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Review

Heavy metals in the environment: Detection techniques and toxicity

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Abstract: Heavy metals are characterized by their relevance, toxicity, and capacity to accumulate in the natural environment. Therefore, their emission into the air can cause long-term environmental hazards. In addition, they can be transported in the atmosphere over long distances and deposited in regions far from the emission location. Among the pollutants currently implicated by their toxicity in the environment, we can cite, in order of importance, mercury, cadmium and lead, which are currently a matter of concern. Mercury is transported over long distances in the atmosphere, and its biotransformation into toxic methylated compounds and bioaccumulation in the trophic chain have made it a major pollutant. Cadmium, which is relatively rare and is mainly found in ores, is considered one of the most toxic metals. Its accumulation in different types of sediment and its capacity for remobilization constitute particularly worrying risks. Finally, although Pb is less toxic than Hg and Cd, it is very abundant in its natural state and is used in large quantities in industry, which makes this ubiquitous toxin a permanent threat to the health of populations. This review provides an analysis of the occurrence of heavy metals in the environment, including Cu, Pb, Ni, Hg, Cr, Zn, Fe, and Cd, their toxicity potential, their impact on human health, and detection technologies using Field-Effect Transistor (FET) sensors.

Keywords: heavy metal; toxicity; pollutants; detection techniques; sensors

1. Introduction

The presence of heavy metals in the environment poses a direct threat to ecosystems as a result of industrial discharges into the air, water, and soil [1].

These discharges are generally characterized by a high presence of inorganic pollutants, which multiplies the risk of heavy metal contamination [2]. The release of these heavy metals into groundwater and soil pollutes the environment and renders it highly toxic due to their high degree of toxicity [3].

Some metals, such as Cu, Zn, Co, Fe, and Mn, are essential for cellular metabolism and act as enzyme cofactors [4]. Some others, such as Cd, Pb, Hg, and Ag, are toxic to living organisms; they inhibit enzymatic activity [5,6]. Unlike organic pollutants, Pb, Cd, Cu, Zn, and Hg cannot be biodegraded, and therefore persist in the environment for long periods [7]. Heavy metals are defined as metallic elements with a density greater than 5 g/cm^3, including Cd, Hg, Pb, Cu, Ni, Zn, Co, Mn, and Cr. They are most often present in trace amounts in the environment. In the Earth's crust, heavy metals are present in the form of ore, from which they can be mobilized by natural phenomena such as erosion or volcanic eruptions, but also by anthropogenic activities. These metals, naturally present at very low concentrations in living tissues, have a high ecotoxicity and could be involved in many pathologies (damage to the central nervous system, liver, kidneys, cancers, and embryonic malformations) [8].

In addition, they are continually added to the soil through various activities, such as the application of sewage sludge or in the metallurgical industry, and the accumulation of heavy metals in the environment can have repercussions on human and animal health [9]. The latter is due to physical discharges linked to metallurgical and mining activities, and to discharges of end-of-life products such as batteries. Atmospheric emissions are a major source of heavy metal pollution. Although many organic molecules can be degraded, heavy metals cannot, and their concentrations increase regularly in soils and water [10,11].

The most toxic compounds are Cd, As, Pb, and Hg. These elements are naturally present in the Earth's crust and in all living organisms at varying concentrations depending on the environment and organisms. Most of the data published thus far on the effects of metals on aquatic organisms indicate that these harmful effects occur at concentrations higher than those generally found in the environment [12,13]. To date, the different health consequences of heavy metals have been studied. Iron is associated with cardiomyopathy; however, excessive iron deposition in heart tissue causes damage, aluminum in the brain tissue is linked to Alzheimer's disease or dementia, mercury accumulation in the brain has been linked to autism spectrum disorders, with epidemiological, toxicological, and clinical studies highlighting significant correlations and parallels with mercury intoxication, and lead in bones can interfere with the production of red blood cells or white blood cells [14].

Traditional methods for detecting heavy metal ions include inductively coupled plasma optical emission spectroscopy (ICP-OES) and inductively coupled plasma mass spectroscopy (ICP-MS). In recent years, the development of effective techniques for the decontamination of polluted sites has become indispensable, and many traditional analytical techniques have been proposed, such as chromatography or spectrometry (gas chromatography coupled with mass spectrometry (GC-MS)), high-performance liquid chromatography (HPLC) coupled with mass spectrometry (HPLC-MS), atomic absorption spectrometry (AAS) or inductively coupled plasma spectrometry (ICP-MS), and *X*-ray fluorescence, and ion-selective electrodes; however, there are still some critical problems to be solved, such as lack of flexibility, the need for competent requirements, expensive and complex instruments, and long response times. Therefore, it is highly desirable to develop a fast and easy-to-implement analysis platform based on simple concepts, it must allow the simultaneous analysis of a large number of samples in real time and therefore the acquisition of numerous data to detect heavy metal ions.

