasrallah, G. K. (2019). Synthesis, bioapplications, and toxicity evaluation of chitosan-based nanoparticles. International journal of molecular sciences, 20(22), 5776.

28. Sadasivuni, K. K., Rattan, S., Waseem, S., Bramhe, S. K., Kondawar, S. B., Ghosh, S., … Mazumdar, P. (2019). Silver Nanoparticles and Its Polymer Nanocomposites—Synthesis, Optimization, Biomedical Usage, and Its Various Applications. Methods in Molecular Biology, 331–373. doi:10.1007/978-3-030-04741-2_11

29. Sadasivuni, K., Ponnamma, D., Rajan, M., Ahmed, B., Al-Maadeed, M. (eds) Polymer Nanocomposites in Biomedical Engineering. Lecture Notes in Bioengineering. Springer, Cham. https://doi.org/10.1007/978-3-030-04741-2_11

30. Sadrolhosseini, A. R., Rashid, S. A., Jamaludin, N., Noor, A. S. M., &Isloor, A. M. (2019). Surface plasmon resonance sensor using polypyrrole-chitosan/graphene quantum dots layer for detection of sugar. *Materials Research Express*, *6*(7), 075028.

31. Saenchoopa, A., Klangphukhiew, S., Somsub, R., Talodthaisong, C., Patramanon, R., Daduang, J., ...&Kulchat, S. (2021). A disposable electrochemical biosensor based on screen-printed carbon electrodes modified with silver nanowires/hpmc/chitosan/urease for the detection of mercury (ii) in water. *Biosensors*, *11*(10), 351.

32. Sano, R., Shinozaki, Y., & Ohta, T. (2020). Sodium–glucose cotransporters: Functional properties and pharmaceutical potential. *Journal of Diabetes Investigation*, *11*(4), 770-782.

33. Shakeel, A., Altaf, A. A., Qureshi, A. M., & Badshah, A. (2016). Thiourea derivatives in drug design and medicinal chemistry: A short review. *J. drug des.med. chem*, *2*(1), 10.

34. Sivanesan, I., Gopal, J., Muthu, M., Shin, J., Mari, S., & Oh, J. (2021). Green synthesized chitosan/chitosan nanoforms/nanocomposites for drug delivery applications. *Polymers*, *13*(14), 2256. https://doi.org/10.3390/polym13142256

35. Spoială, A., Ilie, C. I., Ficai, D., Ficai, A., & Andronescu, E. (2021). Chitosan-based nanocomposite polymeric membranes for water purification—A review. *Materials*, 2021 *14*(9), 2091.

36. Tian, L., Li, Z., Wang, P., Zhai, X., Wang, X., & Li, T. (2021). Carbon quantum dots for advanced electrocatalysis. *Journal of Energy Chemistry*, *55*, 279-294.

37. Tummala, S., Bandi, R., & Ho, Y. P. (2022). Synthesis of Cu-doped carbon dot/chitosan film composite as a catalyst for the colorimetric detection of hydrogen peroxide and glucose. *Microchimica Acta*, *189*(8), 284.

38. Vasantharaj, S., Sathiyavimal, S., Saravanan, M., Senthilkumar, P., Gnanasekaran, K., Shanmugavel, M., ...& Pugazhendhi, A. (2019). Synthesis of ecofriendly copper oxide nanoparticles for fabrication over textile fabrics: characterization of antibacterial activity and dye degradation potential. *Journal of Photochemistry and Photobiology B: Biology*, *191*, 143-149.

39. Vinodh, R., Sasikumar, Y., Kim, H. J., Atchudan, R., & Yi, M. (2021). Chitin and chitosan based biopolymer derived electrode materials for supercapacitor applications: A critical review. *Journal of Industrial and Engineering Chemistry*, *104,* 155-171.

40. Wang, J., Li, Y., Pan, D., Han, H., & Zhang, P. (2021). Self-assembly of silver nanoparticles on chitosan/polyvinylpyrrolidone modified micro-needle electrode for amperometric detection of nitrate in seawater. *Microchemical Journal, 164*, 105965.

