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Review Article

Nanosystems for Heavy Metal detection and Remediation in wastewater: A review

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Abstract

The challenge of heavy metal contamination presents one of the most pressing environmental issues of the 21st century. This issue is aggravated by the persistent presence of toxic heavy metals such as lead, mercury, cadmium, arsenic, and chromium in water ecosystems, which in turn poses risks to human health and global biodiversity. One of the promising ways of dealing with this challenge comes with nanosensors that allow for quick detection of these minute contaminants. This review summarizes nanosensor fabrication and detection mechanisms. It focuses on bio-hybrid nanosensor designs, green synthesis with the application of plant extracts and microorganisms, as well as molecularly imprinted polymers (MIPs). Moreover, it explores the combination of nanosensors with biological remediation (nanobioremediation) and discusses solutions to the problem of simulating the process of detection and removal of heavy metals in real time. The review is based on publications that tackle important challenges of the field, as well as eco-toxicological issues and perspectives in the area of development of intelligent self-powered and sustainable water quality management systems.

Keywords: nanosensor; toxic heavy metals; nanobio-remediation; eco-toxicological issues; green synthesis.

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1. Introduction

1.1. The Heavy Metal Crisis

Industrial activities, including mining, electroplating, battery manufacturing, and chemical processing, release large quantities of wastewater laden with heavy metals into the environment. According to the World Health Organization (WHO), even trace concentrations of heavy metals can cause: Neurological disorders (lead, mercury); Carcinogenic effects (arsenic, cadmium, hexavalent chromium); Kidney and liver damage (cadmium, mercury); Developmental malformations (lead).

The maximum permissible limits set by the WHO and the U.S. Environmental Protection Agency (EPA) are extremely low (parts per billion to parts per million), necessitating the use of highly sensitive detection methods (1).

Traditional detection methods (such as atomic absorption spectroscopy and inductively coupled plasma mass spectrometry) are accurate but require expensive equipment, specialized technicians, and lengthy sample preparation. Nanosensors offer the following advantages, as illustrated in Table 1 (2):

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Table 1- *Nanosensors advantages*

Advantage	Description
Ultra-high sensitivity	Detection at femtomolar to picomolar levels
Rapid response	Real-time monitoring capability
Portability	Potential for on-site and field deployment
Cost-effectiveness	Reduced reagent consumption
Selectivity	Target-specific recognition

2. Fabrication of Nanosensors

2.1. Nanomaterial Fabrication Methods

A. Chemical Reduction

The most common method for fabricating metallic nanoparticles is given by the equation:

$$Au^{3+} + reducing\ agent \rightarrow gold\ nanoparticles + oxidizing\ product$$

For example, the reduction of gold chloride with citrate (Turkevich's method) produces single-dispersion gold nanoparticles (10–50 nm) (3).

B. Hydrothermal/Solution Thermosynthesis

Used to fabricate nanoparticles of metal oxides (ZnO, TiO_2, Fe_3O_4): Temperature: 100–300 °C; Self-pressing; Highly crystalline products.

C. Chemical Vapor Deposition (CVD)

Essential for carbon nanotubes and graphene: primary gases decompose on catalyst surfaces; enables controlled growth of one- and two-dimensional nanostructures

D. Sol-Gel Method

For metal oxides and hybrid materials: hydrolysis and condensation of metal alkoxides; produces high-purity homogeneous materials.

2.2. Functional Surface Modification

Surface modification is critical for selectivity, as shown in Table 2.

