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Emerging and traditional pollutants in water resources: A perspective on the American Continent

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Graphical abstract

Highlights

1. Emerging contaminants (ECs) are increasingly detected in ecosystems, impacting wildlife and human health due to their harmful and persistent nature.

2. Although research on ECs has expanded, further studies are needed to elucidate their complex effects on aquatic ecosystems, including their mechanisms of action and long-term ecological consequences.

3. It is crucial to develop innovative management strategies across the Americas to effectively mitigate the impact of both emerging and traditional pollutants on water resources.

4. Regulatory measures should be enforced to enhance environmental authorities' monitoring of ECs in water, ensuring better control over their release across the Americas.

Abstract

The increasing presence of emerging contaminants (ECs) is directly associated with the widespread use of personal care products, pharmaceuticals, illicit drugs, microplastics, and other organic and inorganic compounds driven by modern consumer culture. These substances, often unregulated, continuously enter the environment through sewage, domestic and industrial effluents, and inefficient wastewater treatment, leading to endocrine disruption and reproductive issues in wildlife, as well as broader ecological and human health risks. In contrast to traditional pollutants (TPs) such as heavy metals, which are better studied, and partially regulated ECs remain a growing concern due to their persistence and unknown long-term effects. Even though efforts have been made to standardize some heavy metals, their toxicity still poses challenges to water quality and public health. Therefore, continuous monitoring of both ECs and TPs is crucial to track contamination sources, assess environmental and health impacts, and support the development of remediation technologies and environmental policies. This review aimed to compile and analyze scientific literature on the incidence and effects of ECs and TPs in water resources, focusing on their most common types, environmental pathways, and biological models used for toxicity testing. The bibliometric analysis encompassed 200 research articles from the Americas, highlighting the most studied contaminants, methodological trends, and data essential for modeling pollution dynamics and guiding evidence-based decisions. The findings provide a foundational framework for improving water resource management and underscore the urgent need to integrate ECs into regulatory and monitoring programs to ensure aquatic ecosystem sustainability.

***Keywords**:* Aquatic toxicology, Endocrine disruption, Emerging pollutants, tropical ecotoxicology

Abbreviations:

Al, Aluminum; As, Arsenic; BEHP, (2-ethylhexyl) phthalate; BM, Biological model; BTBPE, 1,2-bis(2,4,6-tribromophenoxy) ethane; CBD, Convention on Biological Diversity; Cd, Cadmium; Cu, cupper; ClO_4^-, perchlorate; CRB, chlorate-reducing bacteria; DBT, Dibutyltin; DCOIT, 4,5-dichloro-2-n-octyl-4-isothiazolin-3-one; DRCs, declared related compounds; E1, estrone; ECs, emerging contaminants; EDs, endocrine disruptors; EOC, emerging organic compounds; Fe, iron; FR, Flame Retardant; $HClO_4^-$, perchloric acid; Hg, Mercury; HQ, threat coefficient; HMs, Heavy metals; MBT, Monobutyltin; MP, Microplastics; MQL, method quantitation limits; NAS, U.S. National Academy of Sciences; NH^{4+}, ammonium; Ni, nickel; NIS, sodium iodide symporter; Pb, lead; PBEB, pentabromoethylbenzene; PCBs, polychlorinated biphenyls; PAHs, polycyclic aromatic hydrocarbons; PhACs, active pharmaceutical chemicals; POPs, persistent organic compounds; PRB, perchlorate-reducing bacteria; ROS, reactive oxygen species; TBT, Tributyltin; TPs, traditional pollutants; UV, ultraviolet; WHO, World Health Organization; WWTP, wastewater treatment plants; Zn, Zinc.

1. INTRODUCTION

In the Americas, a wide variety of substances generated by human activities have been identified as pollutants, the increase of which is closely linked to urban and industrial growth. These compounds, known as xenobiotics and/or toxicants, have driven the development of global environmental strategies, regulations, and directives to prevent, control, and mitigate their impact on ecosystems (Reichert et al., 2019). However, factors such as population growth, inadequate solid waste disposal, consumer culture, and growing market demands have favoured the production and use of numerous artificial and synthetic substances that, in many cases, lack regulations and maximum permissible levels in environmental matrices such as water (Acevedo-Barrios et al., 2022; Acevedo-Barrios & Olivero-Verbel, 2021).

Industrial development has accelerated the accumulation of pollutants that affect natural resources, organisms, and human health. In recent years, substances have been detected that, although present in minimal concentrations for decades, had gone unnoticed due to the environment's self-purification capacity. This characteristic has deteriorated due to the resistance and solubility of these compounds. Their persistence and lack of efficient identification, elimination, and metabolic transformation techniques have significantly increased their environmental concentrations. These compounds, known as "emerging pollutants" (ECs), are synthetic or natural chemicals that are not regularly monitored, but whose presence in the environment can generate adverse effects on ecosystems (Kumar et al., 2022; Carrasco et al., 2017).