41. Wypij, M., Trzcińska-Wencel, J., Golińska, P., Avila-Quezada, G. D., Ingle, A. P., & Rai, M. (2023). The strategic applications of natural polymer nanocomposites in food packaging and agriculture: Chances, challenges, and consumers' perception. *Frontiers in Chemistry*, *10*, 1106230. https://doi.org/10.3389/fchem.2022.1106230
42. Zargar, V., Asghari, M., & Dashti, A. (2015). A review on chitin and chitosan polymers: structure, chemistry, solubility, derivatives, and applications. *ChemBioEng reviews*, *2*(3), 204-226.

43. Zouaoui, F., Bourouina-Bacha, S., Bourouina, M., Abroa-Nemeir, I., Halima, H. B., Gallardo-Gonzalez, J., ...&Errachid, A. (2020). Electrochemical impedance spectroscopy determination of glyphosate using a molecularly imprinted chitosan. *Sensors and Actuators B: Chemical*, *309*, 127753.

44. Zouaoui, F., Bourouina-Bacha, S., Bourouina, M., Jaffrezic-Renault, N., Zine, N., &Errachid, A. (2020). Electrochemical sensors based on molecularly imprinted chitosan: A review. *TrAC Trends in Analytical Chemistry*, *130*, 115982.

45. Porto, L. S., Ferreira, L. F., Dos Santos, W. T. P., & Pereira, A. C. (2022). Determination of organophosphorus compounds in water and food samples using a non-enzymatic electrochemical sensor based on silver nanoparticles and carbon nanotubes nanocomposite coupled with batch injection analysis. *Talanta*, *246*, 123477.
46. Fathi, S., Rezaee, R., Maleki, A., Amini, N., Safari, M., & Lee, S. M. (2021).Fabrication of a sensitive electrochemical sensor of 2, 4-dichlorophenoxy-acetic acid herbicide based on synergistic catalysis of silver/manganese oxide nanoparticles and polyalizarin at low potential. Desalination and water treatment, 229, 283-290.
47. Bibi, S., Zaman, M. I., Niaz, A., Rahim, A., Nawaz, M., & Bilal Arian, M. (2019). Voltammetric determination of nitrite by using a multiwalled carbon nanotube paste electrode modified with chitosan-functionalized silver nanoparticles. Microchimica Acta, 186, 1-9.
48. Wang, D., Liang, Y., Su, Y., Shang, Q., & Zhang, C. (2019). Sensitivity enhancement of cloth-based closed bipolar electrochemiluminescence glucose sensor via electrode decoration with chitosan/multi-walled carbon nanotubes/graphene quantum dots-gold nanoparticles. *Biosensors and Bioelectronics*, *130*, 55-64.