This paper focuses on eight heavy metals—cadmium, iron, chromium, copper, zinc, nickel, lead and mercury, which are notorious for their high toxicity and the challenges associated with treating compounds containing these metals. Building upon both existing and ongoing research, this study aimed to explore innovative solutions for minimizing metal pollution. A key aspect of this study is the use of Field-Effect Transistor (FET) technology as a recovery method, providing a promising route for these metals to be redirected toward other beneficial applications. Ultimately, the goal is to promote sustainable development by enhancing human well-being, protecting the environment, and fostering economic benefits through efficient metal recovery strategies.

2. Source and toxicity of heavy metals in the aquatic environment

Natural and anthropogenic sources of heavy metals

Heavy metals are naturally redistributed in the environment through geological and biological processes. However, industrial and technological activities reduce the residence time of metals in rocks, form new metallic compounds, and introduce metals into the atmosphere through the combustion of fossiliferous products [15]. It is necessary to differentiate the part resulting from contamination of human origin (anthropogenic) from the natural part (geogenic) [16]. Some significant sources of heavy metal ions are presented in **Figure 1**.

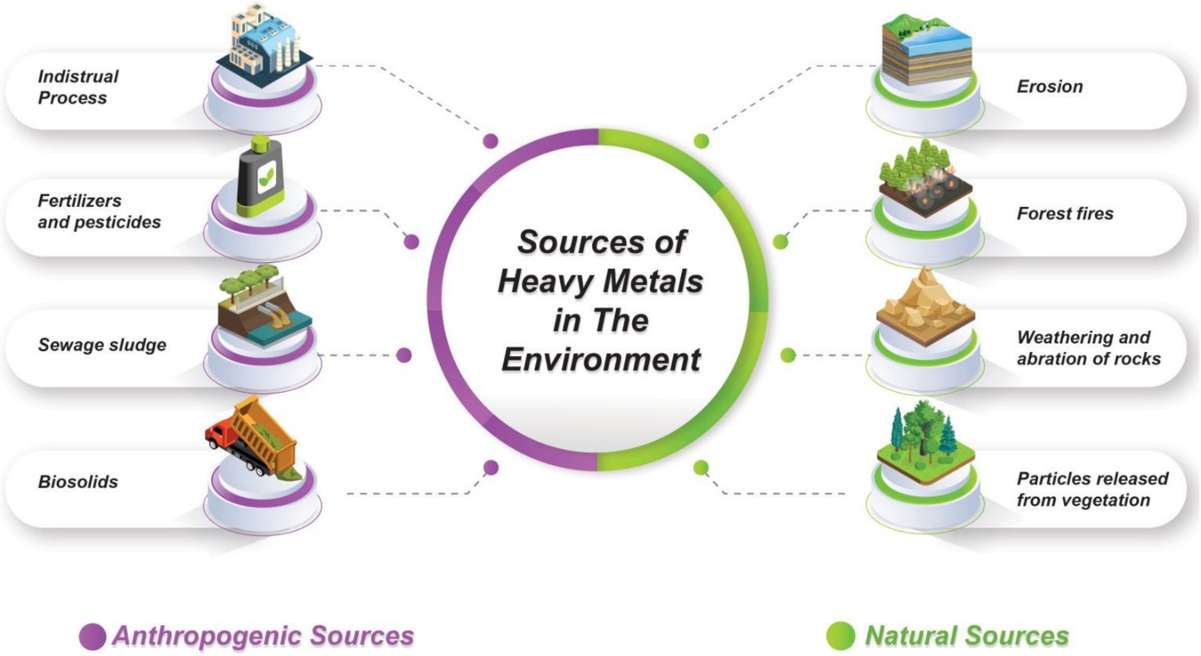

Figure 1. Heavy metal sources in the environment.

a) Natural sources

Heavy metals are found in all environmental compartments. The largest reserves are found in rocks and ocean sediments. Natural deposits are sources of water contamination in the following situations [7].

- Mining;
- Erosion transports metals to soils, surface waters, and sediments;
- Terrestrial or underwater volcanic eruptions;

It is estimated that, on average, 800 to 1400 tons of cadmium are released annually worldwide, and once in circulation, the metals are distributed in all compartments of the biosphere: Land, air, and [17,18].

b) Anthropogenic sources

Pollution of human origin, called anthropogenic pollution, originates from multiple daily human activities. For example: Industrial activities and chimneys, exhaust fumes from cars and trucks, agriculture, power plants that run on coal, oil or gas, mining activities, landfills [19].

It is often difficult for nature to adapt to all of these additional pollutants, and high concentrations of pollutants can be found on a large scale [20].

Anthropogenic pollution can also be divided into two groups according to emission characteristics:

- Controlled emissions, which are authorized by law and are placed under the supervision of specialists,
- Accidental emissions that occur during the destruction of old buildings, quarrying, industrial disasters, or leaks that factories may have.

