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Review

Real-Time Detection of Heavy Metals and Some Other Pollutants in Wastewater Using Chemical Sensors: A Strategy to Limit the Spread of Antibiotic-Resistant Bacteria

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Abstract

The increasing presence of heavy metals in wastewater is a growing environmental and public health concern, particularly due to their role in promoting the spread of antibiotic-resistant bacteria (ARB) through co-selection mechanisms. This review explores recent advances in real-time detection of heavy metals and some other pollutants using chemical sensors as a strategic tool to limit ARB proliferation. It provides an overview of sensor types, including electrochemical, optical, biosensors, and molecularly imprinted polymer (MIP) sensors, and assesses their suitability for monitoring pollutants in complex wastewater matrices. Emphasis is placed on the integration of these technologies with Internet of Things (IoT) platforms, portable and autonomous systems, and data-driven approaches for multi-metal detection, selectivity enhancement, and predictive analysis. The review also discusses current challenges such as sensor stability, interference, and cost-efficiency, and outlines future directions in real-time environmental monitoring and antibiotic resistance control. Overall, chemical sensor-based monitoring offers a promising, scalable solution for safeguarding ecosystems and public health in the face of growing antimicrobial resistance.

Keywords: antimicrobial resistance (AMR); co-selection mechanisms; wastewater-based epidemiology (WBE); heavy metals detection

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1. Introduction

Water resources are under increasing pressure due to rapid population growth and global urbanization. This issue affects both developing and developed countries, where water shortages are often worsened by industrial pollution [1,2]. The need for clean water and effective wastewater management is becoming increasingly urgent, as billions may face water scarcity in the near future. Industries such as textiles, petroleum refining, pharmaceuticals, and food processing consume large volumes of water and generate significant amounts of wastewater [3]. The expansion of industrial production has further increased the discharge of harmful pollutants like heavy metals and persistent organic compounds into water sources [4,5]. One major environmental consequence is the continuous exposure of soil microorganisms to heavy metals, which leads to the development of metal resistance. Through co-selection mechanisms, these microorganisms can also acquire antibiotic resistance, especially when metal and antibiotic resistance genes are located on the same mobile genetic elements [6,7].

Metals and metalloids such as copper, nickel, cadmium, arsenic, and mercury have been shown to facilitate the spread of antibiotic resistance in natural environments [8–11].

Soil polluted with these metals has been linked to resistance against antibiotics like chloramphenicol, tetracycline, and ampicillin. Furthermore, biocides and organometallic compounds also contribute to this process [12–16]. Co-selection operates via (i) co-resistance: when resistance genes for metals and antibiotics are found on the same genetic element, selecting one promotes the other [17]; and (ii) cross-resistance: when both types of stressors affect similar biochemical pathways, allowing shared resistance mechanisms to act [18]. The use of metal-based fertilizers and additives in agriculture allows these pollutants to leach into groundwater and enter the food chain, increasing the risk of hard-to-treat infections resistant to both metals and antibiotics [19–21]. At the same time, climate change adds another layer of complexity. Elevated temperatures promote the accumulation of metals and chemical residues in crops [22–24], while wildfires, driven by drought and heat, release organic pollutants that pollute soil and water [25]. Persistent organic pollutants like pesticides, PCBs, PAHs, and disinfectants further drive the selection of antimicrobial resistance genes [26–28].

Additionally, climate-induced changes in microbial communities may bring previously isolated or harmless bacteria into contact with humans and animals. This increases opportunities for horizontal gene transfer (HGT), a major driver in the emergence and dissemination of antibiotic resistance genes [29,30]. In this context, the development of modern analytical techniques capable of rapidly and efficiently quantifying pollutants from various water sources has become essential [31–33]. Although numerous well-established analytical methods exist, chemical sensors have undergone significant advancements in recent years, emerging as promising tools for monitoring both pollutants and pathogens [31,34,35]. Originally developed for biomedical applications, chemical sensors [36,37] are increasingly being adapted for environmental monitoring, where they are optimized to detect pollutants in air, soil, and water [38]. These sensors offer key advantages, including sensitive, rapid, and cost-effective detection of emerging pollutants and pathogens in wastewater and natural aquatic systems [39,40]. Emerging technologies such as high-resolution mass spectrometry and advanced sensors have greatly enhanced the ability to identify pollutants [41,42]. These advancements are essential for tackling the ongoing and emerging challenges associated with pollutants of emerging concern and for strengthening strategies aimed at controlling antimicrobial resistance. Within this context, the present study gains relevance by exploring the critical connection between heavy metal pollution and the proliferation of antibiotic resistance, a growing and urgent threat to global public health.

2. Heavy Metals and Antibiotic-Resistant Bacteria

The expansion of industrialization leads to the generation of large volumes of wastewater containing high concentrations of heavy metals, posing serious risks to both the environment and human health [43]. Industrial discharges, especially from petrochemical sectors, commonly contain metals such as chromium (Cr), copper (Cu), manganese (Mn), nickel (Ni), cadmium (Cd), lead (Pb), and zinc (Zn) [44]. These heavy metals tend to bioaccumulate in organisms, potentially leading to various adverse health effects [45]. Figure 1 summarizes the major sources and effects of common heavy metals. Phytoremediation treatments have been shown to significantly reduce antibiotic and metal resistance genes (ARGs and MRGs) in wastewater. Also, metagenomic analysis revealed strong correlations between ARG abundance and iron levels, suggesting that metals like Fe may promote resistance [46].

