SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

A Review of Functional Materials for Copper Ions Detection in Water

Muhammad Nil Yafiq Mohd Yusof[1], Affa Rozana Abdul Rashid[1,*], Wan Maisarah Mukhtar[1], Nur Athirah Mohd Taib[1]

[1] Faculty of Science and Technology, Universiti Sains Islam Malaysia, 71800 Nilai, Negeri Sembilan, Malaysia

ARTICLE INFO

Article history:
Received 13 March 2026
Received in revised form 30 May 2026
Accepted 2 June 2026
Available online 5 July 2026

Keywords:
Copper ions detection, Chitosan based, Carbon nanotubes based, Cellulose based, Salt based, Surface plasmonic resonance based

ABSTRACT

Copper ions (Cu^{2+}) are essential trace elements for living organisms; however, excessive concentrations in aquatic environments pose significant risks to human health and ecosystems. The increasing contamination of water resources by Cu^{2+} has created a strong demand for rapid, sensitive, and reliable detection technologies. This review comprehensively discusses recent advances in functional materials employed for Cu^{2+} detection in water, focusing on chitosan-based materials, carbon nanotubes (CNTs), cellulose-derived materials and salt-based sensing systems. The structural characteristics, sensing mechanisms, and performance of these materials are critically compared in terms of detection limits, sensitivity, adsorption capacity, and operational concentration ranges. Biopolymer-based materials such as chitosan and cellulose offer excellent biocompatibility and abundant functional groups for metal ion chelation, while CNTs provide superior electrical conductivity and large surface areas that enhance sensing efficiency. Salt-based chelators and optical sensing configurations further improve selectivity and detection sensitivity to the nanomolar level. Chemical modifications and composite formations are shown to significantly enhance material stability and sensing performance. Overall, this review highlights the potential of advanced functional materials for effective Cu^{2+} monitoring and provides insights into future developments for sustainable water quality assessment and environmental protection.

1. Introduction

Copper (Cu) is an essential trace element that plays a vital role in both environmental and biological systems. It is naturally present in freshwater ecosystems and is also commonly found in various foods and dietary supplements. In living organisms, copper is required in trace amounts for several physiological processes, including enzyme synthesis, tissue formation, iron metabolism, and bone development. Despite its biological importance, copper becomes toxic when present in excessive concentrations, particularly in aquatic environments. From an environmental perspective, copper is widely distributed in nature as a transition metal and is frequently classified among the priority heavy metals due to its potential ecological and health impacts. Among its oxidation states,

* *Corresponding author.*
E-mail address: affarozana@usim.edu.my

https://doi.org/10.37934/araset.61.5.110

Cu(II) ions (Cu^{2+}) are the most stable and commonly encountered form in aqueous systems, and they are considered the most biologically reactive and toxic species at elevated concentrations. Liu et al. [1] reported that copper exists in multiple forms, including elemental copper (Cu^{o}), cuprous ions (Cu^{+}), and cupric ions (Cu^{2+}), with Cu^{2+} being the dominant species in environmental contamination.

Excessive exposure to Cu^{2+} can lead to serious health and environmental consequences. In humans, copper deficiency may result in anemia and connective tissue disorders, whereas overexposure can cause gastrointestinal disturbances, liver enzyme dysfunction, and neurological impairments. For aquatic organisms, elevated Cu^{2+} concentrations can disrupt metabolic processes and affect overall ecosystem stability. According to the World Health Organization (WHO), the maximum permissible limit of copper in drinking water is 2.0 mg/L [3–4], highlighting the need for effective monitoring of copper contamination in water sources. The speciation and behavior of Cu^{2+} in aqueous environments are strongly influenced by pH and ligand interactions. Fathy et al. [5] reported that copper ions may exist as free hydrated ions, soluble salts, or complexes with organic and inorganic ligands. At lower pH values (below pH 6), Cu^{2+} remains soluble and more bioavailable; however, at higher pH levels, the formation of copper hydroxide species such as $Cu(OH)^{+}$ and $Cu(OH)_2$ may occur, leading to precipitation and reduced solubility. Shuhaimen et al. [6] further demonstrated that optimal adsorption of Cu^{2+} occurs in mildly acidic conditions (pH 4–5), where surface interactions between Cu^{2+} and adsorbent functional groups are enhanced.

In response to the increasing concern over copper contamination, various functional materials have been developed for the detection and removal of Cu^{2+} ions in aqueous systems. These include chitosan-based materials, carbon nanotubes, cellulose derivatives, metal oxides, salt-based materials, and surface plasmon resonance–based sensing platforms. These materials have been widely explored due to their high sensitivity, selectivity, and potential for low detection limits (LOD) in water quality monitoring applications. However, despite significant progress in material development, a comprehensive understanding of their comparative performance, sensing mechanisms, and practical limitations remains limited. Therefore, this review aims to systematically discuss and compare recent advances in functional materials for Cu^{2+} detection in water, with emphasis on sensing mechanisms, analytical performance, and future development prospects for environmental monitoring applications.