3. Types of heavy metals and their effects

Cadmium (Cd): Cd has a high resistance to corrosion; its melting point is low; it has good electrical conductivity; its derivatives have good resistance to high temperatures; and they have chemical characteristics close to those of calcium, particularly the ionic radius, thus facilitating their penetration into organisms. Industrial activities, such as the refining of non-ferrous metals, combustion of coal and petroleum products, household waste incinerators, and steel metallurgy are the main sources of cadmium released into the atmosphere [21]. In water, Cd comes from natural erosion, soil leaching (phosphate fertilizers), industrial discharges, and the treatment of industrial and mining effluents. Cd is also one of the most dangerous heavy metals. Even at low concentrations, it tends to accumulate in the renal cortex over very long periods (50 years), where it causes abnormal loss of proteins through urine (proteinuria) and causes urinary dysfunction in the elderly [22].

Copper (Cu): Cu is one of the most widely used metals because of its physical properties, particularly its electrical and thermal conductivities [23]. It is widely used in the manufacture of electrical equipment (wires, motor windings, dynamos, and transformers), plumbing, industrial equipment, the automobile industry, and boilermaking. Copper is present in the environment, and its concentration in the Earth’s crust is estimated to be approximately 70 ppm (30 to 100 ppm) [24]. Transport by wind, dust, soil, volcanic eruptions, plant decomposition, forest fires, and aerosols is the main natural source of exposure. In water, copper comes mainly from soil erosion by watercourses (68%), contamination by copper sulfate (13%), and wastewater discharges that still contain copper even after treatment [25]. Cu is an essential element in humans and animals (trace elements) and is involved in many metabolic pathways, including the formation of hemoglobin and the maturation of polymorphonuclear neutrophils. In addition, it is a specific cofactor for many enzymes and structural metalloproteins. However, excess copper produces free radicals responsible for cellular damage to DNA and organelles such as mitochondria and lysosomes [26–28].

Iron (Fe): Fe is an essential metal used in many alloys, including stainless steels. It is used in machines and various utensils used daily, as well as in the infrastructure of the modern world. Iron is ranked fourth among the elements of the Earth’s crust in order of abundance, and its presence in water can have various origins: leaching of land with dissolution of rocks and ores contained in the subsoil, industrial discharges (mining, metallurgical, steel industry pollution), corrosion of metal pipes (cast iron or steel), or existence of previous deposits [7]. The regulation of iron in blood is controlled by two absorption and export proteins. Iron deficiency or excess can be potentially toxic to cells, which is why iron transport is rigorously controlled. Low iron levels in humans cause anemia, which is one of the most widespread public health problems that can be attributed to nutritional causes, including iron deficiency, inflammatory or infectious disorders, and blood loss [29].

The main toxicity mechanism of iron is its ability to induce the formation of free radicals, resulting in lipid peroxidation. Iron poisoning is described as evolving into five phases: Digestive disorders, transient clinical improvement, systemic toxicity with shock, metabolic acidosis, coma, hepatic toxicity with coagulopathy, and digestive sequelae such as stenosis. Apart from symptomatic treatment, treatment includes digestive decontamination with intestinal irrigation and chelation with deferoxamine [30]. Chronic exposure to iron is mainly of occupational origin and results in overload pneumoconiosis following inhalation of iron dust and oxides. Ocular siderosis is a serious chronic condition that can lead to vision loss in the affected eye. It occurs when a foreign body containing iron enters or comes in contact with the eye [31,32].

Lead (Pb): Pb is a chemical element found in most surface soil layers worldwide, with a typical average concentration of 32 µg/L and ranging from 10 to 0.67 µg/L [33]. Lead ranks fifth among Fe, Cu, Al, and Zn in the industrial production of metals. It has been used for a long time and in many areas, including paints, water distribution networks, stained glass, solders, automotive fuels, and batteries for motor vehicles. Because lead compounds are poorly soluble and non-volatile, their environmental sinks are sediment and soil. Pb is very poorly mobile in soils over a wide pH range from 5 to 9 [34]. Its mobility increases sharply when the pH drops to 4 [35]. Its high affinity to organic matter explains its accumulation in the surface soil horizons and its non-migration into the lower horizons. Pb is not an essential element. It is known to be toxic, and its effects have been examined more thoroughly than those of other trace metals. It is absorbed into the body via three 3 exposure routes (ingestion, inhalation, and cutaneous). Consequently, poisoning can occur during exposure to food, dust, or cosmetic products. Lead is stored in bones and teeth and slowly diffuses into the body. It can cause serious damage to the brain, nervous system, red blood cells, and kidneys [36].

Zinc (Zn): Zn is the most abundant mineral after iron. The most widespread ore is sphalerite or blende (zinc sulfide) [37]. This ore also contains iron and cadmium, which cause toxicity during zinc extraction. The major waste product from this industry is jarosite [38]. This solid is dangerous for the environment because of the presence of Cd, Pb, and Zn. Exposure sources are present in all applications of zinc (industrial, agricultural, medical, veterinary). Zinc and lead mining, zinc refining, electroplating, phosphate fertilizers, insecticides, and pigments are sources of zinc pollution [9]. Toxicity can affect different organs and reproduction, and can be carcinogenic. These toxic effects depend on the route and level of exposure as well as the species considered [39].