3. Detection Mechanisms Using Nanosensors

3.1. Electrochemical Sensing

Heavy metal ions undergo redox reactions on modified electrode surfaces, resulting in measurable changes in current or voltage. Anodic Stripping Voltammetry (ASV): Pre-concentration followed by oxidative abstraction; Cyclic Voltammetry (CV): Voltage-scan analysis; Differential Pulse Voltammetry (DPV): Enhanced sensitivity through pulse modulation. Li et al. (2011) developed a graphene-based electrochemical sensor for the detection of lead ions (Pb^{2+}) with a limit of detection (LOD) of 0.02 µg/L, significantly lower than the WHO guideline limit of 10 µg/L (5). Abdulla and others (2026) developed and tested biosynthesized electrochemical nanosensors from the plants Ficus elastica and Acalypha indica. Metal oxides and metal nanoparticles (CuO, Ag, and ZnO) were obtained from these sensors. The sensor voltage was measured using cyclic voltage (CV) and square wave voltage (SWV). The detection limits range from 0.07 to 0.16 µg/L (6).

3.2 Optical Sensing

A. Color Detection

Based on localized surface plasmon resonance (LSPR) of gold nanoparticles: Color change resulting from aggregation: Single gold nanoparticles appear red; aggregated gold nanoparticles appear blue/violet; Distance-dependent plasmon coupling. Raed Liu and Lou (2004) aggregated DNA-guided gold nanoparticles for lead (Pb^{2+}) ion detection, achieving optical detection at a concentration of 100 nm (7).

B. Fluorescence Sensing

Quantum dots (QDs) exhibit size-tunable fluorescence that is quenched upon interaction with metal ions: Photoinduced electron transfer (PET) or Förster resonance energy transfer (FRET). Chen and Rosenzweig (2002) used thioglycolic acid-modified cadmium sulfide (CdS) quantum dots to detect copper (Cu^{2+}) and zinc (Zn^{2+}) ions (8).

3.3 Piezoelectric/Acoustic Sensing

Quartz Crystal Microbalance (QCM) sensors detect mass changes upon metal binding with the equation that is given in Equation 2:

$$\Delta f = -\frac{2f2\ 0}{A\sqrt{p_q\ \mu_q}}\ \Delta m$$

2

Where f0 is the resonant frequency, ρq and μq are the quartz density and shear modulus.

3.4 Chemiresistive Sensing

Carbon nanotubes and graphene change electrical conductivity upon metal ion adsorption due to charge transfer effects (9).

Table 2. *The importance of modifying nanoparticle surfaces to achieve selectivity towards heavy metals (4):*

Functional Group	Target Metal	Interaction Mechanism
Thiol (-SH)	Hg^{2+}, Pb^{2+}, Cd^{2+}	Soft-soft Lewis acid-base
Amino ($-NH_2$)	Cu^{2+}, Ni^{2+}, Co^{2+}	Coordination complexation
Carboxyl (-COOH)	General cations	Electrostatic/chelation
DNA aptamers	Specific sequences	Molecular recognition
Antibodies	Specific antigens	Immunological binding

4. Types of Nanosensors for Heavy Metal Detection

4.1 Gold Nanoparticle (AuNP)-Based Sensors

Properties: Strong localized surface plasmon resonance (LSPR) absorption (at a wavelength of approximately 520 nm); High extinction coefficient (approximately $10^8\ M^{-1}cm^{-1}$); Biocompatible and chemically stable

4.2. Carbon Nanotube (CNT)-Based Sensors

Single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) offer the following properties: Exceptional electrical conductivity; High aspect ratio (>1000); Large specific surface area (~1000 m^2/g).

The Functionalization strategies of Carbon Nanotube (CNT)-Based Sensors are: Covalent bonds (carboxylation, amidation (formation of amide bonds) and Non-covalent bonds: π-π stacking, surfactant wrapping. Cesarino et al. (2012) utilized L-cysteine-modified multi-walled carbon nanotubes (MWCNTs) for the simultaneous detection of lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+}) ions, with limits of detection (LODs) in the micromolar range (12).