The presence of ECs in aquatic and terrestrial ecosystems is a growing problem that generates concern due to the high volumes of direct discharges that these environments receive without adequate control or prior treatment (Egbuna et al., 2021). Despite their diverse origin and varied chemical composition, many of these compounds have remained off the radar of environmental regulations, which has hindered their identification and classification as substances that pose a risk to human health and biodiversity (Gil et al., 2012). Their persistence in the environment, coupled with their potential toxicity and bioaccumulation capacity, aggravates their impact, as they can infiltrate drinking water sources through urban and industrial waste discharges, leaching of contaminated soils, and filtration into groundwater bodies (Carrasco et al., 2017). This phenomenon compromises the quality of water resources. It exposes ecosystems and human populations to risks that are not yet fully understood, highlighting the urgent need for monitoring strategies, updated regulations, and effective treatment technologies to remove them.

Among the hundreds of ECs that reach water bodies globally are pharmaceuticals, personal care items, hormones, pesticides, organochlorine compounds, detergents, flame retardants, nanoparticles, anticorrosive, plasticizers, microplastics, surfactants, industrial additives, and toxic inorganic salts such as perchlorate (ClO_4^-) (Acevedo-Barrios et al., 2024; Acevedo Barrios et al., 2023; Acevedo-Barrios et al., 2022a; Acevedo-Barrios & Olivero-Verbel, 2021; Egbuna et al., 2021; Gani et al., 2021; De la Parra-Guerra & Olivero-Verbel, 2020; Reichert et al., 2019). Global production of these compounds is estimated to have grown exponentially, from 1 million to 500 million tons annually (Khan et al., 2022). Their high presence in water resources is due to their massive production and the inefficiency of removal processes in drinking water and wastewater treatment plants (WWTPs), which allows these compounds to persist and accumulate in the environment. Furthermore, anthropogenic sources such as domestic, industrial, and agricultural activities contribute significantly to their dispersion (Martini et al., 2021). Environmental surveillance networks do not routinely monitor these pollutants despite their potential impact on human health and ecosystems (Meléndez-Marmolejo et al., 2020).

In 2016, the European Commission's Network of Reference Laboratories, Research Centers and Related Organizations for Monitoring Emerging Environmental Substances (NORMAN) identified 1,036 substances as ECs (Meléndez-Marmolejo et al., 2020). This finding highlights the accelerated proliferation of these compounds and the widespread lack of knowledge about their effects. One of the most significant challenges in their management is the difficulty in determining the precise risks of water pollution, since, in many cases, the individual concentrations of these pollutants are low. However, their danger increases when they coexist in complex environmental mixtures, generating synergistic or cumulative effects on biota (do Amaral et al., 2019; Gil et al., 2012). Some ECs have been identified as endocrine disruptors, causing biological alterations such as feminization and hermaphroditism in particular fish species, which impacts aquatic ecosystems and food chains (De la Parra-Guerra & Acevedo-Barrios, 2023; Martini et al., 2021). Consequently, ECs pose a growing challenge in scientific, academic, and territorial spheres due to their complexity in detecting and managing aquatic ecosystems. Their presence raises uncertainties about their environmental interactions and long-term effects on biota and human health (De la Parra-Guerra & Acevedo-Barrios, 2023; Bedoya-Ríos et al., 2018). Despite increased research in the Americas over the last decade, knowledge about these substances remains limited, mainly due to the speed with which new families of compounds are identified and the lack of studies on their environmental dynamics. An additional challenge lies in the ineffectiveness of many water treatment technologies in removing these compounds, which allows their persistence in ecosystems and their potential bioaccumulation (Gogoi et al., 2018). The lack of specific regulations and health standards makes its control even more difficult, highlighting the need to strengthen monitoring strategies and develop innovative solutions to mitigate its ecotoxicological effects.

Another environmental concern is what we know as traditional pollutants (TPs), specifically heavy metals, which are pollutants widely studied due to their impact on different environmental matrices. Elements such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) are known for their toxicity, persistence, and bioaccumulation in aquatic ecosystems, representing a risk to biodiversity and the communities that depend on these resources (Tchounwou et al., 2012). However, some metals, such as copper (Cu) and zinc (Zn), are essential at low concentrations for the metabolism of living organisms (Bruins et al., 2000). Despite advances in regulations and technologies for monitoring and mitigation, current methodologies still have deficiencies, since many focus on measuring total concentrations without considering their bioavailability or synergistic effects with other pollutants (Ali & Khan, 2018). This limitation highlights the urgency of improving assessment and monitoring approaches, integrating more precise methodologies and innovative strategies to develop more effective and sustainable mitigation plans in aquatic ecosystems.