2. Materials of Cu^{2+} Detection

2.1 Chitosan Based Material

Chitosan (CS) has emerged as a premier biopolymer for environmental remediation and heavy metal detection, particularly for the monitoring of copper ions Cu^{2+} in aquatic environments [7]. Synthesized via the chemical deacetylation of naturally occurring chitin, CS possesses a highly desirable suite of intrinsic properties, including non-toxicity, inherent antibacterial activity, economic viability, biocompatibility, and biodegradability, which collectively underpin its widespread adoption as an adsorbent in wastewater treatment [7, 8]. Structurally, CS is a polysaccharide characterized by an abundance of reactive primary amino ($-NH_2$) and hydroxyl (-OH) groups along its macromolecular backbone [7]. Despite these advantages, raw CS suffers from poor structural stability and a high propensity for dissolution in acidic media, which significantly restricts its practical utility [8]. To mitigate this limitation, Yang et al. [9] successfully cross-linked CS using glyoxal to reinforce its polymeric framework. The resulting modified matrix demonstrated remarkable stability in acidic solutions without undergoing significant structural degradation, an upgrade directly attributed to the formation of robust C-N covalent linkages that secure the polymer chain networks.

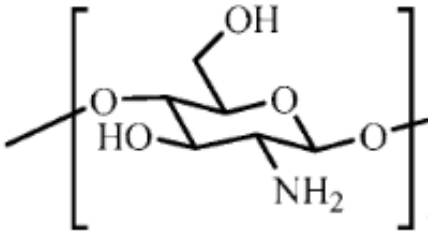


Fig. 1. The Structure of CS [9]

The high adsorption capacity of CS toward transition metal ions is fundamentally governed by the localized chemical reactivity of its backbone functional groups [10]. As elucidated by Osman et al. [10], the chelation mechanism proceeds via the displacement of hydrogen ions, allowing the lone electron pairs residing on the nitrogen atoms of the successive amine linkages to form strong coordinate covalent bonds with incoming metal ions. This dense arrangement of nitrogen-bearing active sites promotes the formation of stable, high-affinity chelation complexes. However, the net chelation efficiency remains a dynamic process that is heavily dependent on critical operational parameters, such as solution pH, contact time, initial metal concentration, and the thermodynamic tendency of the polymer to bind specific target ions [10].

To leverage these native coordination chemistry properties for real-time monitoring, CS has been successfully deployed as an active interfacial coating material in Surface Plasmon Resonance (SPR) fiber optic sensors optimized for Cu^{2+} detection [11]. Depositing a functional CS thin film onto the optical waveguide concurrently enhances chemical sensitivity and improves the structural boundaries of the sensor interface. To prevent acidic degradation while maximizing its binding kinetics, the pristine CS matrix is typically modified via chemical cross-linking with glutaraldehyde. When target Cu^{2+} ions undergo chelation within this cross-linked layer, the resulting complexation triggers a distinct variation in the local refractive index at the fiber core-cladding boundary, thereby inducing a prominent wavelength shift within the sensor's interference spectra [11]. This engineered sensor configuration achieved a commendable sensitivity profile of 24.6 pm/10 ppm across a wide working concentration range of 0 to 330 ppm [11].