49. F. Laghrib, N. Ajermoun, M. Bakasse, S. Lahrich, M.A. El Mhammedi, (2019) Synthesis of silver nanoparticles assisted by chitosan and its application to catalyze the reduction of 4-nitroaniline, International Journal of Biological Macromolecules, 135, 752-759, 0141-8130, https://doi.org/10.1016/j.ijbiomac.2019.05.209.
50. Satyanarayana, M., Goud, K. Y., Reddy, K. K., Kumar, V. S., & Gobi, K. V. (2019). Silver nanoparticles impregnated chitosan layered carbon nanotube as sensor interface for electrochemical detection of clopidogrel in-vitro. *Materials Science and Engineering: C*, *101*, 103-110.
51. Zhao, L., Wang, Y., Zhao, X., Deng, Y., & Xia, Y. (2019). Facile synthesis of nitrogen-doped carbon quantum dots with chitosan for fluorescent detection of Fe3+. *Polymers*, *11*(11), 1731.
52. Zhao, P., Chen, S., Zhou, J., Zhang, S., Huo, D., & Hou, C. (2020). A novel Fe-hemin-metal organic frameworks supported on chitosan-reduced graphene oxide for real-time monitoring of H2O2 released from living cells. *Analytica Chimica Acta*, *1128*, 90-98.
53. Anupriya, J., Velmurugan, S., Chen, S. M., & Hahn, Y. B. (2022). Enhanced electrochemical performance of in-situ synthesized Cu nanoparticle/C spheres composite for highly sensitive sensing of azathioprine immunosuppressive drug. *Composites Part B: Engineering*, *242*, 110079.
54. Khan, S. B., Akhtar, K., Bakhsh, E. M., & Asiri, A. M. (2019). Electrochemical detection and catalytic removal of 4-nitrophenol using CeO2-Cu2O and CeO2-Cu2O/CH nanocomposites. *Applied Surface Science*, *492*, 726-735.
55. Diouf, A., Moufid, M., Bouyahya, D., Österlund, L., El Bari, N., & Bouchikhi, B. (2020). An electrochemical sensor based on chitosan capped with gold nanoparticles combined with a voltammetric electronic tongue for quantitative aspirin detection in human physiological fluids and tablets. *Materials Science and Engineering: C*, *110*, 110665.
56. Monsef, R., & Salavati-Niasari, M. (2022). Electrochemical sensor based on a chitosan-molybdenum vanadate nanocomposite for detection of hydroxychloroquine in biological samples. *Journal of Colloid and Interface Science*, *613*, 1-14.
57. Luo, X., Chen, L., Yang, J., Li, S., Li, M., Mo, Q., ...& Li, X. (2021). Electrochemically simultaneous detection of ascorbic acid, sulfite and oxalic acid on Pt-Pd nanoparticles/chitosan/nitrogen doped graphene modified glassy carbon electrode: A method for drug quality control. *Microchemical Journal*, *169*, 106623.

58. Wu, S., Dai, X., Cheng, T., & Li, S. (2018). Highly sensitive and selective ion-imprinted polymers based on one-step electrodeposition of chitosan-graphene nanocomposites for the determination of Cr (VI). *Carbohydrate polymers*, *195*, 199-206.
59. Wu, S., Li, K., Dai, X., Zhang, Z., Ding, F., & Li, S. (2020). An ultrasensitive electrochemical platform based on imprinted chitosan/gold nanoparticles/graphene nanocomposite for sensing cadmium (II) ions. *Microchemical Journal*, *155*, 104710.

60. Wu, S., Li, K., Zhang, Z., & Chen, L. (2020). Synthesis of imprinted chitosan/AuNPs/graphene-coated MWCNTs/Nafion film for detection of lead ions. *New Journal of Chemistry*, *44*(33), 14129-14135

61. Hassan Nasiri, Karim Abbasian, Hamed Baghban,Highly sensitive quantification of Amlodipine in real samples using graphene oxide-chitosan surface plasmon resonance sensor, Sensors and Actuators A: Physical,Volume 368,2024,115152,ISSN 0924-4247,https://doi.org/10.1016/j.sna.2024.115152

62. Almeida, L. A., Rodrigues, B. V., Balogh, D. T., Sanfelice, R. C., Mercante, L. A., Frade-Barros, A. F., &Pavinatto, A. (2022). Chitosan/Gold Nanoparticles Nanocomposite Film for Bisphenol A Electrochemical Sensing. *Electrochem*, *3*(2), 239-247

63. Surya, S. G., Khatoon, S., Lahcen, A. A., Nguyen, A. T., Dzantiev, B. B., Tarannum, N., & Salama, K. N. (2020). A chitosan gold nanoparticles molecularly imprinted polymer based ciprofloxacin sensor. *RSC advances*, *10*(22), 12823-12832.
64. Motia, S., Bouchikhi, B., & El Bari, N. (2021). An electrochemical molecularly imprinted sensor based on chitosan capped with gold nanoparticles and its application for highly sensitive butylated hydroxyanisole analysis in foodstuff products. *Talanta*, *223*, 121689
65. Ran, P., Song, J., Mo, F., Wu, J., Liu, P., & Fu, Y. (2019). Nitrogen-doped graphene quantum dots coated with gold nanoparticles for electrochemiluminescent glucose detection using enzymatically generated hydrogen peroxide as a quencher. *Microchimica Acta*, *186*, 1-7.
66. Ran, Q., Sheng, F., Chang, G., Zhong, M., & Xu, S. (2022). Sulfur-doped reduced graphene oxide@ chitosan composite for the selective and sensitive electrochemical detection of Hg2+ in fish muscle. *Microchemical Journal*, *175*, 107138.