To delve deeper into the proposed topics, a scoping (bibliometric) review was conducted, an approach that allows for exploring the available evidence on the presence of ECs in water resources in the Americas. This methodology facilitates the identification of gaps in scientific literature, promoting the development of new research that strengthens knowledge in this field. The review offers a detailed analysis of the recent state of the art on various ECs, addressing their presence, effects on aquatic ecosystems, and the use of biological models to assess their impact. It also examines TPs, particularly heavy metals, highlighting advances in their control and persistent deficiencies in their monitoring and management within water bodies. Although regulations and technologies aimed at mitigating them exist, many methodologies still fail to consider key aspects such as their bioavailability and interactions with other contaminants, underscoring the need to improve assessment and control approaches.

Finally, this review article seeks to provide a comprehensive overview of ECs and TPs in water resources, highlighting current knowledge and identifying key areas for future research. Addressing these topics aims to contribute to developing more effective strategies for managing and mitigating these pollutants, aiming to improve environmental and human health. Furthermore, the review emphasizes the importance of understanding the interactions and combined effects of multiple ECs in the environment. This aspect is critical, as mixtures of pollutants can generate synergistic or antagonistic effects that differ from individual impacts. The ECs analyzed include pharmaceuticals, cosmetics, microplastics, and pesticides, whose diversity highlights the complexity of the problem. The need for multidisciplinary approaches that integrate environmental chemistry, toxicology, and water resource management with ecological education is emphasized in this context.

2. METHODOLOGY

The methodology used in this review is detailed below. First, the research question was established: What is the state of knowledge regarding ECs and TPs in water resources in the Americas? Subsequently, a systematic scientific literature search was conducted in high-impact databases, including ScienceDirect, Web of Science, PubMed, and Scopus®. Finally, the selected articles were critically analyzed to identify trends, knowledge gaps, and advances in managing these pollutants.

2.1 Search Strategy

A search for related data was performed in the ScienceDirect and Scopus databases$^{®}$; with the following keywords: "Emerging contaminants" OR "Traditional pollutants" OR "Contaminants of emerging concern" OR "Heavy metals in water sources" OR "Emerging and contaminants" OR "Emerging contaminants in water sources" OR "contaminants in water sources" OR "Emerging contaminants biological models" OR "contaminants biological models".

2.2 Inclusion Criteria

Only studies on ECs and TPs in some water resources in the Americas from the mentioned databases, published during 2005-2024, were included. In addition, only articles published in English were selected.

2.3 Exclusion Criteria

Studies related to ECs and TPs from countries outside the American continent and those not published from 2005 to 2024 were excluded. At the same time, articles duplicated in different databases were discarded, retaining only one. For the evaluation criteria of each article, the title, abstract, and references of each one were evaluated, independently extracting the necessary information**.**

3. RESULTS AND DISCUSSION

A total of 2575 articles were identified through database searches. After eliminating irrelevant and duplicate articles, the final records were 1895 articles. Subsequently, each article was evaluated according to its title and abstract content, with only 200 articles chosen, and finally, a complete review and evaluation were performed.

3.1 Pathways of entry of ECs into Aquatic Ecosystems

The chemical and physical characteristics of ECs are essential in identifying how they enter aquatic ecosystems and how they can affect living beings (Tran et al., 2018). It is possible to establish different moments in the lifetime of an ECs in which it can enter these ecosystems: (i) associated with its presence in the raw material or supplies required in the manufacturing process of a commercial product containing the ECs; (ii) during the manufacture of the commercial product as such; (iii) during its use, some ECs are of single use such as some plastics, and others have a more extended use in time; and (iv) during their disposal, in which they are already spoken of as waste, in which they are mobilized as liquid or solid waste (Gottschalk et al., 2013).

Once incorporated into everyday products, ECs are released into the environment primarily during phases III and IV of their life cycles. Their dispersion is associated with routine household activities, such as personal hygiene, cleaning and disinfection, textile washing, solid waste disposal, and wastewater discharge (Rogers et al., 2021). Furthermore, the mobility of these compounds into aquatic ecosystems is intensified in industrial and agricultural processes, including farming, livestock, grazing, and aquaculture. In these sectors, not only are organic compounds released, but also microorganisms resistant to environmental regulations, antibiotic resistance genes, and viral particles, which are disseminated through solid waste and liquid effluents (Jeevanandam et al., 2018). The ECs in these discharges reach water bodies or the soil directly, ending up in surface water systems, groundwater, or marine environments through runoff processes (Wilkinson et al., 2017). Few discharges worldwide are treated in wastewater treatment plants (WWTPs). Still, when these treatments are performed on wastewater, biosolids are generated that contain complete ECs, or the products of their partial or total degradation associated with the biological activity of these treatments. These biosolids can end up in landfills, where other types of solid waste with higher ECs content converge. These garbage and waste dumps are also a source of ECs contamination and distribution due to the production of leachates that can contaminate soil or water through percolation processes (Propp et al., 2021).