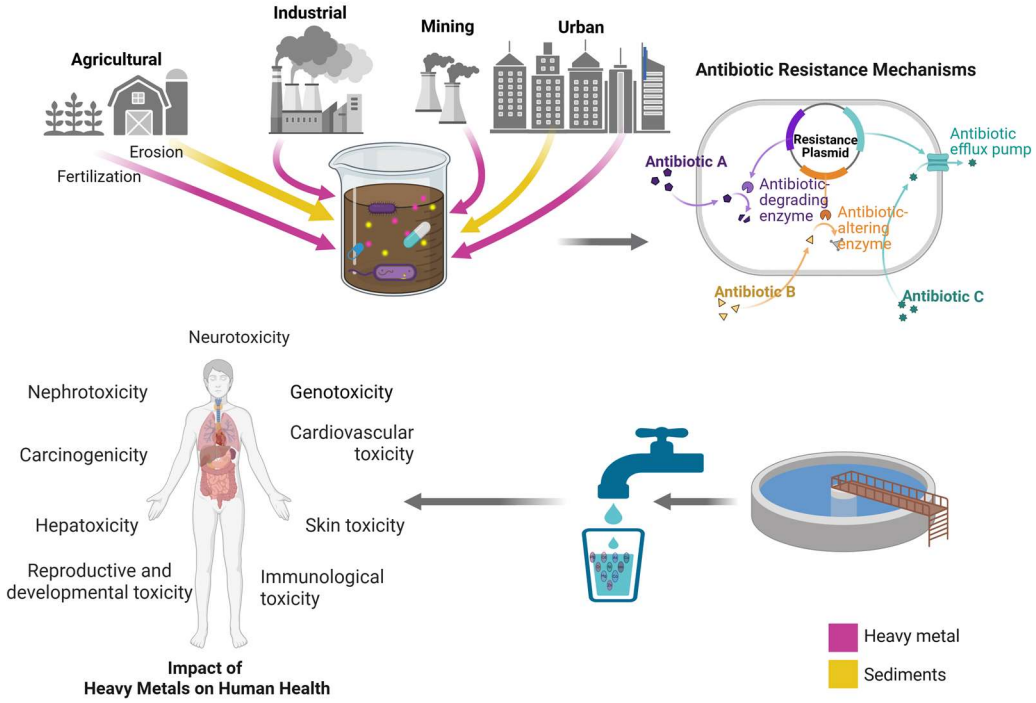


Figure 1. Heavy metals in wastewater and their impact on the human body [Created in https://BioRender.com].

2.1. Cadmium (Cd)

Cd is a highly toxic metal, primarily generated as a byproduct of the zinc manufacturing process [47]. It accumulates in plants and is subsequently ingested by microorganisms and humans. When cadmium levels exceed the threshold of 7 µg/L, harmful effects can occur [48]. This metal exhibits a high transfer rate from soil to plants, resulting in elevated cadmium concentrations in fruits and vegetables [49]. In aquatic environments, cadmium exists in the form of Cd^{2+}, a divalent heavy metal ion with high mobility, which can be easily transported through water and wastewater, thereby facilitating the widespread dispersion of this toxic element. Its mobility is further enhanced by fluctuations in pH, ionic strength, and the redox state of the solution [50]. Moreover, cadmium forms water-soluble complexes with anions, such as chloride ($CdCl^{+}$) and sulfate ($Cd(SO_4)_2^{2-}$), as well as with hydrous oxides, clays, and dissolved organic matter [51]. This ability to remain soluble contrasts with the behavior of most other heavy metals, whose aqueous concentrations are typically reduced through complexation and adsorption [52]. Din et al. highlight the isolation of a cadmium- and antibiotic-resistant *Acinetobacter calcoaceticus* strain (STP14) from a sewage treatment plant, emphasizing the environmental threat posed by heavy metals in wastewater. The strain demonstrated high tolerance to cadmium (up to 1200 mg/L), along with resistance to multiple antibiotics, suggesting a strong potential for co-selection. Proteomic analysis revealed altered protein expression under cadmium exposure, indicating a physiological adaptation to metal-induced stress [53]. Pan et al. investigated the individual and combined effects of cadmium (Cd) and copper (Cu) on the distribution of antibiotic resistance genes in rhizosphere soil. The researchers found that genes such as acrA, acrB, and intI-1 were commonly present in bacterial communities, with cadmium exerting a stronger influence on ARG abundance than copper. Network analysis revealed that most ARGs were associated with bacterial phyla, including Proteobacteria, Actinobacteria, and Bacteroidetes. Structural equation modeling (SEM) confirmed that Cd had a significant direct effect on ARG proliferation, while the influence of bacterial diversity was relatively limited [54]. A study examined the impact of cadmium accumulation on antibiotic resis-

tance in *Salmonella enterica* serovar Typhi. The findings showed that cadmium exposure not only induced antibiotic resistance in previously sensitive strains but also enhanced resistance in already resistant ones. These changes were accompanied by morphological and proteomic alterations, increased biofilm formation, reduced intracellular killing by macrophages, and upregulation of genes involved in metal transport and metallothionein production [55]. Another study reported the isolation of a cadmium-resistant strain, *Pseudomonas* sp. *M3*, from industrial wastewater in Malaysia. The strain showed high cadmium tolerance (MIC 550 μg/mL) and removed over 70% of Cd during active growth. It also displayed resistance to several antibiotics, suggesting co-selection. Protein analysis revealed adaptive responses under metal stress, highlighting both its bioremediation potential and the risk of promoting antibiotic resistance [56]. Likewise, cadmium exposure on *Babylonia areolata* snails increased the abundance and diversity of ARGs, especially for tetracycline, vancomycin, and MLS_B. Gut microbiota shifted with Cd levels, influencing ARG profiles more than Cd itself. Opportunistic pathogens likely carried these genes, highlighting cadmium's role in promoting resistance through microbiome changes [57].

2.2. Arsenic (As)

The main source of As in the environment is its release from arsenic-rich minerals through natural processes such as weathering, geochemical transformations, and biological activity, as well as through human activities. Environmental arsenic pollution is largely attributed to mining, smelting, fossil fuel combustion, and its use in products like pigments, glass, livestock feed, wood preservatives, and various agricultural and industrial applications. Consequently, municipal wastewater may contain arsenic from both natural origins and anthropogenic sources [58]. A study investigated how arsenic pollution affects antibiotic resistance genes (ARGs) in soil microbial communities. Using an arsenic exposure experiment, researchers found that arsenic strongly promotes the spread of ARGs through co-selection, even without direct antibiotic pressure. The study highlights that heavy metal pollution can significantly drive antibiotic resistance in the environment by selecting resistant bacteria [59]. Ahmed et al. investigated the impact of arsenic exposure on antimicrobial resistance profiles in extended-spectrum β-lactamase (ESBL)-producing bacteria isolated from clinical infections. Among 300 ESBL-positive isolates, predominantly *E. coli*, *Klebsiella* spp., *Pseudomonas aeruginosa*, *Proteus mirabilis*, and *Enterobacter* spp., researchers conducted antibiotic susceptibility testing both with and without arsenic supplementation (sodium arsenate at 1.25 g/mL). Results showed that exposure to arsenic significantly increased resistance even to last-resort antibiotics like colistin and polymyxin B [60].

2.3. Chromium (Cr)

Chromium, particularly in its hexavalent form (Cr(VI)), is highly toxic and poses severe risks to human health, including cardiovascular and urinary damage [61]. While natural occurrences of Cr(VI) are extremely scarce (e.g., rare minerals such as $BaCrO_4$), almost all hexavalent chromium present in the environment originates from anthropogenic activities [62]. Chromium(VI)-polluted wastewater also poses serious environmental risks, and a rapid-response adsorbent with –OH and Zr–OH surface groups can efficiently remove Cr(VI) (up to 97.9 mg/g) within 30 min, bringing concentrations within emission limits [63]. Wu et al. explored the interaction between hexavalent chromium (Cr(VI)) and antibiotics in *Bacillus cereus SH-1*. The findings revealed that Cr(VI) exposure triggers oxidative stress, increases antioxidant enzyme activity, and enhances plasmid-mediated gene transfer. As Cr(VI) concentrations increased, resistance to tetracycline and amoxicillin also rose, while susceptibility to azithromycin and chloramphenicol improved [64].