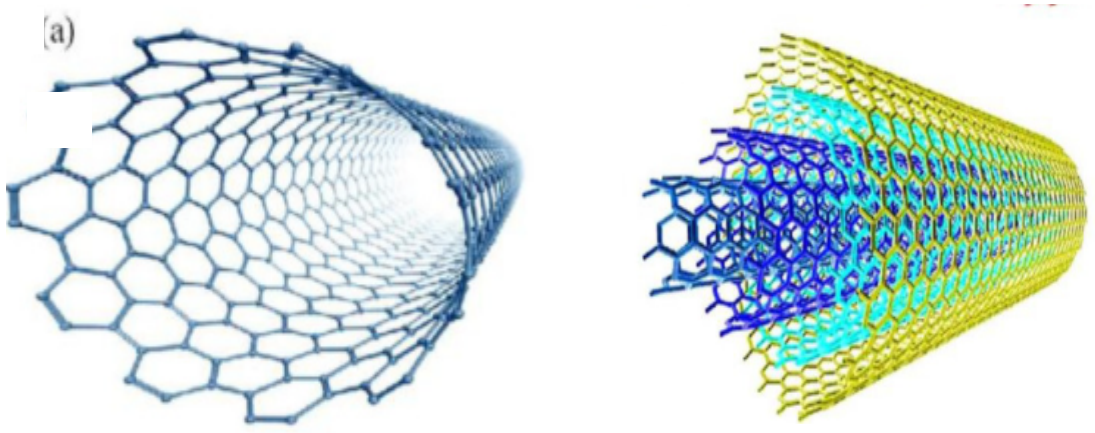
Further breakthroughs in trace-level detection limits have been achieved by blending CS with conducting polymers to synthesize synergistic organic composites. Li et al. [12] demonstrated that pairing CS with polypyrrole (PPy) yields an advanced composite matrix with exceptional adsorption kinetics toward dilute Cu^{2+} concentrations. The integration of PPy successfully addresses the classic mechanical limitations and brittleness of pure polysaccharide films, drastically improving both the mechanical integrity and thin-film uniformity of the cast sensor layer. Fabricated via a highly reproducible and straightforward chemical oxidation technique, this CS/PPy composite layer significantly maximizes the optical interaction cross-section. Consequently, this composite architecture delivered a remarkable sensitivity of 9.12 nm/ppm within an ultra-trace concentration regime of 0.1 to 0.5 ppm, while sustaining a robust resolution of 2.14 nm/ppm as the concentration scaled from 0.5 to 2 ppm [12].

Alternative chemical pathways focus on the hydrophobic modification of the primary amine active sites via condensation reactions to form aromatic Schiff base networks. According to Matias et al. [13], CS can undergo a structural modification by reacting with salicylaldehyde, wherein the primary amine groups on the polymer backbone condense with the aldehyde functionalities of the

reagent to anchor an aromatic ring system. This structural reconfiguration introduces supplementary phenolic hydroxyl pathways that actively participate in multi-dentate metal coordination, thereby reinforcing the complexation stability [13]. Although the newly formed imine (-C=N-) bonds are naturally prone to aqueous hydrolysis, a subsequent controlled chemical reduction step effectively stabilizes the modified polymer matrix against watery degradation. This reduction phase prevents film breakdown while ensuring the restored amine pathways remain fully accessible for targeted ion coordination. Ultimately, this structurally reduced CS framework demonstrated a substantial Cu^{2+} adsorption density of 2.5 mg/mL, alongside an exceptionally high competitive selectivity for copper ions when evaluated against co-existing heavy metal interferences in complex aquatic matrices [13].

2.2 Carbon Nanotube Based Material

Carbon nanotubes (CNTs) have established themselves as an exceptionally reliable material for identifying and trapping heavy metal ions like copper (Cu^{2+}) due to their unique physical and chemical traits. Structurally, CNTs are one-dimensional, cylindrical nanomaterials featuring diameters on the nanometer scale and lengths extending into micrometers. Essentially, a CNT can be envisioned as a flat sheet of graphene rolled into a seamless cylinder, which is generally categorized into two primary types: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) [14]. SWCNTs consist of a single layer of graphene rolled up where the hexagon rings in the lattice sheet overlap typically yielding a diameter of less than 2 nm. In contrast, MWCNTs feature larger diameters ranging from 2 to 200 nm, depending entirely on the number of nested, concentric nanotubes that make up the structure. To describe how MWCNTs are physically configured, researchers generally point to two structural variations: the Russian Doll model and the alternative Parchment model [14]. In the Russian Doll framework, the MWCNT is constructed from separate, individual graphene cylinders neatly nested one inside the other. On the other hand, the Parchment model describes a single, continuous sheet of graphene rolled tightly around itself, closely mimicking a scroll. The distinct geometries of both SWCNTs and MWCNTs serve as the physical foundation for their broad sensing capabilities (as illustrated in Fig. 2).



(a) (b)

Fig. 2. The Structure of (a) SWCNT and (b) MWCNT [14]

Beyond heavy metal tracking, CNTs have earned a reputation as highly versatile, multitasking materials capable of capturing an impressive variety of organic and chemical pollutants from aquatic systems [15]. Studies have proven their efficacy in trapping trace levels of agricultural and industrial contaminants—such as dichlorodiphenyl-trichloroethane, nicosulfuron, thifensulfuron-methyl, and metsulfuron-methyl—alongside polyhalogenated organics, polycyclic aromatic hydrocarbons, and various pharmaceuticals in contaminated water samples [15]. When engineered specifically for Cu^{2+} detection, CNTs can be successfully prepared in sheet form via Chemical Vapor Deposition (CVD) [15]. To optimize their binding affinity, these sheets undergo an acid activation treatment using concentrated nitric acid combined with a chitosan functionalization layer. This dual-action acid/chitosan modification drastically improves adsorption performance, achieving a Cu^{2+} binding capacity of 18.2670 mg/g at a starting concentration of 200 mg/L, which scales up to a remarkable 57.3412 mg/g when exposed to a higher initial concentration of 800 mg/L [15].