Likewise, ECs can be present in the atmosphere because of emissions generated by vehicles and industrial sources, forest fires, solid waste burning, and agricultural practices. Once suspended, these compounds can be transported to water bodies through atmospheric deposition processes, either through rainfall, which facilitates their carryover by surface runoff, or through their adsorption to particulate matter in the air, which favors their dispersion and eventual sedimentation in different aquatic ecosystems (Enyoh et al., 2020). Figure 1 illustrates the main routes of entry of ECs into the environment, considering their production, use, and release in different environmental compartments such as air, soil, and water. Furthermore, the mechanisms through which these compounds reach water bodies are highlighted, emphasizing the influence of anthropogenic activities on their distribution and persistence in aquatic ecosystems.

3.2 Principal ECs of Interest in Aquatic Ecosystems.

3.2.1 Pharmaceuticals, Illicit Drugs, and Personal Care Products.

The presence and fate of pharmaceuticals in aquatic ecosystems have emerged as a central issue in environmental chemistry due to their persistence, transformation, and potential impact on biological processes. Their release into water bodies leads to changes in their chemical composition, which turns them into sources of organic pollution and can also affect the ecological balance and homeostasis of aquatic organisms (Jaimes-Urbina & Vera-Solano, 2020). Pharmaceutical molecules detected in wastewater include various antibiotics for human and veterinary use, prescription and over-the-counter medications, and sex hormones and steroids (Gogoi et al., 2018). Among the most identified pharmaceutical compounds are anti-inflammatories, antidepressants, analgesics, antipyretics, antibacterials, beta-blockers, and steroids (Kar et al., 2021). Substances such as atenolol, carbamazepine, estrone, gemfibrozil, meprobamate, naproxen, phenytoin, sulfamethoxazole, trimethoprim, and ibuprofen have been frequently reported in drinking water, raising particular concern in the scientific community due to the uncertainty surrounding the effects of chronic exposure to low concentrations of these compounds (Noguera-Oviedo & Aga, 2016).

In the case of illicit drugs, which also count among ECs, they are also not completely metabolized in the human body and usually enter the wastewater either unchanged or as secondary metabolites or conjugates (Li et al., 2016). Illicit drugs and their metabolites enter the wastewater network as unchanged drugs and/or their active metabolites by human excretion, saliva, and sweat, after illegal consumption or by accidental or deliberate disposal from clandestine drug laboratories (González-Mariño et al., 2012). Its occurrence in the environment is observed by the presence of methamphetamine and methylenedioxymethamphetamine in effluents (Gil et al., 2012), as well as cocaine and a cocaine metabolite (benzoylecgonine) that were detected in surface waters at concentrations of 120 ng L^{-1} and

750 ng L^{-1}, respectively (Gil et al., 2012). Since then, a growing interest in measuring these drugs in environmental matrices has emerged worldwide. Benzoylecgonine, ecgonine methyl ester, MDMA, methamphetamine, amphetamine, and morphine are the frequent illicit drug residues in WWTP effluents (Noguera-Oviedo & Aga, 2016).

Furthermore, quantifying these compounds in the environment allows for assessing their distribution and persistence. It has also become an indirect tool for estimating community consumption levels and predicting their potential ecotoxicological impact. Although concentrations of pharmaceuticals and their metabolites in surface waters are typically in the nanogram per liter range, their effects on wildlife and human health cannot be underestimated, particularly in vulnerable populations that may be continuously exposed to these substances (Gil et al., 2012; Valcárcel et al., 2012).

Among the most prevalent categories of emerging contaminants, in addition to pharmaceuticals and illicit substances, personal care products stand out in third place. This broad category includes household biocides, disinfectants, cosmetics, personal hygiene products, and fragrances (Lozano et al., 2022). Among their active ingredients, ultraviolet (UV) filters have sparked growing interest in the scientific community due to their persistence in aquatic ecosystems and their potential estrogenic activity. These compounds have been detected at high concentrations in groundwater, suggesting their mobility and accumulation in these water systems (Noguera-Oviedo & Aga, 2016). Notably, the highest number of UV filters reported to date was identified in an aquifer recharged by a contaminated river, with concentrations close to 55 ng L^{-1}, demonstrating infiltration capacity and persistence in the environment.