2.4. Copper (Cu)

Cu is a widely occurring transition metal and the third most used metal globally, classified as a heavy metal [65]. Although essential for human health, playing critical roles in enzyme synthesis, bone development, and tissue function, copper is also considered a highly hazardous metal [66]. Cu(II) is extensively used in industries such as electroplating, paint and dye production, petroleum refining, fertilizers, mining, explosives, pesticides, and steel manufacturing, making it a significant pollutant in industrial wastewater [67]. For human health, copper is vital for the immune system, liver, heart, eyes, and blood function. Deficiency can lead to anemia and connective tissue disorders, while excess copper intake may cause gastrointestinal distress, liver enzyme dysfunction, and, in some cases, neurological disorder [68]. In aquatic environments, Cu(II) can infiltrate surface and groundwater and reach drinking water supplies, posing a serious risk to human health. Its increasing presence in water systems has marked Cu(II) as a major heavy metal pollutant worldwide [65]. Gao et al. investigated the effects of copper (Cu) exposure at concentrations ranging from 0.5 to 10 mg/L on ARGs, MGEs, and microbial communities in activated sludge. Results showed that Cu exposure, especially under an increasing concentration regimen, significantly altered microbial community structure and promoted the dissemination of ARGs, particularly those related to multidrug and sulfonamide resistance. Among MGEs, tnpA-02 played a key role in the co-transfer of ARGs such as *sul2* and *floR*. Most ARGs and tnpA-02 were associated with bacteria, which accounted for 24% of ARG variation, while archaea contributed 19% [69].

2.5. Lead (Pb)

Among heavy metals, Pb(II) is one of the most widely used, with applications across various industries such as electroplating, paint, steel production, batteries, smelting, and the manufacturing of inorganic fertilizers and pesticides. Pb(II) is highly toxic, mutagenic, and carcinogenic, and it can lead to numerous metabolic and physiological disorders in humans, animals, and plants [70]. Lead (Pb) pollution in wastewater has been widely reported, with concentrations ranging from less than 0.001 mg/L to as high as 990 mg/L globally and an average concentration of approximately 0.03 mg/L [71]. A microcosm experiment using water from Lake Michigan demonstrated that lead corrosion products, particularly $Pb_5(PO_4)_3OH$ and β-PbO_2, significantly increased the abundance of antibiotic-resistant bacteria and the presence of resistance genes, in contrast to iron corrosion products, which had minimal impact [72]. Examination of urinary lead levels, a marker of chronic exposure, and colonization by antibiotic-resistant bacteria (including MRSA, VRE, and RGNB) showed significantly higher risk of ARB colonization among individuals in the highest percentiles of lead exposure [73]. In areas with polluted industrial and urban wastewater, such as in Uganda and India, bacterial strains resistant to both lead and antibiotics have been documented, highlighting the co-selection of metal and antibiotic resistance [74].

2.6. Mercury (Hg)

Mercury (Hg) is classified as a priority hazardous substance by countries such as Switzerland, the EU, and the U.S. due to its serious environmental and health risks [75]. Some inorganic mercury released into aquatic environments is converted into the more toxic methylmercury, which accumulates through the food chain and poses a risk of poisoning, particularly through fish consumption [76]. A study conducted in the highly mercury-polluted Almadén mining district in Spain analyzed 53 Bacillus strains from soil and found that 72% were resistant to two or more antibiotics, with a high prevalence of cephalosporin resistance. The research demonstrated a significant co-selection effect, where mercury

exposure, specifically to $HgCl_2$, was linked to increased antibiotic resistance, particularly to cephalosporins and tetracyclines. A study of 38 microbial isolates from various wastewater sources in Egypt showed that 14 of them could tolerate mercury concentrations up to 160 ppm and also resist other heavy metals like Cu, Co, Ni, and Zn. From these, 10 highly resistant strains (9 Gram-negative and 1 Gram-positive) were further analyzed, revealing that six exhibited multi-antibiotic resistance. All nine Gram-negative isolates carried a plasmid-encoded merA gene responsible for reducing toxic mercuric ions to elemental mercury, a key mercury-resistance mechanism [76]. Analysis at a municipal wastewater treatment plant in China of the presence and dynamics of five mercury/silver resistance genes (*merB*, *merD*, *merR*, *silE*, *silR*) alongside five antibiotic resistance genes (*sulI*, *sulII*, *tetO*, *tetQ*, *tetW*) and the class 1 integrase gene (*intI1*) showed that the overall abundance of these genes decreased significantly through treatment stages, with strong correlations between *merB*/*merD* and *silE* as well as between *tetW* and *sulII* [77].

2.7. Nickel (Ni)

Nickel (Ni^{2+}), one of the most produced base metals in 2019, is commonly present in domestic and industrial wastewater and has been classified as a metal of major concern since 1984. Its high persistence poses a serious environmental risk, as Ni^{2+} ions may take up to 10,000 years to be absorbed by plants [78]. A 2014 study reported the isolation of eight nickel-resistant bacterial strains from industrial wastewaters in Isfahan, Iran. The three most tolerant strains, Cupriavidus sp. ATHA3, Klebsiella oxytoca ATHA6, and Methylobacterium sp. ATHA7 exhibited maximum tolerable Ni^{2+} concentrations of 8, 16, and 24 mM, respectively. Klebsiella oxytoca ATHA6 demonstrated exceptional bioremediation potential by reducing nickel levels by 83 mg/mL in just three days [79]. A multi-year field study that assessed soils exposed to 0–800 mg Ni/kg over 4–5 years revealed that increased nickel concentrations corresponded with higher diversity and abundance of ARGs, especially multidrug and β-lactam types. Mobile genetic elements, notably the integrase gene *intI1*, were strongly associated with ARGs, suggesting enhanced potential for horizontal gene transfer induced by nickel bioavailability [80].

2.8. Other Less Common Toxic Metals

Beyond the well-studied heavy metals such as lead, cadmium, mercury, and copper, increasing attention is being directed toward less common but highly toxic elements, including tin, thallium, bismuth, antimony, indium, and germanium. These metals are widely used in modern technologies (e.g., electronics, semiconductors, and renewable energy devices), and their occurrence in the environment is rising, particularly through electronic waste streams [81]. Although studies directly linking these elements to antibiotic resistance remain scarce, their environmental persistence and toxicity suggest they should be considered emerging pollutants with the potential to shape microbial communities and contribute to resistance dynamics [12]. For example, recent studies on antimony have demonstrated both microbial adaptation and potential for bioremediation. When reviewing Sb(III)-oxidizing bacteria, Deng et al. showed how resistance and metabolic pathways can transform the highly toxic antimonite into the less harmful antimonate, highlighting prospects for Sb bioremediation [82]. Similarly, Majerová et al. isolated seven bacterial strains, predominantly *Shewanella*, *Buttiauxella*, and *Aeromonas*, that effectively accumulate antimony in their biomass from contaminated environments [83].