Alternatively, researchers have turned to graphitised multi-walled carbon nanotubes (GMWCNTs) to push the performance limits of electrochemical Cu^{2+} sensors even further. According to Zhang et al. [16], GMWCNTs serve as an ideal surface modifier for sensor electrodes because they offer a drastically enlarged specific surface area, superior electrical conductivity, and excellent long-term chemical stability. In a practical sensing application, GMWCNTs were blended with copper (II) ion carrier IV and deposited onto a glassy carbon electrode (GCE) using a straightforward drop-coating technique. This modification created a highly responsive, ultra-rapid platform specifically optimized for mapping trace Cu^{2+} levels in complex seawater environments. By utilizing this GMWCNT/ Cu^{2+} carrier IV/GCE testing architecture, the sensor successfully registered an exceptionally low detection limit of 0.74 µg/L within a linear working concentration range of 50 to 500 µg/L [16].

2.3 Cellulose Based Material

In the search for sustainable and highly efficient sensing platforms, cellulose nanomaterials (CNMs) have attracted significant interest as green alternatives for monitoring heavy metals like copper ions Cu^{2+}. CNMs are isolated through the structural deconstruction of native crystalline cellulose, a biopolymer widely utilized for aqueous filtration and environmental remediation. Consequently, these resulting nanomaterials exhibit an exceptionally high specific surface area [17]. This nanoscale morphology exposes a dense spatial distribution of reactive, amphiphilic hydroxyl (-OH) functionalities across the matrix interface. This abundance of solvent-accessible coordination sites significantly amplifies interfacial binding kinetics and mass transport, directly enhancing the transducer's analytical sensitivity. Consequently, CNMs have been successfully integrated as functional structural matrices within plasmonic copper nano-antenna (CNA) sensing configurations. Exploiting the intrinsic mechanical stability and low thermal expansion coefficient of the crystalline cellulose network, these CNA-based sensors effectively mitigate baseline drift to deliver rapid, reproducible, and highly stable optoelectronic responses, enabling the high-fidelity quantification of trace divalent copper Cu^{2+} ions down to a lower detection limit $2.5x10^{-7}$ [17].

To tailor its chemical performance further, the cellulose backbone can be chemically modified with specific functional groups. Introducing carboxymethyl groups, for example, adds an abundance of oxygen-rich carboxyl and hydroxyl active sites, yielding carboxymethyl cellulose (CMC) [18]. As shown in Fig. 3, CMC is a highly versatile, water-soluble natural polymer typically processed as a sodium salt. It is favored in sensor design because it is non-toxic, biocompatible, biodegradable, and exceptionally easy to chemically modify. Because of these traits, CMC serves as an ideal structural carrier for developing advanced fluorescent materials. By blending the CMC matrix with reactive

compounds like glycidyl ether (GE) and 8-aminoquinoline (AQ), researchers have synthesized a novel fluorescent sensing film that exhibits excellent coordinating affinity for heavy metals. When exposed to contaminated water, this CMC-based material can successfully detect Cu^{2+} concentrations as low as $6.4x10^{-8}$ mol/l [18].

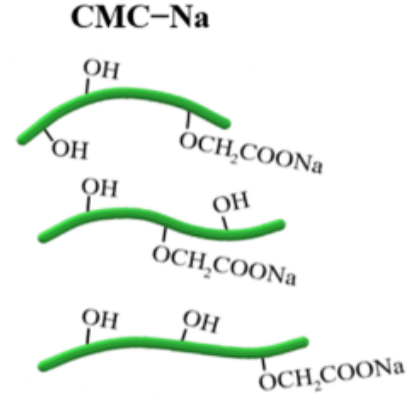


Fig. 3. The Structure of CMC [18]