As a result of the occurrence of many environmental contaminants, evaluations have been carried out in different water sources (rivers, reservoirs, estuaries, beaches, bays, wetlands, and others) in Latin American countries such as Argentina, Brazil, Colombia, and Mexico, where the presence of compounds such as antibiotics is observed; amoxicillin, ofloxacin, cefotaxime, doxycycline, organophosphate esters, anti-inflammatory drugs betamethasone, dexamethasone, naproxen, prednisone, caffeine, methylparaben, sulfamethoxazole, carbamazepine, loratadine, cocaine, benzoylecgonine, already mentioned, and which have been detected not only in water samples, but also in sediments and biofilms. Most case studies demonstrate the high environmental risk of these substances, and some manifest a high risk of resistance selection (Cristale et al., 2021; de Aquino et al., 2021; Quadra et al., 2021; Roveri et al., 2021; Valdés et al., 2021; Chaves et al., 2020; Santos et al., 2020; Sotão-Neto et al., 2020; Cruz-López et al., 2020; Campestrini & Jardim, 2017).

3.2.2 Endocrine Disruptors.

The World Health Organization (WHO), through the United Nations Environment Program, identified a list of 176 compounds, including industrial materials, pharmaceuticals, pesticides, and other pollutants, capable of altering reproductive processes and hormonal functions, either directly or indirectly, in various organisms, including mammals and humans. These compounds, known as endocrine disruptors (EDs), constitute an environmental and public health concern due to their ability to interfere with the hormonal balance of exposed organisms (Seralini & Jungers, 2021). EDs are synthetic chemicals that can mimic, block, or modify the action of endogenous hormones, thereby altering normal physiological processes and generating adverse effects on homeostasis, development, and reproduction of multiple species (De la Parra-Guerra & Acevedo-Barrios, 2023; De la Parra-Guerra & Olivero-Verbel, 2020).

Exposure to EDs is especially critical during embryonic development, given that hormonal regulation at this stage is exact, and any alteration can affect the differentiation and maturation of developing tissues. Various EDs can cross the placenta, acting as teratogenic agents that can compromise the reproductive, neurological, immunological, and endocrine development of the unborn child, with potential repercussions not only in adulthood but also in future generations through transgenerational and multigenerational effects (Mattiske & Pask, 2021; De la Parra-Guerra & Olivero-Verbel, 2020). Although the presence of these substances has been widely documented in different ecosystems, including aquatic environments, information on their incidence and potential risks remains limited in developing countries (Bedoya-Ríos et al., 2018). DEs have been detected in wastewater at extremely low concentrations (ng L^{-1} or µg L^{-1}), which raises significant concern since the effects of chronic exposure to these compounds on human health have not yet been fully understood (Gogoi et al., 2018).

There is evidence demonstrating the persistence of EDs in aquatic ecosystems. A Bogotá, Colombia study analyzed the urban water cycle and revealed that plasticizers such as phthalates and bisphenol A are the most prevalent compounds. Regarding pharmaceuticals, carbamazepine had the highest concentrations, with values between 0.68 and 31.45 µg L^{-1}. Furthermore, the threat coefficient analysis (CGA) highlighted the environmental relevance of bis(2-ethylhexyl) phthalate (BEHP) and estrone (E1), which can reach surface water bodies through domestic and industrial discharges (Bedoya-Ríos et al., 2018). Similarly, in São Paulo, Brazil, nine EDs and 26 active pharmaceutical products (APPs) were assessed in coastal areas affected by wastewater discharges through submarine outfalls. Results showed EDs concentrations ranging from below the method quantification limit (MQL) to 72.5 ng g^{-1} in sediments. For APPs, all concentrations detected were below the MQL; however, the environmental risk assessment indicated that, considering the measured ecological concentrations and ecotoxicity data reported in the literature, some of the outfalls studied posed a high potential risk to the marine ecosystem (dos Santos et al., 2018).

3.2.3 Organic Compounds.

As mentioned at the beginning of this review, the slowdown in population growth over the last century has been closely linked to the demand for and reuse of water resources. However, various anthropogenic activities, such as the intensive use of pesticides, biocides, insecticides, and fertilizers, along with the improper disposal of solid waste and the filtration of industrial effluents or leaking septic tanks, have generated significant environmental impacts on surface and groundwater bodies. These activities have led to the continued introduction of emerging organic compounds (EOCs), which can bioaccumulate and generate toxic effects on marine organisms once released into aquatic ecosystems. Furthermore, these effects can be transmitted to humans through the food chain, representing a potential risk to public health and ecological balance (Mukhopadhyay et al., 2022; Khan & Pathak, 2020; Magro et al., 2020; Meffe & de Bustamante, 2014).