In contrast, bismuth has demonstrated noteworthy antimicrobial properties. Chelated bismuth compounds have been shown to inhibit aquaculture pathogens and reduce fish mortality; they may be used as a strategy to lower antibiotic use [84]. This activity is further supported by studies reporting the efficacy of bismuth compounds against resistant

strains of *Pseudomonas aeruginosa* and *Staphylococcus aureus* [85]. More recent research has shown that bismuth compounds can inhibit metallo-β-lactamases and enzymes responsible for inactivating tigecycline, thereby restoring the effectiveness of key antibiotics against resistant bacteria [86].

3. Chemical Sensors Used in Wastewater Monitoring

Wastewater pollution with hazardous substances poses significant environmental and public health risks, requiring thorough monitoring. Sensors play a vital role in detecting and measuring these pollutants, including electrochemical, optical, biosensors, and molecularly imprinted polymer (MIP) sensors. While conventional sensors offer accuracy, real-time monitoring systems are more portable, durable, cost-effective, and energy-efficient [87]. An integrated overview of real-time heavy metal detection in wastewater is presented in Figure 2.

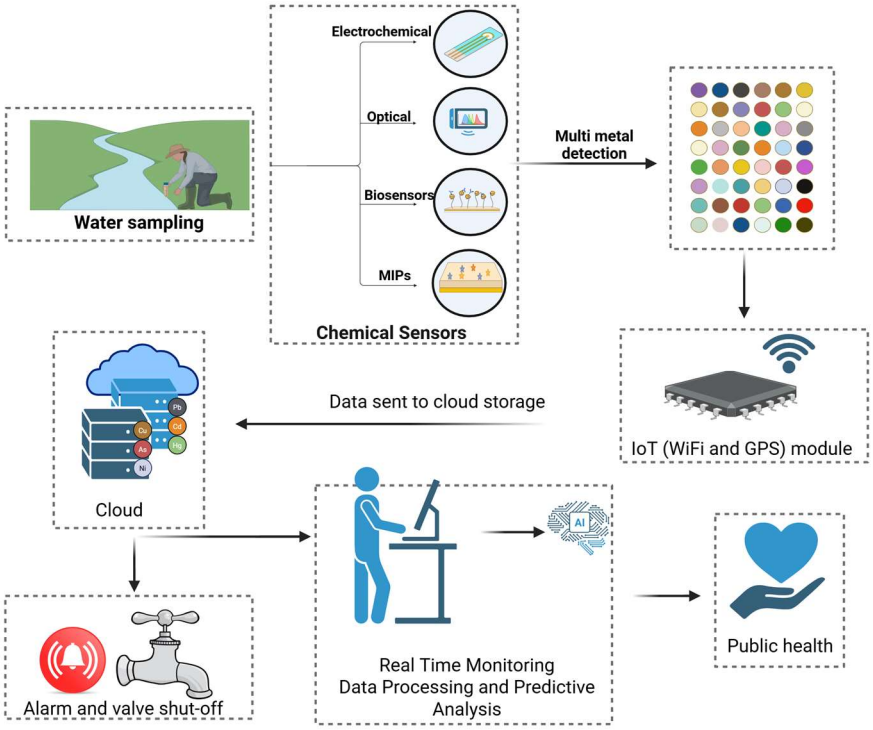


Figure 2. Integrated overview of real-time heavy metal detection in wastewater [created in https://BioRender.com].

3.1. Types of Sensors for the Detection of Pollutants in Wastewater

3.1.1. Electrochemical Sensors

Electrochemical sensors, including those based on screen-printed electrodes, glassy carbon, or carbon paste, have been widely used for the rapid detection of pollutants in water, while chemical sensors offer enhanced sensitivity and selectivity due to their recognition capabilities [88]. The main types of electrochemical sensors applied in wastewater analysis are summarized in Table 1.

Table 1. Electrochemical sensors used for wastewater.

Types of Sensors	Target Analytes	Processes That Generate the Analytical Signal	References
Impedimetric aptasensor-based TiO_2-g-C_3N_4 and gold nanoparticles	Antibiotics (Amoxicillin)	Oxidation	[88]
Nitrogen-doped carbon nanodots and nanosized cobalt phthalocyanine conjugate-modified glassy carbon electrode	Anti-inflammatory, analgesic, and antipyretic drugs (ibuprofen, aspirin)	Oxidation	[88]
Carbon paper electrode	Anti-inflammatory, analgesic, and antipyretic drug (ketoprofen)	Reversible redox process	[88]
Microbial Electrochemical Sensor (SENTRY™, MFC-based)	Biodegradable organic matter (e.g., ethanol, poultry blood, toxic dilutions)	Electroactive bacteria oxidize organics, producing electrons that generate a measurable electric current correlated with pollutant concentration	[89]
Low-cost electrochemical copper electrode	Chemical oxygen demand (COD); volatile fatty acids (VFAs); sodium bicarbonate	Oxidation/reduction reactions at the copper electrode surface are analyzed via chemometric models (PCR, PLS, ANN) to predict concentrations based on the electrode current response	[90]
Molecularly Imprinted Polymer (MIP) sensor, composed of polydopamine/electro-reduced graphene oxide, enhanced with Prussian blue nanoparticles	Hydrocortisone	Indirect detection: Prussian blue redox activity decreases proportionally to hydrocortisone concentration, measured via cyclic voltammetry or DPV	[91]
Aptamer-based sensors	Small molecules or biomarkers	Aptamer–target binding leads to measurable changes in current or electrical properties	[92]
Polyaniline–gold nanoparticle (PANI–AuNP) modified glassy carbon electrode	Cadmium ions (Cd^{2+})	Cd^{2+} undergoes oxidation at the electrode surface during voltammetric scans; amplified electron transfer through PANI–Au synergy generates a current peak proportional to Cd concentration	[93]
Nanostructured potentiometric sensors	Cd^{2+}, Cu^{2+}	Voltage shift at ion-selective membranes due to ion activity	[94]
Voltammetric sensors (SWASV, DPV)	Cd^{2+}, Pb^{2+}, Cr^{3+}	Oxidation/reduction peaks during potential sweep; current intensity correlates with ion concentration	[94]
Electrochemiluminescent sensors	Pb^{2+}, Hg^{2+}	Light emission generated by redox-triggered reactions involving the metal ion	[94]

3.1.2. Optical Sensors

Optical sensors utilizing fluorescence, absorbance, scattering, and reflectance detection enable real-time, in situ monitoring of wastewater quality by detecting organic compounds such as proteins and humic substances, as well as physicochemical variables like nitrate,

dissolved organic carbon, and turbidity, often supported by full-spectrum analysis and machine learning integration for improved accuracy and early pollution detection [95]. The main types of optical sensors applied in wastewater analysis are summarized in Table 2.