Zinc has three routes of entry into the human body:

- Inhalation of zinc-containing dust is generally industrial and mainly affects workers. The most frequent consequence of inhalation is an acute illness that presents with a variety of symptoms, including fever, muscle pain, nausea, fatigue, and respiratory problems. Respiratory effects generally disappear within one to four days.

- Skin contact. Irritation was observed, depending on the type of zinc involved. Zinc chloride was clearly the most irritating zinc species, followed by zinc acetate and zinc sulfate. In principle, ZnO does not have an irritating effect on the skin.

In contrast to the potentially harmful effect of zinc on the skin described above, it should be noted that zinc is a well-known supplement for the topical treatment of wounds and several dermatological conditions.

Owing to its nature as an essential trace element, the oral absorption of small amounts of zinc is essential for survival. The Recommended Dietary Allowance (RDA) for zinc is 11 mg/day for men and 8 mg/day for women. These values are well below the LD50 value (Lethal Dose 50: This indicator measures the dose of substance causing the death of 50% of a given animal population (mice or rats)), which has been estimated to be 27 g of zinc per day. In general, the absorption of such a quantity is unlikely, as it corresponds to an absorption of 225–400 mg of zinc, and immediate symptoms following absorption of toxic quantities of zinc are abdominal pain, nausea, and vomiting. Anemia and dizziness were observed [40].

Chromium (Cr): Cr is a hard, steel-gray metal. The main characteristic is that it resists tarnishing and corrosion. Oxidation states +4 to +6 are the most common. Hexavalent chromium is particularly oxidizing, whereas divalent chromium is a reducing agent. It is most frequently used in metallurgy to provide a shiny finish, in addition to improving corrosion resistance [41]. Chromium, particularly tetravalent chromium, is a toxic metal in humans. Its toxicity is highly dependent on its form, such as nanoparticles, oxides, and valence. It is bioaccumulated in certain organisms, such as food plants. However, trivalent chromium is essential and its deficiency can have consequences for the heart or diabetes. Excess inhaled pentavalent chromium can cause nosebleeds or nasal irritation. Its mode of action is not fully understood, but it is known that Cr acts as a cofactor of insulin, thus facilitating the assimilation of glucose by cells [42–44].

Nickel (Ni): Ni is a chemical element that is omnipresent in our environment, as it is used in the manufacture of stainless steel, non-ferrous alloys (coins, kitchen utensils, guitar strings, etc.), and Ni-Cd batteries. It has also been used as a catalyst in organic chemistry. Finally, nickel is released during the incineration of household waste and combustion of coal and fuel. In nature, nickel can be found in different oxidation states (+II, +III, and +IV) but is mainly found in its +II state. The chemical forms of Ni in the soil are Ni^{2+}, $NiSO_4$, $NiHCO_{3+}$, and $NiCO_3$ [45–47]. Thus, nickel compounds of the acetate, chloride, nitrate, and sulfate types are highly soluble, followed by carbonates and hydroxides, sulfides, and disulfides, whereas oxides are practically insoluble. Like other metals, its mobility increases with the acidic nature of the medium; we also see that when the concentration of sulfate in the medium increases, this leads to a decrease in adsorption by complexation and therefore, an increase in mobility. Nickel compounds are mainly absorbed by humans via the respiratory tract and can cause chronic bronchitis and asthma [48–50].

Mercury (Hg): Hg is a hazardous heavy element that is abundant in nature. The majority of human exposure comes from eating fish or using dental amalgams [51]. Mercury can be found in various forms such as inorganic mercury (metallic, vapor, mercuric salts, and mercury dioxide), organic mercury (which includes compounds in which mercury is bonded to a structure containing carbon atoms), and mercury in the form of compounds (methyl, ethyl, phenyl, or similar groups) [52]. Elemental and methyl mercury are toxic to the central and peripheral nervous systems. Inhalation of mercury vapor can have harmful and fatal effects on the nervous, digestive, and immune systems, as well as on the lungs and kidneys. Inorganic mercury salts are corrosive to the skin, eyes, and gastrointestinal tract, and can be toxic to the kidneys if ingested [53].

3.1. The impact of heavy metals on the environment

The use of heavy metals is the result of urbanization and industrialization. These can generate three types of pollution: Soil, water, and air. When present in soil, they are not degradable, affect the biodegradability of organic pollutants [20], and their toxicity can increase by reacting with other components. Water pollutants are transported over long distances and introduced into sediments or on the surface. Passing into the food chain by direct or indirect ingestion presents risks to the entire biosphere. Finally, heavy metals can be present in the atmosphere in different forms (particles, droplets, gaseous form, etc.) and cause acid rain and serious health problems [54].

All chemical substances present in soil, air, and water are potential sources of contamination by living organisms. Recall that bioaccumulation occurs in two ways: Direct (bioconcentration) and indirect (bioamplification). In the first case, the organism absorbs the pollutants present in the air, water, or soil through respiratory or cutaneous routes. Second, they absorb them trophically via an already contaminated diet. Pesticides, insecticides (DDT), fertilizers (nitrates and phosphates), hydrocarbons, drug residues, household products and other micropollutants such as flame retardants, plastics or glue residues. These harmful materials, resulting from our production and consumption cycles, are released into the environment [55,56]. However, it is important to note that many of these chemical substances degrade very slowly and can persist for many years or even decades. This is the case for DDT, which, even 50 years after its ban on agriculture, still contaminates ecosystems and thus fuels bioaccumulation.