The literature search identified scientific studies analyzing the presence of EOCs in aquatic ecosystems. Among the most relevant works is the study by Abreu et al. (2021) in Brazil, which assessed the environmental impact of the accumulation of persistent organic compounds (POPs) in the Viloria estuary. In this study, residues of antifouling biocides, such as diuron, irgarol, chlorothalonil, dichlofluanid, and 4,5-dichloro-2-n-octyl-4-isothiazolin-3-one (DCOIT), as well as organotin compounds, including tributyltin (TBT), dibutyltin (DBT), and monobutyltin (MBT), and antifouling paint (APP) particles were analyzed. Despite being at an all-time low ($\Sigma BT \leq 113$ ng Sn g^{-1} dry weight), these pollutants present a significant risk to both local biota and the health of the surrounding human population. This risk is due to the persistence of POPs in the environment, their capacity for bioaccumulation and biomagnification, and multiple diffuse sources of contamination that make their management and control difficult.

Similarly, a study conducted in various bays in the south of the country by Hernández-Guzmán et al. (2017) documented the presence of several types of pyrethroids, classified as insecticidal EOCs, which are widely used in the control of pests and disease vectors in both residential and agricultural areas.

In their research, eight pyrethroids were identified, along with fipronil and its two metabolites, with bifenthrin, permethrin, and cypermethrin being the most prevalent in the study areas. These compounds were found dispersed in sediments, mussels, and wastewater-treated effluents. Total pyrethroid concentrations in sediments ranged from 0.04 to 1.95 ng g^{-1} dry weight in the Punta Banda estuary (n=13), and from 0.07 to 6.62 ng g^{-1} dry weight in Todos Santos Bay (n=19). Furthermore, the muscles had concentrations ranging from 1.19 to 6.15 ng g-1 wet weight. These findings underscore pyrethroids' persistence and potential impact on local aquatic ecosystems, affecting sediment and marine organisms.

Among the identified EOCs are persistent organic compounds (POPs), which are known for their ability to accumulate in organisms and biomagnify along food webs due to their persistent properties and hydrophobic nature. Among these compounds, the category of flame retardants (FRs) stands out, which includes brominated compounds, such as pentabromoethylbenzene (PBEB) and 1,2-bis(2,4,6-tribromophenoxy) ethane (BTBPE), as well as chlorinated flame retardants, considered related compounds (DRCs) (Pizzochero et al., 2019; Navarro et al., 2016; 2017). Although POPs are restricted and regulated under the Stockholm Convention, a 2019 study in Guanabara Bay and Sepetiba Bay, Brazil, provided new data on the contamination of these coastal ecosystems by specific organic pollutants. In this study, the presence of brominated flame retardants in meagre fish from the Southwest Atlantic Ocean was reported for the first time, albeit at low concentrations. Furthermore, commercial mixtures of polybrominated diphenyl ethers were detected in all samples analyzed. Concentrations of tri-, tetra-, and penta-BDEs, as well as ΣDRC, DP, and the anti-DP isomer, were also found. Their levels showed a positive correlation with δ^{-6}N, suggesting a biomagnification process along the food web, which explains the levels observed in meagre fish.

3.2.4 Microplastics.

Plastics represent a growing challenge for ecosystems and human health; their production was estimated at 390.7 million tons globally in 2021 (Li et al., 2023). And a discharge of 53 million tons in 2030 is predicted in aquatic ecosystems (Borrelle et al., 2020). Microplastics (MP) are plastic fragments less than 5 mm in size from various sources, such as decomposed plastic waste, personal care products, and textile fibers. Due to their small size, these microplastics are challenging to detect with the naked eye, but their impact on marine ecosystems is significant. MPs are mainly classified into two types: primary (manufactured in MP sizes) and secondary (by fragmentation from larger plastic items) (Nguyen et al., 2023).

There are several pathways for PM entry into ecosystems, such as the textile and plastics industries, which are anthropogenic sources that massively release these materials. In Colombia, PM has been evidenced in surface waters and different aquatic organisms (Miranda-Peña et al., 2023; Rojas-Luna et al., 2023), demonstrating their persistence and bioaccumulation. On a global scale, 80% of plastics and PMs in the marine environment come from the terrestrial environment (Mani et al., 2015). The aquatic environment also receives PMs from various sources, including fishing gear and near-shore dumping of PMs (Pinho et al., 2022). Groundwater also has PMs from soil infiltration (Kim et al., 2023). PM is also found in the atmosphere and can be transported up to 1000 km through the atmosphere, deposited in terrestrial and aquatic environments (Wang et al., 2020).

Given their high mobility, PMs are present in surface waters (Yu et al., 2022), and even marshes (Rojas-Luna et al., 2023), as well as in deep waters, marine sediments, and in a variety of marine organisms, from zooplankton to fish and aquatic mammals. These organisms can ingest microplastics, which can cause obstructions in their digestive systems, toxicity, and alterations in their diet (Wang et al., 2020). On the other hand, MPs can absorb and transport chemical contaminants, which increases the exposure of marine organisms to hazardous toxins. For example, the presence of persistent organic pollutants, including polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), has been detected in MPs on coastal beaches (Frias et al., 2010).