Table 2. Optical sensors used for wastewater.

Types of Sensors	Target Analytes	Processes that Generate the Analytical Signal	References
Optical absorbance/ scattering sensor	Water quality indicators (e.g., turbidity, organic load, pollution events)	Measures light absorbance and scattering at selected wavelengths; changes correlate with water composition	[96]
Fluorescence	Pb^{2+}, As^{3+}	Rely on quenching/enhancement due to metal–ligand or metal–nanomaterial interactions.	[97]
Absorbance	Hg^{2+}, Cd^{2+}, As^{3+}	Rely on electronic transition changes (colorimetric).	[97]
AI-enhanced optical system	Pattern recognition of normal vs. abnormal wastewater states	Machine learning algorithms analyze spectral patterns to classify, detect anomalies, and predict pollution events	[96]
Fiber-optic absorbance sensors	Wastewater color	Changes in light absorbance through fiber strands due to colored dissolved species	[98]
Fiber-optic fluorescence sensors	COD (Chemical Oxygen Demand), BOD	Fluorescence quenching or emission signals vary with the concentration of organic compounds	[98]
Intrinsic fiber-optic sensors	Multiple indicators: turbidity, dissolved organics	Light scattering intensity or evanescent-field interactions indicate particulate/content changes	[98]
Graphene-metasurface optical sensor (glass substrate)	Cu^{2+}	Change in refractive index of the surrounding medium due to Cu^{2+} binding, causing shifts in transmittance resonance frequency; measured via THz/infrared transmittance drop.	[99]
Graphene-metasurface optical sensor (glass substrate)	Mg^{2+}	Similar principle: Mg^{2+} alters refractive index, shifting transmission characteristics of the metasurface; resonance shift detected via transmittance analysis.	[99]
UV absorbance sensors	BOD, COD, Total Organic Carbon (TOC)	Measured reduction in UV light transmission due to organic load	[100]
Fluorescence-based sensors	Organic compounds (e.g., tryptophan-like fluorophores), DOM	Fluorescent emission intensity correlated with organic concentration	[100]
Sensor arrays/ “electronic noses”	Headspace emissions reflecting organic pollutants	Pattern recognition of sensor array signals detecting VOCs or odors	[100]
Fiber-optic UV/Vis absorbance	Nitrate, dissolved organic carbon (DOC), turbidity	Reduction in transmitted UV/Vis light; changes reflect organic load or suspended solids	[101]
Fiber-optic fluorescence	Biochemical oxygen demand (BOD), DOM, proteins, microbial markers	Fluorescent emission intensity varies proportionally with specific organic compounds	[101]

3.1.3. Biosensors

Biosensors are advanced analytical tools widely used in healthcare, environmental monitoring, food safety, and drug discovery due to their sensitivity, rapid response, low cost, and portability [102,103]. These devices detect various targets using biological recognition elements (e.g., enzymes, antibodies, nucleic acids) and convert biochemical reactions into measurable signals. They are particularly valuable for on-site analysis and can be operated by non-experts. In wastewater analysis, biosensors help assess pharmaceutical and drug usage, offering real-time data that support public health monitoring and early warning systems for disease outbreaks. Their results also aid in evaluating the toxicity of pollutants and enhancing wastewater detection systems [104] (Table 3).

Table 3. Biosensors used for wastewater.

Transducer Type	Target Analytes	Biological Element	References
Electrochemical	BOD	*Pseudomonas aeruginosa*, *Bacillus cereus*, and *Streptomyces*	[105]
Microbial fuel cells	Heavy metals (Cd, Cu, and Zn)	Electrogenic bacteria on the anode surfaces	[105]
Optical	Ag^{+}, Hg^{+}, Co^{2+}, and Ni^{2+}	Luminous *Vibrio* sp. 6HFE	[105]
Electrochemical	SARS-CoV-2 RNA, heavy metals (Pb^{2+}, Hg^{2+}), drugs	Aptamers, DNA probes, enzymes (oxidoreductase)	[106]
Optical (SPR, fluorescence)	SARS-CoV-2 RNA, antibiotics, toxins	Antibodies, nucleic acids, aptamers	[106]
Open-type bioelectrochemical sensor (Microbial Fuel Cell—MFC)	Biochemical Oxygen Demand (BOD_5—biodegradable organic matter)	Exoelectrogenic bacteria (e.g., *Geobacter* spp.) forming a biofilm on the anode	[107]
Whole-cell transcription-factor-based biosensor	Gold ions (Au^{3+})	Genetically engineered Cupriavidus metallidurans CH34 with a CupR-regulated promoter controlling reporter gene expression	[108]
Enzymatic biosensors	Organophosphates, organochlorines, fungicides	Enzymes (e.g., acetylcholinesterase, peroxidase)	[109]
Immunosensors (optical/electrochemical)	Specific pesticide molecules (e.g., chlorpyrifos, atrazine)	Antibodies immobilized on electrode or sensor surface	[109]
Aptasensors/DNA-based	Neonicotinoids, herbicides, insecticides	Synthetic nucleic acid aptamers selected via SELEX	[109]

3.1.4. Molecularly Imprinted Polymer Sensors

Molecularly imprinted polymers (MIPs) are synthetic receptors with high selectivity and stability, making them ideal for in-field diagnostics and environmental monitoring [110]. Created through a template-assisted polymerization process, MIPs form specific binding sites that match the shape and functional groups of a target analyte. After removing the template, the polymer retains molecular cavities that enable selective re-binding [111]. MIPs are valued for their robustness, reusability, and compatibility with electrochemical sensors. When integrated into such devices, they offer a portable, sensitive, and selective solution for detecting emerging pollutants in aquatic ecosystems [112].

Moreover, the versatility of MIPs allows for the detection of a wide range of chemical classes, including pharmaceuticals, pesticides, hormones, and heavy metals. Their compatibility with various transducer platforms—such as voltammetric, impedimetric, and optical systems—further enhances their utility across different sensing environments [113,114]. Recent advances in nanomaterial integration, surface imprinting, and photopolymerization techniques have significantly improved the sensitivity, imprinting efficiency, and miniaturization potential of MIP-based sensors. Computational modeling, including molecular docking and density functional theory (DFT), now plays a key role in rational MIP design by optimizing monomer–template interactions [115]. In wastewater applications, various MIP-based sensors have been reported, as summarized in Table 4.

Table 4. Molecularly Imprinted Polymer (MIP) sensors used for wastewater.