The toxic molecules contaminate soil, air, and water (rivers, seas, and oceans) before being absorbed by bioconcentration or bioamplification by aquatic and terrestrial plants, fungi, insects, birds, fish, mammals, and humans [57]. Between contamination by direct contact with air or water and absorption by trophic networks, living organisms can concentrate large quantities of polluting materials. **Figure 2** outlines the health risks associated with heavy metal ions in the human body.

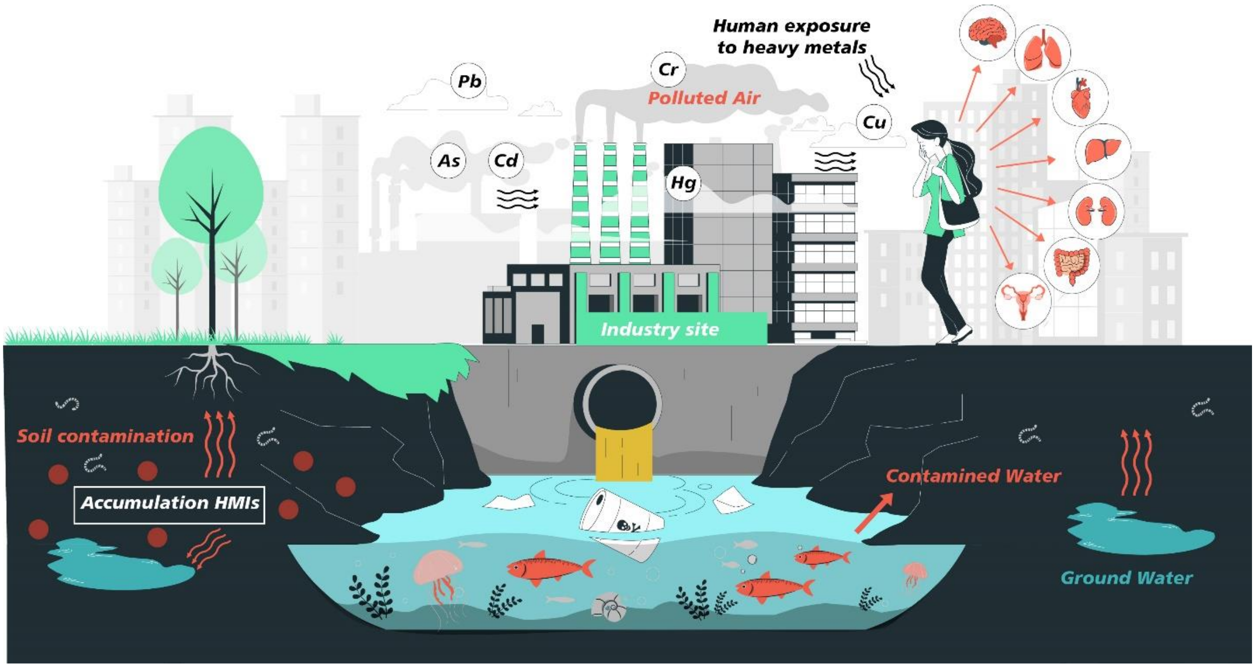

Figure 2. Impacts of heavy metals toxicity on human health.

3.2. Soil contamination

All the soils naturally contained trace metal elements. Soil contamination occurs when the trace element content is higher than the natural concentration but does not influence soil quality. The natural concentration of trace elements in the soil results from their evolution from the initial rock. Soil pollution by trace elements occurs when trace elements are present at a dose that threatens biological activity or soil functions [58]. Diffuse contamination, which affects the surface levels of soils, results from natural phenomena, such as atmospheric fallout of volcanic aerosols, or from intentional or unintentional anthropogenic actions, such as dust and atmospheric deposits, mineral fertilizers (copper contained in phosphates), pesticides, slurry and manure, sludge from sewage treatment plants, mining activities, industrial (buildings) or urban waste, and transport [59,60].

Precipitation and irrigation are the main sources of soil water. Some were evacuated by evaporation or surface runoff. Some of it penetrates the soil and then heads either towards the roots of plants or, by gravity, towards deep horizons and water tables. During this transport, water is loaded with dissolved trace elements [61].

3.3. Air contamination

Heavy metals are dispersed in the upper layers of the atmosphere and fall elsewhere after being transported over very long distances. It is estimated that a particle of mercury in the atmosphere remained in it for a year before falling back [62,63]. Heavy metals in the air can be found in two main forms:

- Either in gaseous form for certain volatile metal compounds or those with a high saturated vapor pressure
- In the form of solid metal compounds deposited on very fine particles or dust formed during combustion. The main sources of metals in the air are fixed

sources. Heavy metals are transported by atmospheric particles from high-temperature combustion, metallurgical fusion, and vehicles [64].