The relationship between PM in marine ecosystems and human health is an emerging concern. Although research is still in its early stages, some possible direct links have been identified, such as contamination of food with these materials, which can enter the food web through ingestion by fish and shellfish (Marsden et al., 2019). The main associated effects are endocrine disruption and carcinogenicity (Eriksen et al., 2014; Browne et al., 2011). Given the growing interest in these ECs, environmental studies for their identification and quantification have increased. In South America, for example, in the Ciénaga de Santa Marta, (Colombia), PM was detected, with a greater abundance of fibers and fragments, finding polypropylene, polyethylene, and high density polyethylene as the most frequent polymers, highlighting that the presence of PM is greater near river mouths and in urban areas with a high density of fishing and aquaculture activities. These infrastructures are essential sources of contaminants (Garcés-Ordóñez et al., 2022).

In the Laguna de Términos, a Natural Protected Area located in the southern Gulf of Mexico, Celis-Hernández et al. (2021) examined the accumulation of PM in marine sponges, sediments, and water from two mangrove areas with different levels of human disturbance. The study evaluated whether the concentration of PM in these compartments varied spatially (between sites), finding evidence that the three sponge species can incorporate PM and the concentrations of this pollutant are reflected in spatial variations in the degree of exposure to potential sources, finding average concentrations between 1861 and 3456 items kg^{-1} dry weight in marine sponges, from 130 to 287 items kg^{-1} in water and from 6 to 11 items kg^{-1} in sediment.

Additionally, there is evidence of PM in oceans around the world, especially in Latin America, the presence of this pollutant has been reported in urban Caribbean beaches in a city with tourist stressor in Colombia (Acosta-Coley & Olivero-Verbel, 2015), concentrations of trace metals (Br, Cr, Rb, Sr, Ce, Zr, Ni, Pb, among others) in microplastics collected on beaches around industrialized cities (Acosta-Coley et al., 2019a). Finally, works that indicate toxicity due to the presence of PM allow us to say that these ECs can cause cell damage associated with oxidative stress, reactive oxygen species (ROS) in organisms, and also that PMs act as carriers of other biologically active pollutants (Acosta-Coley et al., 2019b).

3.2.5 Inorganic Salts; Case Perchlorate.

Among the ECs of environmental concern is (ClO_4^-), an inorganic anion present in all ecological matrices and characterized by its persistence in diverse ecosystems (Acevedo-Barrios et al., 2019a; Acevedo-Barrios et al., 2019b; Acevedo-Barrios et al., 2018), strong oxidant capable of contaminating water and soils when solid salts of ammonium (NH^{4+}), potassium (K^{1+}), magnesium ($Mg^{2+)}$, sodium (Na^+), and perchloric acid ($HClO_4^-$) are dissolved in water (Kumarathilaka et al., 2016). These ECs have both natural and anthropogenic origins. Naturally, ClO_4^- is formed in the atmosphere by the reaction of chlorine with ozone in photochemical processes or during electrical activity in storms (Acevedo-Barrios et al., 2018). A study by Jackson et al. (2015) observed the presence of this pollutant in nitrate deposits from the Atacama Desert in Chile, with concentrations of 1000 mg/kg^{-1} of ClO_4^-, confirming that ClO_4^- can be present in diverse environments, including specific ecosystems with arid, hyper-arid, and semi-arid soil conditions, as well as in hypersaline environments, in volcanic eruptions, and Antarctic soils and ice zones (Acevedo Barrios et al., 2024; Acevedo-Barrios et al., 2023; Acevedo-Barrios et al., 2022a; Acevedo-Barrios et al., 2022b; Acevedo-Barrios & Olivero-Verbel, 2021). Its persistence is due to its chemical stability under normal environmental conditions. In addition, perchlorates' most remarkable characteristics are their high solubility in aqueous media and polar organic solvents (Rzymski et al., 2024).

The anthropogenic origin of ClO_4^- is through different industrial processes, used in military brigades, aerospace industry, pyrotechnic games, explosives, fertilizers, and agriculture (Liao et al., 2020). This occurs because although $ClO_4^-$is stable at room temperature, when it is elevated, its molecules become highly reactive, generate heat and explosion, which allows its presence in surface and groundwater. The presence of ClO_4^- in water is harmful, in low concentration this inorganic anion can harm public health (Steinmaus, 2016). The current use of ClO_4^- in military installations, data on production sites, and production quantities is somewhat uncertain and partial, as this information has not been published accurately. Therefore, the data held on annual production is inherently incomplete and, consequently, is far from real (Niziński et al., 2021). Annual global production is estimated to be a few hundred thousand tons, and the most prominent producers are in the USA, France, Germany, Italy, China, and Brazil (Niziński et al., 2021). Anthropogenic sources also include the importation and use of Chilean nitrate ($NaNO_3$), as a fertilizer mined in deposits in the Atacama Desert in Chile a fertilizer containing approximately 98% $NaNO_3$ and between 0.05 and 0.4% ClO_{4-} and a wide range of industrial applications such as; Gas drying agents, lubricating oils, tanning, leather finishing, electronic tubing, fabric arrangement, dyes, cloud seeding, electroplating, aluminum refining, road signs and flares, rubber manufacturing, paint and enamel production, cattle feed, and magnesium batteries (Kumarathilaka et al., 2016).