Types of Sensors	Target Analytes	Processes that Generate the Analytical Signal	References
Electrochemical impedance sensors (EIS) with MIP-functionalized electrodes	Benzophenone-3 (BP-3), Octocrylene (OC)	Binding of UV filter molecules to molecularly imprinted cavities increases interfacial charge-transfer resistance, measurable by impedance spectroscopy	[116]
Electrochemical voltammetric + impedance sensor using MIP/Fe_3O_4 nanoparticles on a glassy carbon electrode	Emtricitabine (FTC)	DPV: Analyte binding hinders redox activity, causing decreased voltammetric peak current; EIS: Analyte binding increases charge-transfer resistance (Rct)	[115]
MIP-based electrochemical sensors (e.g., DPV, SWV, EIS)	Heavy metals (e.g., Cr(VI), Cd(II), Pb(II)), pesticides (e.g., chlorpyrifos, parathion), pharmaceuticals	Binding of analyte to MIP cavities alters electron transfer kinetics—evident in peak current changes (DPV/SWV) or increased resistance (EIS)	[117]
Ion-imprinted polymers (IIPs) on modified electrodes	Specific metal ions (e.g., Cd^{2+}, Cr^{3+})	Selective rebinding blocks redox probe access, increasing impedance or decreasing current response	[117]
MIP-integrated carbon nanomaterials (carbon paste, CNTs)	Organophosphorus pesticides (e.g., chlorpyrifos, diazinon, methyl-parathion)	Analyte binding reduces voltammetric peak height (SWV/DPV); EIS: increased R_ct from target binding	[117]
MIP-based voltammetric/potentiometric sensors on modified electrodes (e.g., GCE/ZnO/GNPs/MIP membranes)	Chlorophenols (e.g., 2,4-dichlorophenol (2,4-DCP) and other phenolic pollutants)	Binding to imprinted cavities alters electrode surface potential (potentiometric slope) or blocks redox interactions, leading to changes in peak current (voltammetry) or changes in potential response	[118]
Electrochemical MIP sensors enhanced with carbon nanomaterials or magnetic nanoparticles	Antibiotics (e.g., tetracycline, ciprofloxacin, amoxicillin)	Binding of the target molecule to the MIP cavity blocks the redox probe or alters charge transfer—detected as a decrease in voltammetric peak current or increased impedance	[118]
Magnetic MIP-based sensors (IIPs or MIPs)	Specific antibiotic molecules	Rebinding of target to imprinted sites on magnetic core@MIP blocks electron flow, raising resistance in EIS or reducing current in voltammetric readout	[118]

Table 4. *Cont.*

Types of Sensors	Target Analytes	Processes that Generate the Analytical Signal	References
Surface plasmon resonance (SPR) with nano-MIPs	Antibiotics and protein biomarkers	Binding provokes refractive index shift at sensor surface, modulating SPR angle or intensity	[118]
Conducting MIP (MICP)-based electrochemical sensors	Diverse small molecules: PFOS, biomarkers (e.g., cortisol, myoglobin), pesticides, pharmaceuticals	Conductive polymer transducer + imprint recognition: target binds to imprinted cavities within conducting polymer film; direct electron transfer yields measurable electrochemical signals (e.g., current, resistance)	[111]
Non-conducting MIP (MINP)-based electrochemical sensors	Wide-ranging analytes: phenols, hormones, antibiotics, food compounds, environmental pollutants	Non-conductive polymer layer immobilized on electrode: analyte binding alters access of redox probe, producing signal via decreased current or increased impedance	[111]

3.2. Real-Time Monitoring of Pollutants in Wastewater

Traditional laboratory-based water quality assessments relying on off-line sampling and time-consuming analysis are being superseded by modern in situ, real-time monitoring approaches, which are essential for rapid detection of pollutants and immediate response to pollution events in wastewater [119]. An AI-enabled multispectral sensor platform for real-time water quality assessment in smart urban systems, integrating an AS7265x optical module with a NODEMCU ESP8266 microcontroller, was recently developed. The system processes spectral signals from clean, polluted, and UV-disinfected water via machine learning models, Random Forest, SVM, and Neural Networks, all achieving 100% classification accuracy among water states. The setup also successfully detects spectral signatures of UV treatment and microbial pollution (*E. coli*), offering a non-contact, wireless, rapid method for continuous water quality surveillance and UV disinfection validation [120]. A 2025 study by Jørgensen et al. presents a dynamic headspace gas chromatography–mass spectrometry (DH-GC–MS) method for real-time monitoring of pollutants of emerging concern (CECs) in wastewater effluent. Targeting semipolar aromatic compounds such as UV filters, fuel-related chemicals, and odorants, the method demonstrated detection limits ranging from 15 to 3000 ng/L, influenced by analyte polarity and matrix effects. The approach enables both targeted and non-targeted screening using proprietary (MassHunter) and open-source (PARADISe) software, allowing time-resolved profiling of pollutants [121]. Likewise, Scholten et al. developed a non-contact, camera-based sensor for real-time monitoring of low turbidity (0–15 NTU) in wastewater. Using multispectral LED illumination and machine learning models, the system accurately classifies and predicts turbidity and absorbance levels, achieving over 96% accuracy. Unlike traditional sensors, it avoids fouling, requires minimal maintenance, and offers a low-cost, scalable solution for continuous wastewater quality assessment [122]. A real-time monitoring system combining deep-UV Raman and fluorescence spectroscopy with AI (CNNs) to detect micropollutants in wastewater, developed by Post et al., identified compounds like naproxen and carbamazepine at μg/L levels and achieved over 95% accuracy in nitrate detection. This non-invasive approach offers a promising tool for continuous, high-resolution water quality assessment [123]. Fluorescence-based sensors can enable real-time monitoring of pollutants of emerging concern (CECs) in wastewater, offering promising routes for integration into sensor implementations and process control strategies for water treatment systems [124].

4. Real-Time Detection of Heavy Metals Using Chemical Sensors

As noted earlier, real-time detection of heavy metals in water has become increasingly critical due to growing industrial pollution and associated toxicity risks, with electrochemical sensors enhanced by advanced nanomaterials (such as MOFs, carbon nanotubes, and quantum dots) offering sensitive, selective, and miniaturized platforms for continuous wastewater monitoring [125].