4.3. Graphene and Graphene Oxide (GO) Sensors

Structure-property relationship is: **Graphene:** A zero-bandgap semiconductor characterized by high charge-carrier mobility (200,000 $cm^2/V{\cdot}s$), and **Graphene oxide (GO):** Oxygen-rich functional groups (epoxy, hydroxyl, carboxyl) that facilitate binding to metals. Guo et al. (2011) developed an electrochemical sensor based on graphene oxide (GO) for the detection of trivalent arsenic ions (As^{3+}), with a limit of detection (LOD) of 0.5 nM, utilizing a modification based on DNA aptamers (13). Abdulla et al. (2026), also developed a graphene oxide sensor with Eruca sativa leaf extract to proceed with solid-phase microextraction (SPME) for the removal of mercury and arsenic (LOD) 0.12 µg/L (Hg) and 0.18 µg/L (As) (14).

4.4 Metal oxide nanoparticle sensors

A. Zinc oxide (ZnO) nanostructures

Wide bandgap (3.37 eV); High exciton binding energy (60 meV); Piezoelectric properties. Omar et al. (2013) fabricated biosensors based on zinc oxide (ZnO) nanorods for the detection of cadmium ions

(Cd^{2+}), achieving a limit of detection (LOD) of 0.1 nM (15).

B. Titanium dioxide (TiO_2) nanoparticles

Excellent photocatalytic activity; Chemical stability; Low cost. Lee et al. (2010) utilized titanium dioxide (TiO_2) nanotube arrays for the simultaneous photoelectrochemical detection and degradation of hexavalent chromium (Cr(VI)) (16).

4.5 Magnetic Nanoparticle Sensors (Fe_3O_4)

Advantages: Superparamagnetism enables magnetic separation; Ease of surface functionalization; Reusability. Wang et al. (2013) developed $Fe_3O_4@SiO_2$ core-shell nanoparticles functionalized with amino groups for the removal of Pb^{2+}, Cd^{2+}, and Cu^{2+} ions, achieving adsorption capacities of 227, 187, and 165 mg/g, respectively (17).

4.6. Metal-Organic Framework (MOF)-Based Sensors

Exceptional properties: Ultra-high surface areas (up to 7,000 m^2/g); Tunable pore sizes (0.5–5 nm); Customizable chemical functionalities. Rapti et al. (2016) designed a zirconium-based MOF (UiO-66-NH_2) for the selective detection of mercury (Hg^{2+}) and lead (Pb^{2+}) ions, with a limit of detection (LOD) of 10 nM (18).

4.7. Quantum Dot (QD)-Based Sensors

Types: II-VI semiconductors, such as CdS, CdSe, and ZnS; III-V semiconductors, such as InP and InAs. Carbon dots: a promising, eco-friendly alternative. Gao and colleagues (2016) developed carbon dots using citric acid for the highly selective detection of multiple ions (Fe^{3+}, Cu^{2+}, Hg^{2+}) (19).

Table 3- *Applications of Gold Nanoparticle (AuNP)-Based Sensors for Heavy Metal Detection*

Target	Functionalization	LOD	Reference
Hg^{2+}	DNAzyme	0.2 nM	Li et al., 2009 (5)
Pb^{2+}	G-quadruplex DNA	10 nM	Liu & Lu, 2004 (7)
Cd^{2+}	Glutathione	50 nM	Xue et al., 2008 (10)
As^{3+}	Ars-3 aptamer	5 nM	Wu et al., 2015 (11)

5. Integrated Detection and Removal Systems

5.1. Sensor, Adsorbent, and Photocatalyst Module

5.2 Case Studies of Integrated Applications

Case 1: Magnetic adsorbent nanomaterials with real-time monitoring

The system consists of $Fe_3O_4@SiO_2$-NH_2 nanoparticles + electrochemical sensor. Its application is in Industrial wastewater treatment. The removal efficiency exceeds 95% for lead (Pb^{2+}), cadmium (Cd^{2+}), and mercury (Hg^{2+}) ions; real-time monitoring at parts-per-billion (ppb) levels (20)