Beyond basic modifications, cellulose is also widely used to build three-dimensional porous networks for heavy metal capture. Accounting for more than 50% of the carbon content in plants, cellulose is the most abundant natural polysaccharide on Earth, making it a prime candidate for engineering biodegradable, eco-friendly hydrogels [19]. While basic cellulose-based hydrogels show a modest baseline adsorption capacity of 28.4 mg/g for Cu^{2+}, advanced structural formats offer vastly superior performance. Fu et al. [19] demonstrated this by utilizing cellulose nanocrystals (CNCs) to synthesize a high-performance green-fluorescent carbon dot-integrated aerogel (GCDiA). By simply cross-linking carbon dots (C-dots) within the CNC matrix using epichlorohydrin (ECH) as a bridging agent, they created a highly porous, functionalized network. This aerogel architecture drastically enhances ion capture, achieving a remarkable maximum Cu^{2+} adsorption capacity of 149.62 mg/g when treated with an initial concentration of 1000 mg/l [19]. Another highly effective variant used in optical and electrochemical sensing is bacterial cellulose (BC). Unlike plant-derived options, bacterial cellulose possesses an exceptionally high degree of crystallinity, which provides excellent mechanical tensile strength and a highly stable, interconnected 3D nanofibrous network [20]. Because it is highly sustainable, hydrophilic, affordable, and biocompatible, BC is an outstanding eco-friendly substitute for non-degradable synthetic polymers. The material features a dense concentration of surface hydroxyl groups that readily form robust, tight hydrogen bonds with C-dots. This strong interaction ensures that the immobilisation is stable and under control, preventing them from leaching out when submerged in aquatic environments. Consequently, this stable matrix offers user-friendly handling and highly reliable performance, successfully mapping trace Cu^{2+} contamination down to an ultra-sensitive detection limit of 7.758 nM [20].

2.4 Salt Based Material

Salt-based chemical derivatives and organic salts represent another highly effective class of materials for monitoring copper Cu^{2+} ions. Among these, bathocuproinedisulfonic acid disodium salt (BCS) is widely used as a targeted copper chelator, frequently working in tandem with noble metal nanostructures like silver nanoparticles (AgNPs) [21]. Wang et al. [21] demonstrated that combining

BCS with AgNPs yields a highly responsive colorimetric platform, significantly intensifying the visible color transition and lowering the overall detection limit for single-use paper test strips. This performance boost is driven by the sulfonic acid groups present in the BCS structure, which readily bind to the surface of the AgNPs to establish excellent colloidal stability and rapid reaction times. Operating at an optimal 1:2 binding ratio between BCS and AgNPs, this nanoparticle-based colorimetric essay achieved a reliable Cu^{2+} detection limit of 0.06 mg/l [21].

Beyond simple colorimetric test strips, the analytical performance of BCS has also been extensively explored via fluorescence spectroscopy [22]. Fluorescence methods offer superior sensitivity, making them highly suited for mapping trace metal contamination at ultra-low concentrations. However, measuring these optical signals can become complicated in the infrared region due to background interference and scattering. To avoid these measurement difficulties, researchers typically capture the fluorescence emission within the visible blue region of the spectrum. When exposed to contaminated water samples, the baseline fluorescence of the BCS molecule undergoes a distinct quenching process upon binding with Cu^{2+}. This fluorescent attenuation approach allows for highly precise tracking, reaching an ultra-trace detection sensitivity on the order of 10^{-8} mol/l [22].

In parallel with molecular probes, optical fiber interferometers particularly Fabry-Perot sensors have gained prominence as exceptionally precise instruments for detecting heavy metal ions. To make these sensors responsive to chemical changes, their optical cavities are often functionalized with hybrid composite materials. A notable example is the pairing of sodium alginate (SA), a natural salt-based polymer, with graphene oxide (GO) to synthesize a hybrid SA/GO hydrogel matrix [23]. When coated onto a Fabry-Perot sensor tip, this cross-linked hydrogel serves as a functional, porous target layer. As Cu^{2+} ions diffuse into the hydrogel network, they trigger a localized volume or refractive index shift within the cavity, altering the light's optical path length and shifting the interference signal. In experimental trials, this SA/GO hydrogel-coated Fabry-Perot sensing platform demonstrated an outstanding sensitivity within a narrow, trace-level working concentration range of 0 to 1.4 mg/l [23]. To provide a clear, high-level overview of the performance benchmarks across all the distinct material technologies discussed so far, Table 1 compiles a comparative summary of their target mechanisms, linear ranges, and specific detection limits for Cu^{2+} ions.

Table 1
The Comparison of Cu^{2+} Ions Detection Materials

Material	Composition / Modification	Detection or Adsorption Capacity	Concentration Range	Method / Application	Advantages / Key Properties	Ref.
Chitosan	Pure chitosan (from chitin)	75.40 mg/g	100 mg/l	Adsorption	Biopolymer; reactive amino & hydroxyl groups; good for wastewater treatment	[9]
Chitosan (film form)	Unmodified	0.3339 mg/L (≈33% of initial Cu^{2+})	1 mg/l	Adsorption film test	High nitrogen content; forms chelates; affected by pH, contact time	[10]
Chitosan (with glyoxal)	Chitosan + glyoxal crosslinking	75.40 mg/g	100 mg/l	Enhanced stability in acid	Increased acid stability via C–N covalent bond	[9]
Chitosan (with glutaraldehyde)	Chitosan + glutaraldehyde (fiber sensor coating)	Sensitivity: 24.6 pm/10 ppm	0–320 ppm	Surface Plasmon Resonance	Enhanced structure strength; higher refractive index sensitivity	[11]