3.4. Water contamination

Heavy metals present in water and sediments are absorbed by marine plants and animals, and exceeding a given quantity in these species causes their accumulation in organisms and throughout the food chain. They can reach concentrations that threaten the survival of certain natural populations and present dangers for consumers of marine products due to their possibility of concentration in marine species, their difficult elimination, and their wide distribution in the aquatic environment. In the 1950s, their highly harmful effects were highlighted following fatal poisoning that occurred in Minamata, Japan. The inhabitants had eaten fish contaminated by mercury discharged from a nearby factory. This disease spreads to the entire younger generation via breast milk [65].

The indirect effects of heavy metal contamination can be devastating. For example, pollution of waterways can make surrounding wetlands inhospitable to aquatic species and migratory birds that depend on them. In addition, the loss of plant biodiversity owing to heavy metal toxicity can reduce soil quality and affect nutrient cycles and ecosystem productivity.

4. Proposed solution against metal pollution: FETs sensor

The application of pollution control methods has proved to be very effective especially at the local level, where it is important to design the assessment and control of point and non-point sources of pollution in a global perspective. The application is based on a systematic analysis of the source and nature of the release, its interaction with the environment, and the development of appropriate techniques to mitigate and monitor impacts. Nanomaterials, in addition to their use in electrochemical approaches, have opened new possibilities for water pollutant detection owing to their unique electrical characteristics (**Figure 3**). New channel materials have been studied to meet this type of need: We can cite semi-conductor oxides, carbon nanotubes or graphene and WSe_2 nanosheets by various electronic sensors as field-effect transistor (FET) sensors [66,67]. Nanomaterial-based FET sensors often exhibit high sensitivity and quick response to water pollutants, owing to their high carrier mobility and sensitivity to electronic disturbances. These distinct qualities enable the quick identification of water pollutants, overcoming the limitations of traditional sensing methods. When contaminants bind to the sensing material surface, electrical measurements for analytical purposes have been widely used for many applications, including environmental monitoring (detection of heavy metals, organic pollutants, etc.), industrial quality control, and biomedical analysis (disease biomarkers, biological substances, etc.). Because the amplitude of the conductivity shift is generally proportional to the pollutant concentration, FET sensors might also quantify the contaminants in water [68,69].

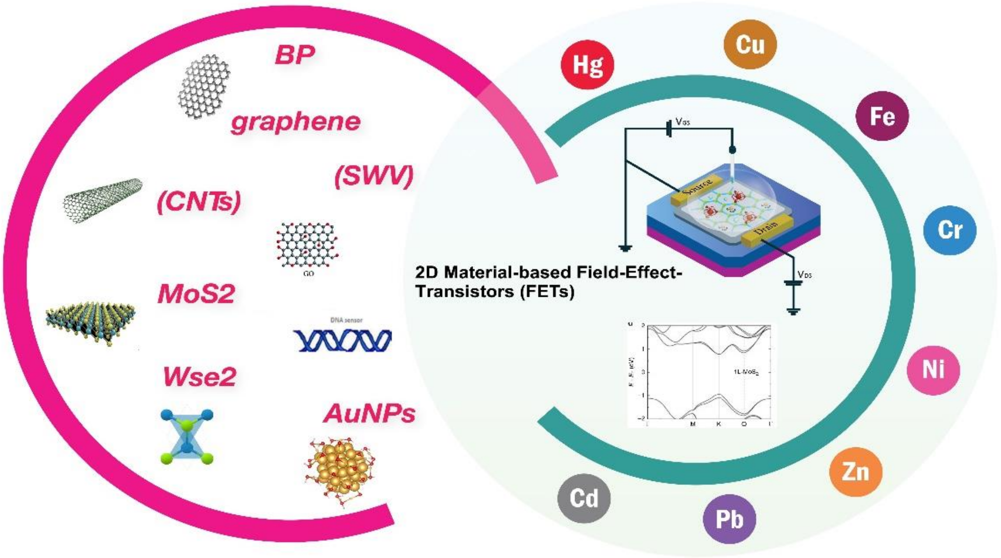

Figure 3. Overview of sensors based on FETs categorized into the following sections.

There are three general classifications of polluted water treatment operations and processes, between physical, chemical and biological [70–72]. Great advances have been made in instrumentation, but the presence of interfering compounds greatly impairs the sensitivity of the devices, which also require a great deal of expertise at high cost. Before detection, a separation and concentration step may be considered. We therefore reach problems of selective treatment of metals, necessary for their upgrading. A cross-sectional view of a field-effect transistor (FET) is featured in **Figure 4**.