Case 2: Photocatalytic degradation with optical sensing

The system consists of a TiO_2-AuNP nanocomposite. The mechanism is optical detection of hexavalent chromium (Cr(VI)) via localized surface plasmon resonance (LSPR) shift in gold nanoparticles (AuNPs); Photocatalytic reduction to trivalent chromium (Cr(III)) under UV/visible light; Optical confirmation of Cr(VI) removal. Complete reduction of hexavalent chromium (Cr(VI)) within two hours; sensor regeneration via self-cleaning under light (21)

Case 3: Smart filters based on Metal-Organic Frameworks (MOFs)

The system is a ZIF-8 membrane with integrated quantum dot (QD) sensors. It can be applied in drinking water purification. The performance is an adsorption capacity of 680 mg/g for lead ions (Pb^{2+}); Real-time monitoring using fluorescence; Selective capture of heavy metals while allowing water permeation (22)

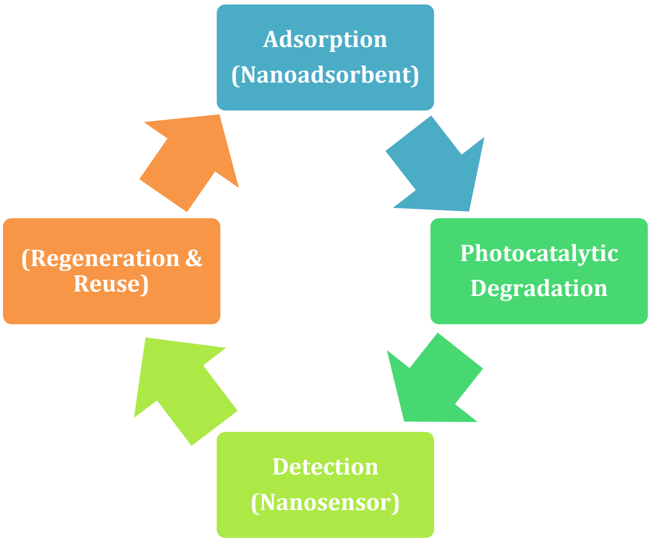

Figure 1- *Integrated System*

Table 4. *Performance Comparison of Nanosensor Platforms*

Nanomaterial	Target	Detection Method	LOD	Linear Range	Response Time	Ref.
AuNPs	Hg^{2+}	Colorimetric	0.2 nM	0.5-100 nM	<5 min	(9)
MWCNTs	Pb^{2+}	Electrochemical	0.1 µM	0.1-50 µM	<30 s	(12)
GO	As^{3+}	Electrochemical	0.5 nM	1-100 nM	<2 min	(13)
ZnO NRs	Cd^{2+}	Potentiometric	0.1 nM	0.1-100 nM	<10 s	(14)
Fe_3O_4 NPs	Hg^{2+}	Magnetic/Colorimetric	1 nM	1-100 nM	<1 min	(15)
UiO-66-NH_2	Pb^{2+}	Fluorescence	10 nM	10-1000 nM	<5 min	(16)
Carbon dots	Cu^{2+}	Fluorescence	5 nM	5-500 nM	<2 min	(17)
CdSe QDs	Hg^{2+}	Fluorescence	0.1 nM	0.1-50 nM	<1 min	(8)

6. Challenges and Limitations

6.1. Technical Challenges: Table 5 summarizes the most important technical challenges in the preparation of nanoparticles and the Potential Solutions

Table 5. Technical Challenges

Challenge	Description	Potential Solutions
Aggregation	Nanoparticles agglomerate in high ionic strength media	Surface coating with polymers (PEG, PVP)
Interference	Non-target ions produce false signals	Molecular imprinting, aptamer engineering
Stability	Nanomaterials degrade over time	Protective shells (SiO_2, carbon)
Reproducibility	Batch-to-batch variation	Standardized synthesis protocols
Regeneration	Sensor surface fouling	Photocatalytic self-cleaning, chemical regeneration

6.2. Environmental and Safety Concerns

A. Nanomaterial Toxicity:

Cadmium-based quantum dots release toxic cadmium ions (Cd^{2+}); Carbon nanotubes may cause pulmonary inflammation; Silver nanoparticles exhibit broad-spectrum antimicrobial activity (beneficial in some cases, concerning in others).