4.1. Integration with IoT for Remote Monitoring

Real-time detection using chemical sensors represents a critical advancement in modern sensing technologies, particularly when integrated with Internet of Things (IoT) systems. These sensors enable the rapid and continuous monitoring of environmental and health-related parameters, offering immediate responses to the presence of hazardous substances. Among the most concerning pollutants are heavy metal ions such as lead (Pb^{2+}), chromium (Cr^{6+}), and arsenic (As^{3+}), which pose significant risks even at trace levels due to their toxicity, persistence, and bioaccumulation potential. The ability of chemical sensors to detect these pollutants in real time allows for timely interventions, minimizing exposure and preventing long-term ecological and health damage. However, while wearable sensing systems have shown promise in detecting such ions, they often expose users to toxic environments, highlighting the need for safer, autonomous real-time sensing solutions [126]. Building on this need, recent developments have focused on integrating chemical sensors into autonomous, IoT-enabled platforms that operate without direct human intervention. These systems combine wireless data transmission, cloud-based analytics, and artificial intelligence to process complex datasets in real time, allowing for remote monitoring and predictive alerts. By embedding sensors in distributed networks such as smart water grids or unmanned monitoring stations, critical parameters like heavy metal concentrations can be tracked continuously across multiple locations. This approach not only enhances safety by eliminating direct user exposure but also improves scalability, making it possible to monitor large or hard-to-access areas effectively. As these intelligent sensing infrastructures evolve, they hold the potential to revolutionize environmental surveillance by enabling data-driven, real-time decision-making at both local and systemic levels [127]. For example, recently Lahari et al. developed an IoT-integrated electrochemical sensor enhanced with deep learning for the simultaneous detection of Cd^{2+}, Pb^{2+}, Cu^{2+}, and Hg^{2+} in water samples. Using gold nanoparticle-modified carbon thread electrodes and differential pulse voltammetry (DPV), the sensor achieved detection limits between 0.62 and 1.38 μM, with strong linearity ($R^2 \geq 0.957$) across a 1–100 μM range. Embedded machine learning models enabled highly accurate quantification, with precision, recall, and F_1-scores above 94%, and near-perfect classification of Cu^{2+}. Real-time data were streamed to a Streamlit-based IoT dashboard, offering remote access, visualization, and control, making the system well-suited for field-based environmental monitoring of heavy metals [128].

4.2. Wearable, Portable, and On-Site Devices

Recent advances in portable and wearable analytical technologies, such as smartphone-integrated sensors, microfluidic test strips, and field-deployable potentiostats, are enabling rapid, on-site detection of pollutants with high sensitivity, user-friendliness, and minimal reliance on laboratory infrastructure [129]. Moreover, recent reviews emphasize the growing shift from traditional laboratory-based heavy metal detection to portable and wearable sensor platforms capable of reliable in situ analysis. These field-ready systems, ranging from electrochemical strips and fluorescence-based assays to microfluidic lab-on-a-chip devices, offer trace-level detection of ions like lead, cadmium, mercury, arsenic, and chromium, with detection limits often comparable to those achieved in centralized labs [130]. Alqattan et al.

evaluated the accuracy and reliability of portable X-ray fluorescence (pXRF) for analyzing heavy metal concentrations, including arsenic (As), barium (Ba), calcium (Ca), copper (Cu), manganese (Mn), lead (Pb), and zinc (Zn), in surface soil samples from residential and public areas across Arizona and New York. pXRF results showed no significant differences compared to the reference technique (ICP-MS) for most elements, demonstrating strong agreement in concentration measurements [131]. Thus, the development of portable and smart devices for detecting heavy metal ions in environmental samples has the potential to replace traditional lab-based methods like ICP-MS and AAS, which, although accurate, are costly and unsuitable for field use. Several miniaturized optical and electrochemical platforms, such as fluorescence sensors, colorimetric assays, and stripping voltammetry devices, many enhanced with nanomaterials like carbon nanotubes and gold nanoparticles, have been proposed and developed. These systems offer trace-level sensitivity, often in the ppb range, and increasing integration with mobile technologies (e.g., smartphones, Bluetooth) enables real-time data transmission and remote monitoring [132].

4.3. Autonomous and Self-Powered Systems

Autonomous and self-powered sensing systems are emerging as a transformative solution for real-time environmental monitoring, offering the ability to operate independently, without external power sources, while enabling wireless, intelligent detection of hazardous substances in remote or inaccessible locations [132]. For instance, Huang et al. demonstrated a fully self-powered triboelectric nanosensor system, integrated with a thermoelectric generator, capable of wireless detection of heavy metal ions like Pb^{2+}, Cr^{6+}, and As^{3+} through a robotic "touch-and-sense" mechanism, eliminating the need for batteries or wired infrastructure [133]. Complementing this, De Vito-Francesco et al. developed an autonomous surface vehicle equipped with a microfluidic electrochemical sensor using square-wave anodic stripping voltammetry, which enabled in situ detection of lead and copper pollution plumes in surface waters, with detection limits as low as 4 μg/L for Pb^{2+} and 7 μg/L for Cu^{2+} [134]. The importance of leveraging chemometrics and multivariate data analytics to enhance sensor performance in complex environments, enabling smarter interpretation of multiplexed sensor outputs and robust detection in mixed or interferent-laden matrices, has been highlighted [135]. Other authors engineered graphene oxide-based microbots (GOx-microbots), self-propelled tubular nanoswimmers combining an outer graphene oxide layer for adsorption, a platinum inner layer for propulsion via hydrogen peroxide decomposition, and a nickel layer enabling magnetic control. These autonomous microbots removed lead (Pb^{2+}) from water at a rate ten times faster than non-motile counterparts, reducing concentrations from 1000 ppb to below 50 ppb within 60 min. The microbots were magnetically retrievable and reusable, with lead desorbed under acidic conditions achieving recovery rates up to ~95%. When tested in a microfluidic prototype, magnetic guidance effectively navigated them for pollutant capture and retrieval, demonstrating a promising automated platform for heavy metal remediation and recovery [136].

4.4. Multi-Metal Detection and Selectivity Challenges

Simultaneous detection of multiple heavy metal ions poses significant challenges in terms of selectivity and sensitivity, primarily due to mutual interferences among metal species and the limited ability of sensors to distinguish between ions with similar electrochemical properties [137]. This challenge is particularly acute in real-world matrices such as wastewater or food samples, where competing ions and organic matter can obscure or distort sensor responses. Recent advances have focused on multiplexed sensing strategies leveraging quantum dot-based fluorescent probes and nanomaterial-enabled platforms,

which offer enhanced discrimination among heavy-metal ions through distinct optical or electrochemical signatures. These systems often integrate ratiometric or multi-emission quantum dots with functional components such as tailored ligands, DNAzymes, or molecularly imprinted polymers to enable the simultaneous and selective detection of ions like Cd^{2+}, Pb^{2+}, Hg^{2+}, and Cu^{2+}, while minimizing cross-interference [138].