67. Akhter, S., Basirun, W. J., Shalauddin, M., Johan, M. R., Bagheri, S., Akbarzadeh, O., & Anuar, N. S. (2020). Hybrid nanocomposite of functionalized multiwall carbon nanotube, nitrogen doped graphene and chitosan with electrodeposited copper for the detection of anticancer drug nilutamide in tablet and biological samples. *Materials Chemistry and Physics*, *253*, 123393.
68. Velmurugan, S., Palanisamy, S., Yang, T. C., Gochoo, M., & Chen, S. W. (2020). Ultrasonic assisted functionalization of MWCNT and synergistic electrocatalytic effect of nano-hydroxyapatite incorporated MWCNT-chitosan scaffolds for sensing of nitrofurantoin. *Ultrasonics sonochemistry*, *62*, 104863.
69. Nontipichet, N., Khumngern, S., Choosang, J., Thavarungkul, P., Kanatharana, P., &Numnuam, A. (2021). An enzymatic histamine biosensor based on a screen-printed carbon electrode modified with a chitosan–gold nanoparticles composite cryogel on Prussian blue-coated multi-walled carbon nanotubes. *Food Chemistry*, *364*, 130396.
70. Li, F., Liu, R., Dubovyk, V., Ran, Q., Li, B., Chang, Y., ...&Komarneni, S. (2022). Three-dimensional hierarchical porous carbon coupled with chitosan based electrochemical sensor for sensitive determination of niclosamide. *Food Chemistry*, *366*, 130563.
71. Li, G., Zeng, J., Zhao, L., Wang, Z., Dong, C., Liang, J., ...& Huang, Y. (2019). Amperometric cholesterol biosensor based on reduction graphene oxide-chitosan-ferrocene/platinum nanoparticles modified screen-printed electrode. Journal of Nanoparticle Research, 21, 1-16.
72. Li, S., Noroozifar, M., & Kerman, K. (2019).Nanocomposite of ferricyanide-doped chitosan with multi-walled carbon nanotubes for simultaneous senary detection of redox-active biomolecules. *Journal of Electroanalytical Chemistry*, *849*, 113376.
73. Naghshgar, N., Hosseinzadeh, S., Derakhshandeh, A. *et al.* Introducing a portable electrochemical biosensor for *Mycobacterium avium* subsp. *paratuberculosis* detection using graphene oxide and chitosan. *Sci Rep* **14**, 34 (2024). https://doi.org/10.1038/s41598-023-50706-z
74. Yongzhi Chen, Zhengkai Liu, DoushengBai,Determination of imatinib as anticancer drug in serum and urine samples by electrochemical technique using a chitosan/graphene oxide modified electrode,Alexandria Engineering Journal,Volume 93,2024,Pages 80-89,ISSN 1110-0168,https://doi.org/10.1016/j.aej.2024.03.001.
75. Salvo-Comino, C.; Rassas, I.; Minot, S.; Bessueille, F.; Arab, M.; Chevallier, V.; Rodriguez-Mendez, M.L.; Errachid, A.; Jaffrezic-Renault, N. Voltammetric Sensor Based on Molecularly Imprinted Chitosan-Carbon Nanotubes Decorated with Gold Nanoparticles Nanocomposite

Deposited on Boron-Doped Diamond Electrodes for Catechol Detection. *Materials* **2020**, *13*, 688. https://doi.org/10.3390/ma13030688