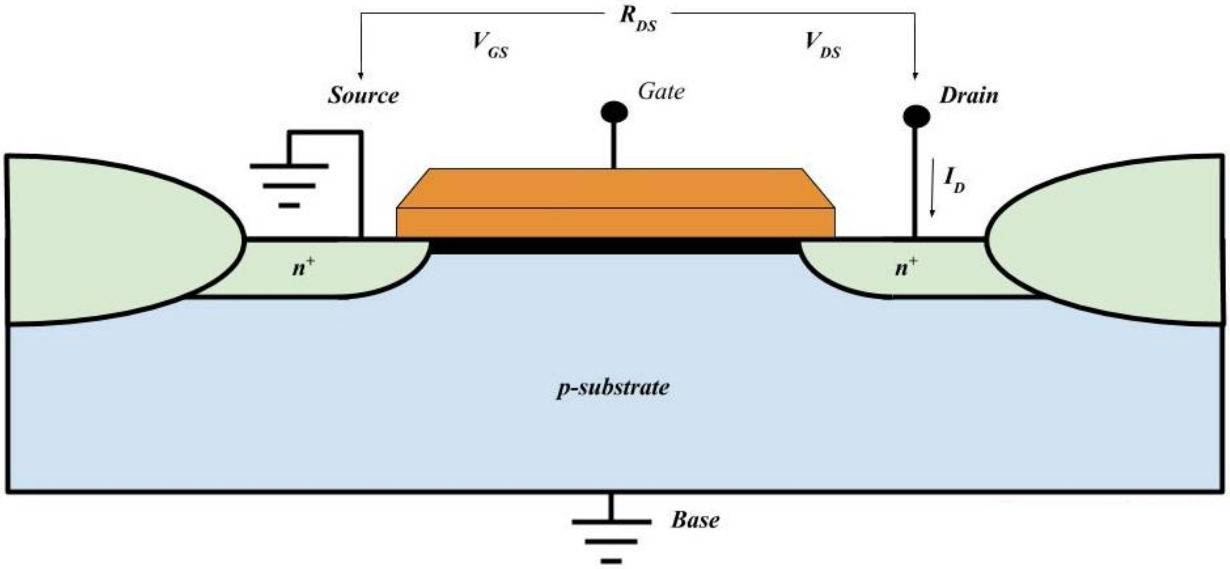

Figure 4. Cross-sectional view of a field-effect transistor (FET) [73].

Field-effect transistors (FET) use an electric field to control the conductivity of a semiconductor channel, thereby facilitating the flow of electronic current. This makes it crucial for the fabrication of integrated circuits, which play a key role in amplifying and switching electrical signals. FETs are prioritized for their low power consumption and high input impedance, making them essential in modern technologies. Two major types of FET transistors available commercially exist. These are Metal-Oxide-Semiconductor FET (MOSFET) and Junction FET (JFET) transistors. The structural properties of MOSFET transistors include metals, oxides, and semiconductors. The properties of the JFET transistors are those of the PN junctions that they are made of [57].

FET types are also known as unipolar transistors (involve single-carrier-type operation) and are famous for being considered as attractive potentiometric bio and/or chemical measurement devices thanks to their fast response, low output impedance and potential for miniaturization in standard integrated circuit manufacturing technologies.

Many scientific researchers are focalizing on the use of FET sensors for the removal of heavy metal ions. In fact, Sayyad et al. attempt to remove Pb^{2+} and Cu^{2+} ions from aqueous medium and in ambient temperature by FET sensor based on L-Cysteine composite material, reaching a limit of detection of 2.36 µg/L and 0.33 µg/L [74,75]. Nigam et al. published a paper treating the same metals, his work consists of eliminating the six metal ions from water systems by developing semiconductors (metal oxides, transition metal dichalcogenides, and graphene), playing on their physico-chemical properties such as electron transfer kinetics, powerful adsorption ability, energy storage, mechanical strength and thermal conductivity and concluded by underlining the necessity to study the lifetime of the sensor, the time and accuracy of detection and their connection to smart systems [76].

Among the nanomaterials, metal nanoparticles have attracted wide interest as nanosensors, biomarkers, and catalysts. The enormous use of these nanoparticles for sensor development is explained by their large surface-to-volume ratio, surface reaction activity, high electrical conductivity, and high catalytic capacity [77,78].

Carbon nanomaterials also have several advantages such as ease of preparation, renewability, mechanical and chemical stability, and high electrical conductivity. In addition, they can functionalize surfaces with different functions. Moreover, they are widely used in the modification of various electrodes to improve their sensitivity and achieve low detection limits [79].

Table 1 highlights some performance in terms of reaction time and detection limit (M in mol/L). According to some studies of the sensing mechanism analysis, producing films with a larger band gap, better carrier mobility, and a smaller film thickness might result in a lower limit of detection (LOD) and higher sensitivity. The degree of decrease can be used to tune the bandgap of rGO. The low stability of BP in the ambient environment owing to oxidation is difficult; however, it might potentially be solved by using a passivation layer or encapsulation to prevent BP from being exposed to O_2, thereby enhancing the sensor stability.

Table 1. 2D nanomaterial-based FET sensors and their application in aqueous sensing.