In addition to quantum dot-based systems, other nanomaterials such as carbon dots, nanozymes, and metal–organic frameworks (MOFs) have been used to enhance selectivity and sensitivity in complex matrices. These materials support various detection modalities—electrochemical, fluorescent, or colorimetric—with some sensors reaching sub-ppb (parts per billion) detection limits for multiple ions simultaneously. However, significant obstacles remain, including the suppression of non-specific responses, signal overlap, sensor fouling, and long-term stability under practical environmental conditions [139]. Complementing these innovations, traditional analytical techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma optical emission spectrometry (ICP-OES), X-ray fluorescence (XRF), and atomic force microscopy (AFM) remain indispensable for heavy metal analysis, particularly in wastewater. These methods offer excellent sensitivity and multi-element capability, often achieving detection limits below µg/L. Although not suitable for on-site use due to cost and operational complexity, they serve as benchmarks for calibrating and validating emerging sensor technologies [140]. Overall, the development of portable, selective, and interference-resistant sensors for multi-metal detection remains a central goal. Future progress will likely rely on smart hybrid systems that combine advanced nanomaterials, robust signal-processing algorithms, and miniaturized detection platforms suitable for in situ monitoring in diverse environmental settings.

4.5. Data Processing and Predictive Analysis

Predictive analysis for heavy metals in wastewater has significantly advanced through the application of machine learning and deep learning techniques, which offer high accuracy, cost-effectiveness, and scalability compared to traditional laboratory-based methods. Recurrent neural networks, particularly Gated Recurrent Units (GRUs), have demonstrated superior performance over conventional neural networks in forecasting the concentrations of heavy metals such as Cu, Zn, Ni, and Cr, using easily accessible urban and environmental input variables such as conductivity, pH, temperature, and flow rate. These models allow for real-time, low-cost predictions and can be deployed as soft sensors in industrial wastewater systems. Additionally, interpretability tools like SHAP (Shapley Additive Explanations) help identify the most influential parameters while eliminating redundant inputs, thereby enhancing model transparency and efficiency [141]. Complementary to this, CatBoost models have been successfully applied to predict the removal efficiency of metals such as Cd, Cu, Pb, and Zn in sulfate-reducing bacteria (SRB) systems. These models achieved high predictive accuracy (R^2 = 0.83–0.92), outperforming other algorithms, and identified key factors like temperature, pH, sulfate concentration, and the chemical oxygen demand-to-sulfate (COD/SO_4^{2-}) ratio as critical to optimizing biological metal removal. Operational optimization was most effective at ~35 °C and sulfate concentrations between 1000 and 1200 mg/L [142]. Meanwhile, remote sensing technologies integrated with machine learning have emerged as promising tools for large-scale heavy metal monitoring in aquatic systems. Spectral reflectance in the 600–810 nm range, often correlated with total suspended matter (TSM), can be used to estimate metal concentrations (e.g., Cu, Cd, Pb). Advances in hyperspectral imaging and deep learning algorithms are enhancing detection accuracy, although their widespread adoption is still constrained by limited availability of labeled training data [143].

Furthermore, ensemble machine learning models, including Random Forest, AdaBoost, Gradient Boosting, XGBoost, and LightGBM, have been used to predict heavy metal adsorption efficiencies (Pb, Cd, Ni, Cu, Zn) based on the physicochemical properties of biochar. Among them, XGBoost demonstrated the highest predictive power ($R^2 \approx 0.92$), with the initial metal-to-biochar concentration ratio and pH emerging as the most influential variables. Interestingly, features like surface area and pore volume contributed minimally, suggesting a shift toward more functionally relevant descriptors in model development. This approach supports the data-driven design and operational control of adsorption-based remediation technologies [144]. Lastly, computational geochemical modeling of trace metal speciation (e.g., Al, Co, Cr, Cd, Fe, Cu, Ni, Zn, Pb, and Ti) provides mechanistic insight into the fate and transformation of metals in wastewater treatment systems. By simulating accumulation and mobility within activated sludge and biofilm systems via mass balance equations, these models aid in optimizing treatment processes and can be integrated with machine learning to enable adaptive control strategies under varying operational conditions [145].

5. Challenges and Future Perspectives

The real-time detection of heavy metals in wastewater presents both significant opportunities and complex challenges, particularly in the context of antimicrobial resistance (AMR). Heavy metals such as Cd, Pb, Cu, and Zn are not only environmental pollutants but also co-selective agents that promote the persistence and dissemination of antibiotic resistance genes (ARGs) through horizontal gene transfer mechanisms. This co-selection effect is further intensified in the presence of microplastics, which act as carriers for both metals and resistant bacteria, supporting biofilm formation and gene exchange [22]. Wastewater-based epidemiology (WBE) has emerged as a promising strategy for community-level surveillance of ARGs; however, current limitations, such as lack of standardization, real-time integration, and insufficient sensitivity in complex wastewater matrices, restrict its applicability in early warning systems [23]. Real-time chemical sensors offer a compelling solution but face technical obstacles including limited selectivity, sensor fouling, cross-interference, and challenges in maintaining long-term stability and reproducibility, especially when exposed to harsh environmental conditions or high concentrations of interfering substances [32]. Several emerging strategies show potential as follows: (i) the development of multi-analyte sensor arrays capable of simultaneously detecting heavy metals and ARG-related biomarkers; (ii) integration of sensor outputs with AI-powered data analytics, such as machine learning models that can filter noise, detect trends, and trigger alerts in real time; (iii) embedding sensors into WBE frameworks to support dynamic surveillance of AMR at the population level; and (iv) embracing a One Health approach, linking environmental monitoring with public health, veterinary, and agricultural practices to control AMR at its environmental source [15]. Ultimately, bridging sensor innovation with microbial risk monitoring offers a strategic opportunity to mitigate antibiotic resistance spread through wastewater pathways, an urgent frontier in global health and environmental protection.

6. Conclusions

The growing body of evidence linking heavy metal pollution in wastewater to the selection and spread of antibiotic-resistant bacteria (ARB) highlights the urgent need for real-time monitoring strategies. Chemical sensors, including electrochemical, optical, biosensors, and molecularly imprinted polymer (MIP)-based platforms, have demonstrated increasing potential for rapid, sensitive, and in situ detection of heavy metals under complex environmental conditions. This review has shown that the integration of these sensors with Internet of Things (IoT) technologies, autonomous systems, and data analytics enhances

their functionality for remote, continuous, and cost-effective monitoring. Advanced data processing methods, including machine learning algorithms, further enable predictive analysis and support early-warning systems for pollution control. However, significant challenges remain: ensuring multi-metal detection with high selectivity in complex matrices, maintaining long-term sensor stability, reducing interference from organic and inorganic constituents, and achieving large-scale deployment in real settings. Additionally, the role of heavy metals in co-selecting antibiotic resistance genes (ARGs) calls for a One Health perspective, where environmental sensing contributes directly to public health surveillance. Future research should align with ongoing efforts to develop integrative, real-time wastewater surveillance systems capable of simultaneously monitoring chemical pollutants such as heavy metals and genomic signatures of pathogenic microorganisms, thereby enabling early warning strategies for both environmental pollution and emerging public health threats.

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