76. Šišoláková,I.Hovancová J., Oriňaková R., Electrochemical determination of insulin at CuNPs/chitosan-MWCNTs and CoNPs/ chitosan-MWCNTs modified screen printed carbon electrodes, Journal of Electroanalytical Chemistry (2020), https://doi.org/10.1016/j.jelechem.2020.113881
77. Choi, Y. B., Kim, H. S., Jeon, W. Y., Lee, B. H., Shin, U. S., & Kim, H. H. (2019). The electrochemical glucose sensing based on the chitosan-carbon nanotube hybrid. *Biochemical Engineering Journal*, *144*, 227-234.
78. Elugoke, S. E., Fayemi, O. E., Adekunle, A. S., Ganesh, P. S., Kim, S. Y., &Ebenso, E. E. (2023). Sensitive and selective neurotransmitter epinephrine detection at a carbon quantum dots/copper oxide nanocomposite. *Journal of Electroanalytical Chemistry*, *929*, 117120.
79. Abazar, F., &Noorbakhsh, A. (2020). Chitosan-carbon quantum dots as a new platform for highly sensitive insulin impedimetric aptasensor. *Sensors and Actuators B: Chemical*, *304*, 127281
80. Eddin, Faten Bashar Kamal, *et al*. "Femtomolar detection of dopamine using surface plasmon resonance sensor based on chitosan/graphene quantum dots thin film." *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 263 (2021): 120202
81. Mirzaie, A., Hasanzadeh, M., &Jouyban, A. (2019). Cross-linked chitosan/thiolated graphene quantum dots as a biocompatible polysaccharide towards aptamer immobilization. *International journal of biological macromolecules*, *123*, 1091-1105
82. Santana, E. R., Martins, E. C., & Spinelli, A. (2021). Electrode modified with nitrogen-doped graphene quantum dots supported in chitosan for triclocarban monitoring. *Microchemical Journal*, *167*, 106297
83. Bartolomé, M., Soriano, M. L., Villaseñor, M. J., & Ríos, Á. (2023). γ-Cyclodextrin-graphene quantum dots-chitosan modified screen-printed electrode for sensing of fluoroquinolones. *Microchimica Acta*, *190*(2), 60.
84. Santos, A. M., Wong, A., Cincotto, F. H., Moraes, F. C., &Fatibello-Filho, O. (2019). Square-wave adsorptive anodic stripping voltammetric determination of norfloxacin using a glassy carbon electrode modified with carbon black and CdTe quantum dots in a chitosan film. *Microchimica Acta*, *186*, 1-10
85. Tashkhourian, J., Nami-Ana, S. F., &Shamsipur, M. (2018). Designing a modified electrode based on graphene quantum dot-chitosan application to electrochemical detection of epinephrine. *Journal of Molecular Liquids*, *266*, 548-556
86. Buddhadev Purohit, Ashutosh Kumar, Rohini Kumari, Kuldeep Mahato, Sharmilli Roy, Ananya Srivastava, Pranjal Chandra,3D gold dendrite and reduced graphene oxide-chitosan nanocomposite-based immunosensor for carcinoembryonic antigen detection in clinical settings,

Surfaces and Interfaces, Volume 47, 2024,104197, ISSN 24680230, https://doi.org/10.1016/j.surfin.2024.104197.