B. Mitigation Strategies:

Developing biocompatible alternatives (carbon dots, silicon dots); Green synthesis using plant extracts; Encapsulation to prevent leakage.

6.3. Economic Barriers

High cost of precious metal raw materials (gold, platinum); Complex employment procedures; Limited scalability of the bottom-up synthesis process.

7. Future Prospects and Emerging Trends

7.1. Smart, Self-Powered Nanosensors

Nanogenerators based on the triboelectric or piezoelectric effect: Harnessing mechanical energy from water flow; Powering autonomous sensor networks; Enabling battery-free remote monitoring. Wang (2013) demonstrated the effectiveness of self-powered zinc oxide (ZnO) nanowire sensors in detecting heavy metals in flowing water (20).

7.2. Integration with the Internet of Things (IoT)

Wireless data transmission via NFC, Bluetooth, or LoRaWAN technologies; Cloud-based data analysis and machine learning; Real-time water quality mapping.

7.3. Artificial Intelligence and Machine Learning

Applications: Pattern recognition in complex arrays; Predictive modeling of sensor performance; Optimizing nanomaterial design via high-throughput screening

7.4. Nature-Mimicking and Nature-Inspired Nanosensors

DNA origami: Programmable nanostructures for precise metal positioning

Protein cages: Ferritin and virus-like particles as templates

Cellular biosensors: Bacteria engineered with nanomaterial-based indicators

7.5. Sustainable and Eco-friendly Nanosensors

Green synthesis methods: Plant-mediated reduction (tea, citrus extracts); Microbial synthesis (bacteria, fungi, algae); Waste-derived nanomaterials (agricultural residues, plastic waste). Mittal et al. (2013) reviewed green synthesis methods for metal nanoparticles using plant extracts, highlighting the reduced environmental impact and cost (22).

8. Bio-Hybrid Nanosystems for Heavy Metal Sensing and Remediation

8.1. Biorecognition and Enzymatic Mechanisms in Nanosensors

The combination of biological recognition technology and specialized nanomaterials indicates a major change in environmental analytical chemistry from the limited capabilities of standard chemical surface modification (7). Biorecognition-based nanosensors make use of the plant-made or lab-engineered macromolecules such as functional oligonucleotides, catalytic DNA, modified enzymes, and synthetic peptide receptors to create highly reactive identification systems for the toxins and heavy metals in the environment (7).

8.1.1. Aptamer- and DNAzyme-Based Nanosensing (Aptasensors)

Oligonucleotides in the presence of any of the ligands associated with SELEX processes, whether in the form of DNA or RNA aptamers, tend to change shape, leading to the formation of different structures in the case where heavy metals are involved as the ligand to be tested (7). Such transitions explain why it is possible to observe changes in distances between particles in the case where aptamers are bound to some nanoparticles (7). Further, the use of DNA (DNAzyme) molecules based on catalytic cleavage is a must, since the process of cleavage of certain strands containing additional signals and interactions in the presence of heavy metals allows evaluation of how much substance is present within a particular liquid (7, 9, 14). The most recent research proves that CRISPR-Cas technology needs to be utilized in cases when considerable transformation of DNA strands takes place because of the presence of ligands being examined (23).