				fiber sensor		
Chitosan–Polypyrrole Composite	Chitosan + conductive polymer (polypyrrole)	9.12 nm/ppm (0.1–0.5 ppm); 2.14 nm/ppm (0.5–2 ppm)	0.1–2 ppm	Conductive polymer composite	Better mechanical strength; uniform film; simple synthesis	[12]
Reduced Chitosan	Chitosan + salicylaldehyde	2.5 mg/mL	–	Adsorption (chelation)	Enhanced complexation; selective for Cu^{2+} over Ni^{2+}, Cd^{2+}, Pb^{2+}	[13]
CNTs (SWCNTs & MWCNTs)	Acid-treated, chitosan-functionalized	18.2670 mg/g (200 mg/L); 57.3412 mg/g (800 mg/L)	200–800 mg/l	Adsorption / Detection sheets	High surface area; electrical conductivity; multifunctional	[15]
Graphitized MWCNTs (GMWCNTs)	Combined with Cu(II) ion carrier IV & CGE electrode	0.74 µg/L	50–500 µg/l	Electrochemical (drop-coating)	High conductivity; chemically stable; high surface area	[16]
Cellulose Nanomaterials (CNMs)	Cellulose-based, with copper nano-antenna (CNA)	2.5×10^{-7} M	–	CNA sensor	High hydroxyl group content; rapid & stable response	[4]
Carboxymethyl Cellulose (CMC)	CMC + glycidyl ether (GE) + 8-aminoquinoline (AQ)	6.4×10^{-8} mol/L	–	Fluorescent detection	Biocompatible, biodegradable, water-soluble polymer	[18]
Cellulose Hydrogel (CNC–GCDiA)	CNC + carbon dots crosslinked with ECH	149.62 mg/g	1000 mg/L	Adsorption hydrogel	High adsorption capacity; biodegradable	[19]
Bacterial Cellulose (BC)	BC + carbon dots	7.758 nM	–	Fluorescent sensing	High mechanical strength; 3D network; biodegradable	[20]
BCS + AgNPs	Bathocuproinedisulfonic acid disodium salt + silver nanoparticles	0.06 mg/L	–	Colorimetric (paper strip)	Strong chelating agent; color change detection; stable nanoparticles	[21]
BCS (fluorescent)	Same as above, using fluorescence	~10^{-8} mol/L	–	Fluorescence quenching	Sensitive in visible blue region; not suitable in IR	[22]

4. Conclusions

The development of efficient and reliable technologies for Cu^{2+} detection remains essential for environmental monitoring, water quality management, and public health protection. This review has comprehensively summarized recent advances in functional materials employed for Cu^{2+} sensing, including chitosan-based materials, carbon nanotubes (CNTs), cellulose-derived materials, salt-based systems, and optical sensing platforms. Each material class exhibits distinct advantages in terms of sensitivity, selectivity, biocompatibility, adsorption capacity, and structural stability, demonstrating their potential for practical water monitoring applications. The findings reveal that material modification and composite engineering play crucial roles in enhancing sensing performance. Chemical cross-linking, surface functionalization, and the incorporation of conductive or

nanostructured components significantly improve mechanical stability, active binding sites, and signal transduction efficiency. Furthermore, the integration of these functional materials with optical fiber sensors, surface plasmon resonance (SPR) devices, and fluorescence-based systems has enabled the detection of Cu^{2+} at remarkably low concentrations, reaching nanomolar and even sub-micromolar levels. Such advancements highlight the synergistic relationship between material science and sensing technology in developing high-performance environmental monitoring systems.

Despite these achievements, several challenges remain, including long-term material stability, selectivity in complex water matrices, large-scale fabrication, and the transition from laboratory demonstrations to portable, real-time sensing devices. Future research should therefore focus on the development of sustainable, low-cost, and multifunctional sensing materials with enhanced durability and regeneration capabilities. In addition, emerging technologies such as smart sensors, Internet of Things (IoT)-enabled monitoring systems, and machine learning-assisted data analysis may further improve the efficiency and applicability of Cu^{2+} detection platforms. Overall, continued innovation in functional materials and sensor integration will contribute significantly to the realization of robust, environmentally friendly, and highly sensitive water quality monitoring technologies for sustainable environmental management.

Acknowledgement
The authors would like to thank Universiti Sains Islam Malaysia (USIM) for the resources and through grant scheme PPPI/USIM/FST/USIM/110823 provided.