87. Zhang, J., Oueslati, R., Cheng, C., Zhao, L., Chen, J., Almeida, R., & Wu, J. (2018). Rapid, highly sensitive detection of Gram-negative bacteria with lipopolysaccharide based disposable aptasensor. *Biosensors and Bioelectronics*, *112*, 48-53
88. Baccarin, M., Santos, F. A., Vicentini, F. C., Zucolotto, V., Janegitz, B. C., &Fatibello-Filho, O. (2017). Electrochemical sensor based on reduced graphene oxide/carbon black/chitosan composite for the simultaneous determination of dopamine and paracetamol concentrations in urine samples. *Journal of Electroanalytical Chemistry*, *799*, 436-443"
89. Zou, J., Yuan, M. M., Huang, Z. N., Chen, X. Q., Jiang, X. Y., Jiao, F. P., ... & Yu, J. G. (2019). Highly-sensitive and selective determination of bisphenol A in milk samples based on self-assembled graphene nanoplatelets-multiwalled carbon nanotube-chitosan nanostructure. *Materials Science and Engineering: C*, *103*, 109848.
90. Kaur, N., Bharti, A., Batra, S., Rana, S., Rana, S., Bhalla, A., & Prabhakar, N. (2019). An electrochemical aptasensor based on graphene doped chitosan nanocomposites for determination of Ochratoxin A. *Microchemical Journal*, *144*, 102-109.
91. Nagles, E., Bello, M., & Hurtado, J. J. (2022). Electrochemical Determination of Morin in Natural Food Using a Chitosan–Graphene Glassy Carbon Modified Electrode. *Sensors*, *22*(20), 7780.
92. Mashuni, M., Ritonga, H., Jahiding, M., Rubak, B., & Hamid, F. H. (2022). Highly sensitive detection of carbaryl pesticides using potentiometric biosensor with nanocomposite Ag/r-graphene oxide/chitosan immobilized acetylcholinesterase enzyme. *Chemosensors*, *10*(4), 138.
93. Wei, P., Zhu, Z., Song, R., Li, Z., & Chen, C. (2019). An ion-imprinted sensor based on chitosan-graphene oxide composite polymer modified glassy carbon electrode for environmental sensing application. *Electrochimica Acta*, *317*, 93-101.
94. Fu, J., Yao, Y., An, X., Wang, G., Guo, Y., Sun, X., & Li, F. (2020). Voltammetric determination of organophosphorus pesticides using a hairpin aptamer immobilized in a graphene oxide-chitosan composite. *Microchimica Acta*, *187*, 1-8.
95. Fatma, S., Prasad, B. B., Jaiswal, S., Singh, R., & Singh, K. (2019). Electrochemical simultaneous analysis of dopamine and epinephrine using double imprinted One MoNomeracryloylated graphene oxide-carbon black composite polymer. *Biosensors and Bioelectronics*, *135*, 36-44.

96. Silva, T. A., Lourencao, B. C., da Silva, A. D., &Fatibello-Filho, O. (2023). An electrochemical sensing platform based on carbon black and chitosan-stabilized platinum nanoparticles. *Analytical Methods*, *15*(8), 1077-1086.
97. Veloso, W. B., Almeida, A. T. D. F. O., Ribeiro, L. K., de Assis, M., Longo, E., Garcia, M. A. S., ...& Dantas, L. M. F. (2022). Rapid and sensitivity determination of macrolides antibiotics using disposable electrochemical sensor based on Super P carbon black and chitosan composite. Microchemical Journal, 172, 106939.
98. Mahmoudi, Z., Tashkhourian, J., &Hemmateenejad, B. (2022). Voltammetric determination of lactic acid in milk samples using carbon paste electrode modified with chitosan-based magnetic molecularly imprinted polymer. *Journal of Applied Electrochemistry*, *52*(1), 35-44
99. Hassanpour, S., Saadati, A., & Hasanzadeh, M. (2020). Sensitive monitoring of riboflavin in commercial multivitamins using poly (chitosan)□based nanocomposite. *Journal of Molecular Recognition*, *33*(2), e2817.
100. Nagarajan, S., & Vairamuthu, R. (2021). Electrochemical detection of riboflavin using tin-chitosan modified pencil graphite electrode. *Journal of Electroanalytical Chemistry*, *891*, 115235.
101. Liu, R., Chang, Y., Li, F., Dubovyk, V., Li, D., Ran, Q., & Zhao, H. (2022). Highly sensitive detection of carbendazim inC based on mung bean-derived porous carbon@ chitosan composite modified electrochemical sensor. *Food Chemistry*, *392*, 133301.
102. Mahmoudi, Z., Tashkhourian, J., &Hemmateenejad, B. (2022). Voltammetric determination of lactic acid in milk samples using carbon paste electrode modified with chitosan-based magnetic molecularly imprinted polymer. *Journal of Applied Electrochemistry*, *52*(1), 35-44.
103. Ghanei-Motlagh, M., Taher, M. A., Fayazi, M., Baghayeri, M., &Hosseinifar, A. (2019). Non-enzymatic amperometric sensing of hydrogen peroxide based on vanadium pentoxide nanostructures. *Journal of The Electrochemical Society*, *166*(6), B367