8.1.2. Enzymatic Inhibition and Biomimetic Nanosensors

The irreversible inhibition of the enzymatic activity of the enzymes by the environmentally undesirable ions is utilized in many enzymatic nanosensor applications (7, 15, 24); the most well-known examples include urease, acetylcholinesterase (AChE), and alkaline phosphatase (ALP) enzymes with reactive thiol (-SH) and imidazole groups which exhibit a very high affinity for soft Lewis acids like Hg2+, Cd2+, and Pb2+ (7, 15). The immobilization of such enzymes onto conductive nanomaterial substrates (e.g., carbon nanotubes or zinc oxide nanostructures) allows observing the reverse correlation between sample concentration of heavy metals and the performance of the enzyme reaction (7, 15). MIPs have resulted from attempts to turn the vulnerability of enzymes to denaturation into their advantage by working with nanomaterials (7, 25). MIPs consist of synthetic polymers capable of mimicking antibody-antigen interactions for selective separation and sensing of heavy metals from streams of wastewater. (7, 25).

8.2. Green Nanobiotechnology and Microbial Synthesis

The concept of Green Nanobiotechnology includes the use of biological organisms and plant extracts as environmentally safe and sustainable alternatives to hazardous chemical reducing agents (such as sodium borohydride and hydrazine) used for the synthesis of nanoparticles (7, 26, 27).

8.2.1. Plant-Mediated Phyto-Synthesis

Aqueous extracts obtained from plants like Eruca sativa, Acalypha indica, and Ficus elastica contain various secondary metabolites, the most significant of which are flavonoids, polyphenols, terpenoids, and alkaloids. The complex effect of these biologically active substances enables them to perform the role of both reducing and stabilizing agents, taking part in the process of nucleation of nanoparticles. The nanoparticles produced using phyto-synthesis methods such as copper oxide (CuO), silver (Ag), and zinc oxide (ZnO) possess greater stability and biocompatibility due to the presence of biological caps formed around them (7, 14, 22).

8.2.2 Microbial and Biomass-Mediated Synthesis

Microorganisms such as bacteria, fungi, and microalgae have unique biochemical detoxifying reactions that allow them to eliminate the dangers of heavy metal pollutants through intracellular retention and extracellular enzyme breakdown (7, 28). Biogenic iron oxide nanoparticles and precious metal nanoparticle materials formed as a result of microbial processes have excellent chemical properties and can be easily used (7, 28). Furthermore, mixing these biogenic nano products with plant waste or fungal filaments creates very effective nano-biosorption agents (7, 14, 28). In addition, endophytic bioproduction involves working together with fungi and actinobacteria to produce important nanomorphic structures with selected glycoprotein surface characteristics that help to resist biofouling during a long time period of water monitoring (28).

Table 6. *Bio-Functionalized Nanosensing and Remediation for Heavy Metals*

Bio-Recognition Green Component	Nanomaterial Matrix	Target Heavy Metal	Analytical Technique & Mechanism	LOD	Ref.
G-Quadruplex Aptamer	Gold Nanoparticles (AuNPs)	Pb^{2+}	Colorimetric, Target-induced aggregation (LSPR)	10nM	**(7)**
RNA-Cleaving DNAzyme	AuNP-Oligonucleotide Hybrids	Hg^{2+}	Fluorescence, Cofactor-stimulated strand cleavage	0.2nM	**(9)**
Urease Enzyme	ZnO Nanorods	Cd^{2+}	Potentiometric, Enzymatic activity inhibition	0.1 nM	**(14)**
***Eruca sativa* Phytochemicals**	Graphene Oxide (GO)	Hg^{2+}, As3+	Electrochemical (SPME), Bio-reduction & chelation	0.12 µg/L	**(6)**
***Ficus elastica* Extract**	Metal Oxides (CuO, ZnO)	Heavy Metal Ions	Cyclic Voltammetry, Phyto-capped surface sensing	0.07 µg/L	**(14)**
Genetically Engineered Microbes	Multi-Walled Carbon Nanotubes	Cd^{2+}, Pb^{2+}	Amperometric, whole-cell bioaccumulation	1.2 nM	**(29)**

8.3. Nanobioremediation: Synergistic Coupling of Nanosensors and Biological Remediation

Traditional bioremediation approaches typically suffer from slow degradation rates, extreme sensitivity to environmental variations, and no real-time measurements (7). Nanobioremediation combines tailored nanomaterials with biological agents of remediation to develop independent systems that can, at the same time, sense, adsorb, and transform heavy metal pollutants (7).