References

[1] Liu, Yongming, Haishuang Wang, Yuanyuan Cui, and Nan Chen. 2023. "Removal of Copper Ions from Wastewater: A Review." *International Journal of Environmental Research and Public Health* 20 (5). https://doi.org/10.3390/ijerph20053885.

[2] Kamaruzaman, Sazlinda, Najihah Nasir, Yugarani Arivalagan, Noorfatimah Yahaya, Saw Loh, Nor Suhaila, Mohamad Hanapi, Wan Nazihah, Wan Ibrahim, and Ili Syazana. 2023. "A Comprehensive Review of Graphene Nanoplatelets for Removal and Detection of Heavy Metals and Endocrine Disrupting Compounds." *Malaysian Journal of Analytical Sciences* 27: 1389–1425. https://mjas.analis.com.my/mjas/v27_n6/pdf/Kamaruzaman_27_6_17.pdf.

[3] Jagadeeswara Reddy, B., Sneha Latha Pala, Wondwosen Kebede Biftu, M. Suneetha, and Kunta Ravindhranath. 2021. "Effective Removal of Cu2+ Ions from Polluted Water Using New Bio-Adsorbents." *Water Practice and Technology* 16 (2): 566–81. https://doi.org/10.2166/wpt.2021.019.

[4] Alharbi, Walaa, Fadiah G. Alharbi, Khadijah H. Alharbi, M.A. El-Morsy, M.O. Farea, and A.A. Menazea. 2024. "Modification and Development in the Microstructure of Carboxy Methyl Cellulose-TiO2/Cr2O3 Nanocomposites Films for Optoelectrical Applications." *Inorganic Chemistry Communications* 159 (January): 111700. https://doi.org/10.1016/j.inoche.2023.111700.

[5] Fathy, Aya T., Mohamed A. Moneim, Ezzat A. Ahmed, Abdalla M. El-Ayaat, and Fatma M. Dardir. 2025. "Effective Removal of Heavy Metal Ions (Pb, Cu, and Cd) from Contaminated Water by Limestone Mine Wastes." *Scientific Reports* 15 (1). https://doi.org/10.1038/s41598-024-82861-2.

[6] Shuhaimen, Muhammad Shahrain, Erna Normaya Abdulah, Rosliza Mohd Salim, Mohd Armi Abu Samah, Muhammad Nor Omar, and Mohammad Norazmi Ahmad. 2019. "Adsorption Study on the Removal of Copper Ions from Aqueous Solution Using Sodium Hydroxide-Modified Carica Papaya Peels." *Malaysian Journal of Analytical Sciences* 23, no. 6: 926–37. https://doi.org/https://doi.org/10.17576/mjas-2019-2306-02.

[7] Miron, Andreea, Tanta-Verona Iordache, Artur J. M. Valente, Luisa Maria Rocha Durães, Andrei Sarbu, Georgeta Ramona Ivan, Anamaria Zaharia, Teodor Sandu, Horia Iovu, and Anita-Laura Chiriac. 2024. "Chitosan-Based Beads Incorporating Inorganic–Organic Composites for Copper Ion Retention in Aqueous Solutions." *International Journal of Molecular Sciences* 25 (4): 2411. https://doi.org/10.3390/ijms25042411.

[8] AL-Lami, Nagham Jawad Kadam, and Salah Shaker Hashim. 2024. "Design and Characterize Ion-Imprinted Smart Polymers from Carboxymethyl Chitosan for Selective Removal of Cadmium (II) Ions." *Discover Chemistry* 1 (1). https://doi.org/10.1007/s44371-024-00047-1.

[9] Yang, Chai, Zeng, Gao, Zhang, and Ji. 2019. "Efficient Removal of Copper Ion from Wastewater Using a Stable Chitosan Gel Material." *Molecules* 24 (23): 4205. https://doi.org/10.3390/molecules24234205.

[10] Osman, Nurul Huda, Adilah Idris, Abu Bakar, Mohammad Abdull, and Josephine Ying. 2019. "Detection of Copper (II) Ion on Chitosan Film Using Microstrip Ring Resonator - Universiti Putra Malaysia Institutional Repository." Upm.edu.my. http://psasir.upm.edu.my/id/eprint/81109/1/COPPER.pdf.

[11] Chen, Qiaoling, Wenlong Yang, Changxu Li, Chenshuai Guan, Min Wang, Jianming Lai, Xiaoyang Yu, et al. 2021. "High Sensitivity In-Situ Copper (Ⅱ) Detection of Chitosan Based on the Knotted-Shaped Fiber." *IEEE Sensors Journal* 21 (21): 24114–20. https://doi.org/10.1109/jsen.2021.3111960.