Channel material	**Key sensing structure**	**Target**	**LOD**	**Advantages**	**Disadvantages**	**Ref**
Monolayer rGO	rGO/AuNPs/GSH	Pb^{2+}	10 nM	quick response, good selectivity		[80]
Monolayer rGO	rGO/TGA/Au NP	Hg^{2+}	25 nM	quick response, good selectivity		[81]
Monolayer rGO	rGO/ferritin/FET	HPO$_4^{2-}$	26 nM	quick response, good selectivity		[82]
Mono and multilayer graphene	DNAzyme AuNP graphene	Pb^{2+}	20 pM	high selectivity, extreme sensitive	long response time (20 min)	[83]
Multilayer-rGO	MT-II functionalized	Hg^{2+} and Cd^{2+}	1 nM, 1 nM	rapidly, sensitive	lack of selectivity	[84]
Large sized graphene film	anti-E. coli antibody functionalized	E.coli	10 cfu/mL	fast, label-free		[85]
Multilayer MoS$_2$	MoS$_2$/AuNPs/DNA	Hg^{2+}	0.1 nM	higher sensitivity that rGO		[86]
Four-layer MoS$_2$	MoS$_2$/HfO$_2$/biotin	streptavidin	100 fM	73-times higher sensitivity comparing to graphene		[87]
Multilayer MoS$_2$	MoS$_2$/HfO$_2$/anti-PSA antibody	PSA	375 fM	low detection limit		[88]
Multilayer MoS$_2$	MoS$_2$/DNA	DNA	10 fM	good selectivity		[89]
Multilayer BP	BP/AuNPs/DTT	As (V) and As(III)	1 nM		easy to be oxidize, encapsulation is needed	[90]
Multilayer BP (12 nm)	BP/lead ionophore	Pb^{2+}	1 ppb/5 nM	high selectivity		[91]

New sensors (GrFETs) using field-effect transistors (FETs) incorporating monolayer graphene obtained by chemical vapor deposition (CVD) as the sensing element with the aim of detecting micro pollutants in water, particularly Pb(II). The experience acquired in the preparation of FETs has made it possible to obtain microelectrodes that can be subsequently used for the development of an electrochemical micro sensor. The graphene of the GrFET and GrE electrodes was then functionalized with dicarboxyphenyl groups via the electrochemical reduction of a diazonium salt to increase the sensitivity to Pb(II) ions. Both sensor technologies were used to detect Pb(II) in water. The GrE micro sensor achieved a limit of detection (LOD) of 3.4 nM, which is more than ten times below the WFD threshold, and a limit of quantification (LOQ) of 11.4 nM. For the GrFET micro sensor, the development of an original design enabling grafting by diazonium salts on the graphene surfaces of 15 FETs under identical conditions has led to the study of new signal transduction methods via measurement of the resistance of the graphene layer or measurement of the position of the Dirac point. The initial results obtained showed a detection limit of 0.1 µM. These results provide an original proof of concept for the application of a CVD graphene FET for the detection of Pb(II) lead in aqueous media [92].

5. Conclusion and future prospects

It is generally difficult to protect oneself from exposure to heavy metals because they are ubiquitous in the environment. Heavy metals pose a significant threat to the water quality and health of the environment and organisms. It is essential to make a conscious effort to reduce and regulate the release of these pollutants to ensure that water resources remain pure and healthy for future generations. It is important to take steps to reduce exposure to heavy metals, both at the individual level and through the implementation of sustainable policies and technologies. One of the most effective ways to reduce the release of heavy metals into the environment is to use clean industrial technologies. These technologies aim to minimize the production of waste and the emission of toxic substances, including heavy metals. Nanotechnology seeks to exploit these unique properties to design and create new applications, devices, and materials that can have significant benefits in a variety of fields, such as electronics, medicine, manufacturing, energy, and water treatment. Nanotechnology researchers have worked on the manipulation and control of matter at the atomic and molecular scales, allowing for the creation of customized structures and material properties tailored to meet specific needs.

However, it should be noted that nanotechnology also raises questions regarding safety, ethics, and potential health and environmental impacts. Because nanomaterials and nanodevices may have different effects than larger-scale materials, it is important to conduct in-depth research to understand and mitigate any potential negative impacts. The potential of these technologies to effectively remove a diverse range of pollutants, combined with their adaptability and increased efficiency, opens the door to more sustainable solutions for the environmental challenges we face. However, it is crucial to note that despite the undeniable benefits of nanotechnologies, concerns about their long-term effects on human health and the environment remain. Therefore, appropriate regulations and constant monitoring are essential to ensure that their use does not create new problems while solving old ones.

Artificial intelligence and machine learning have the potential to transform heavy metal detection by analyzing large amounts of data and providing predictive models. For example, AI can help quickly identify contaminated samples and predict future contamination events based on historical data. Real-time monitoring and predictive modeling should become more widespread as these technologies improve.

Portable devices that can be used in the field without expensive equipment are becoming increasingly common. For example, a new portable ICP-OES device has been developed that can be used in remote areas for real-time monitoring of heavy metals. These devices are likely to become more widespread, as they offer significant advantages in terms of convenience and cost. By forging a balance between innovation and prudence, we can aspire to a future where industrial water is purified efficiently and sustainably, thus contributing to the preservation of our planet for future generations.

Conflict of interest: The author declares no conflict of interest.

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