8.3.1. Whole-Cell Engineered Microbial Nanosensors and Accumulators

Genetically modified microorganisms (GEMs), including Escherichia coli, Pseudomonas putida, and Saccharomyces cerevisiae, have been genetically altered with metal sensor transcription factors that generate measurable output signals upon contact with metal (7, 29). Immobilization of the GEMs on conductive nanomaterial surfaces includes multi-walled carbon nanotubes (MWCNTs) and reduced graphene oxide (rGO), providing better electron transfer kinetics, bio-accumulation capacity, and in-situ electrochemical signal detection. (7, 29).

8.3.2. Functional Nano-Biosorbents and Magnetic Bio-Separation

When inactivated microbial biomass or natural biopolymers (like chitin, chitosan, and alginate) are mixed with superparamagnetic iron oxide nanoparticles ($Fe3O4$), highly effective hybrid bio-adsorbents are created. These systems integrate the efficient chelation attributes of natural polymers and swift magnetic separation of biological agents with embedded sensors (7, 28). Moreover, in order to minimize the complete removal of the desired molecule, nanocatalytic bio-reduction technologies are integrated into magnetic biosorbent systems to transform a soluble and carcinogenic species such as Cr(VI) into an inert and harmless oxidation state (Cr(III)) through microbial extracellular electron transfer mechanisms coupled to magnetic nanoparticle cores (28).

8.4. Biomimetic and Bio-Inspired Nanosensing Architectures

In order to overcome the issue of thermal denaturation and enzymatic breakdown of natural biomolecules involved in the treatment of industrial wastewater, synthetic bio-inspired nanostructures have been developed (7).

8.4.1. Molecularly Imprinted Polymer-Based Nanosensors (Nano-MIPs)

To overcome the issues of thermal denaturation and enzymatic breakdown of natural biomolecules within the industrial wastewater treatment process, new synthetic bioinspired nanostructures were created. (7, 25, 30).

8.4.2. Protein Cages and Structural DNA Nanotechnology (DNA Origami)

One example of such structures is ferritin protein cages and VLPs that act as monodisperse and subnanometer bio-capsules to trap and mineralize metals. Around the same time, DNA nanotech was developed, allowing for subnanometer positioning of ligands responsible for coordination of ions, enabling the creation of programmable binding platforms for heavy metal detection in the environment. Additionally, the latest biomimetic technologies have been incorporating the use of peptidomimetic self-assembling materials, where short peptides are arranged into nanostructured hydrogels resembling metallothionein pockets in terms of spatial arrangement and thus extremely resistant to chemical influences (31, 32).

9. Conclusion

Nanosensors represent a transformative technology for addressing heavy metal contamination in industrial and environmental water; the exceptional properties of nanomaterials—such as high surface area, quantum confinement effects, and tunable surface chemistry—enable detection with unprecedented levels of sensitivity and selectivity. Integrating adsorption and photocatalysis technologies leads to the development of comprehensive treatment solutions.

However, a successful transition from the laboratory to field application requires addressing challenges related to stability, scalability, cost, and environmental safety. Future research should focus on: Developing sustainable, non-toxic nanomaterials; Creating self-powered, autonomous sensor networks; integrating artificial intelligence into smart water quality management; Establishing standardized protocols for verifying nanosensor efficiency.

The convergence of nanotechnology, biotechnology, and information technology heralds a new era of smart systems for water monitoring and treatment—systems capable of safeguarding global water resources for future generations.

Author Contributions

Author 1: Data Curation, Conceptualization, Visualization, Writing – original draft, Supervision. Author **2:** Data curation, Writing – original draft, Writing – review & editing. **Author 3:** Data curation, Writing – original draft.

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Conflicts of Interest

The authors declare no conflict of interest.

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