[12] Li, Yaowei, Ting Liu, Kaixin Ge, Wenbo Gan, Shixun Dai, Tiefeng Xu, and Peiqing Zhang. 2023. "Detection of Copper Ions in an Aqueous Solution by a Dual-Peak Long Period Fiber Grating Functionalized with a Polypyrrole–Chitosan Composite." *Optics Express* 31 (4): 6590. https://doi.org/10.1364/oe.482236.

[13] Matias, P. M. C., Sousa, J. F. M., Bernardino, E. F., Vareda, J. P., Durães, L., Abreu, P. E., Marques, J. M. C., Murtinho, D., & Valente, A. J. M. 2023. "Reduced Chitosan as a Strategy for Removing Copper Ions from Water." *Molecules* 28 (10): 4110–10. https://doi.org/10.3390/molecules28104110.

[14] Ferrier, David C., and Kevin C. Honeychurch. 2021. "Carbon Nanotube (CNT)-Based Biosensors." *Biosensors* 11 (12): 486. https://doi.org/10.3390/bios11120486.

[15] Tofighy, Maryam Ahmadzadeh, and Toraj Mohammadi. 2015. "Copper Ions Removal from Aqueous Solutions Using Acid-Chitosan Functionalized Carbon Nanotubes Sheets." *Desalination and Water Treatment* 57 (33): 15384–96. https://doi.org/10.1080/19443994.2015.1072738.

[16] Zhang, Chao, Wei Tao, Chengjun Qiu, Wei Qu, Yuan Zhuang, Yang Gu, Huili Hao, and Zizi Zhao. 2024. "Detection of Copper Ions in Seawater Using a Graphitised Multi-Walled Carbon Nanotubes-Copper Ion Carrier Modified Electrode." *Water* 16 (15): 2128–28. https://doi.org/10.3390/w16152128.

[17] Alharbi, Arwa, Abdullah A.A. Sari, Ali H. Alessa, Razan M. Snari, Hatun H. Alsharief, Ibrahim S.S. Alatawi, E.F.M. El-Zaidia, and Nashwa M. El-Metwaly. 2024. "High-Sensitivity Detection of Copper Ions in Water via Cellulose Nanomaterial Nano-Antennas and DFT Studies." *Chemical Engineering Journal Advances* 20 (November): 100675. https://doi.org/10.1016/j.ceja.2024.100675.

[18] Zhao, Fei, Zhiyuan Meng, Zhonglong Wang, and Yiqin Yang. 2022. "A New Cellulose-Based Fluorescent Probe for Specific and Sensitive Detection of Cu2+ and Its Applications in the Analysis of Environmental Water." *Polymers* 14 (11): 2146. https://doi.org/10.3390/polym14112146.

[19] Fu, Guanyan, Chenzhan Peng, Jiangrong Yu, Jiafeng Cao, Shilin Peng, Tian Zhao, and Dong Xu. 2025. "Carbon Dot Integrated Cellulose-Based Green-Fluorescent Aerogel for Detection and Removal of Copper Ions in Water." *Gels* 11 (8): 655. https://doi.org/10.3390/gels11080655.

[20] Zhang, Hongyuan, Qian Zhang, Xiaona Ji, Bing Han, Jieqiong Wang, and Ce Han. 2025. "Portable Bacterial Cellulose-Based Fluorescent Sensor for Rapid and Sensitive Detection of Copper in Food and Environmental Samples." *Molecules* 30 (17): 3633. https://doi.org/10.3390/molecules30173633.

[21] Wang, Yali, Tian Ma, Joseph Brake, Zhong-Xi Sun, Jiayu Huang, Jing Song Li, and Xiaobin Wu. 2023. "A Novel Method of Rapid Detection for Heavy Metal Copper Ion via a Specific Copper Chelator Bathocuproinedisulfonic Acid Disodium Salt." *Scientific Reports* 13 (1). https://doi.org/10.1038/s41598-023-37838-y.

[22] Koga, Toshiaki, Kazuhiro Nonaka, Yoshitaro Sakata, and Nao Terasaki. 2018. "Spectroscopic and Electrochemical Analysis of Cu(I) in Electroplating Solution and Evaluation of Plated Films." *Journal of the Electrochemical Society* 165 (10): D467–71. https://doi.org/10.1149/2.0811810jes.

[23] Wang, Ning, Shiqi Liu, Liang Xu, Longjiao Wang, Ming He, Chuanjie Lei, and Linyufan Xiao. 2025. "Fiber Fabry–Perot Sensor Based on Ion-Imprinted Sodium Alginate/Graphene Oxide Hydrogel for Copper Ion Detection Using Vernier Effect." *Sensors* 25 (3): 920. https://doi.org/10.3390/s25030920.