There is growing evidence of the presence of this contaminant in natural environments, which has generated increasing concern. Although there is no specific treatment for removing ClO_4^- from environmental matrices, remediation methods have been proposed and have shown some progress in research. One of these approaches is biological methods, which employ microbial species and strains that, in the presence of a suitable electron acceptor (such as ClO_4^- NO_3^-, or O_2) and carbon sources, can enzymatically convert ClO_4^- into less toxic compounds. This process significantly reduces the concentration of harmful substances in drinking water. In general, perchlorate-reducing bacteria (PRBs) are divided into two groups: those that can reduce both chlorates and perchlorate, and those that are chlorate-reducing bacteria (CRBs), which contain enzymes specialized for the reduction of chlorates exclusively (Niziński et al., 2021).

ClO_4^- can enter our body in three ways: transdermal, inhalation, and oral. The inhalation route consists of inhaling dust particles together with the air in which ClO_4^- molecules are adsorbed. In particular, workers in ClO_4^- factories and the population of large cities where the smog phenomenon occurs are the most vulnerable groups to this type of exposure (Cao et al., 2019). The oral route is the best known and most important, ClO_4^- is rapidly absorbed from the stomach and small intestine and then enters the bloodstream, because the adverse effects of chronic ingestion of small doses of ClO_4^- on the functioning of the organism are still unknown; in 2005, the U.S. National Academy of Sciences (NAS) established a daily dose of ClO_4^- that causes no observable adverse effects of 0.0007 mg/kg body weight and an acceptable concentration of ClO_4^- in drinking water of 24.5 $\mu g\ L^{-1}$ (Cao et al., 2019).

ClO_4^- is distributed in ecosystems through runoff water, accumulating in many everyday foods such as lettuce, carrots, rice, and spinach. It is also found in milk, sauces, instant mixes, meats, fish, tea, sodas, plants, and tobacco products (Kumarathilaka et al., 2016). Due to its persistence, ClO_4^- in beaches, drinking water, and agricultural soils represents a serious public health problem. When not removed, this pollutant is irreversibly assimilated by foods such as fish, mollusks, vegetables, and water, reaching humans through the food web. This shows that ingesting contaminated food and water are the most common routes of exposure to ClO_4^-in the population. Additionally, it is confirmed that ClO_4^- is part of the group of endocrine disruptors, affecting iodine uptake by the thyroid gland (Acevedo-Barrios et al., 2018; Maffini et al., 2016). The thyroid gland is the main target of ClO_4^- toxicity. ClO_4^{-1} interferes with the uptake of iodide ions by the thyroid gland, both ClO_4^- anions and iodide ions have the same ionic charge and approximately the same ionic radius. As a result, ClO_4^- ingestion can inhibit iodide uptake by the sodium iodide symporter (NIS) of thyroid follicle cells, therefore at high concentrations, ClO_4^- can hinder the proper functioning of the thyroid gland in biological organisms (Acevedo-Barrios et al., 2019a; Acevedo-Barrios et al., 2018).

In recent years, ClO_4^{-1} was used as an agent for the treatment of hyperthyroidism, although it was withdrawn from medical use due to its severe adverse effects ClO_4^- is classified as a bocigen (i.e., a substance that inhibits the uptake of iodine by thyroid cells), which alters the metabolism of thyroid hormones, and, consequently, can cause health problems and multisystemic damage (Niziński et al., 2021). Finally, the study of ClO_4^- in environmental matrices is crucial and imperative due to its persistence and solubility, which facilitates its dispersion and accumulation in various food and drinking water sources. This inorganic anion, present from both natural and anthropogenic causes, represents a serious risk to public health and natural ecosystems, as it has been shown to affect many aspects, mainly thyroid function, by interfering with iodine uptake, a vital process for human development and metabolism. Identifying and monitoring its concentrations allow us to assess its impact on ecosystems and biota, and they are essential to develop mitigation and regulatory strategies that protect the environment and the health of exposed populations.

3.3 Biological Models Used in the Toxicity Evaluation of ECs

The effect of ECs in different biological models is fundamental for studying behavior, physiology, molecular damage, and metabolic pathways, among others, caused by exposure to these pollutants in the organism. Biomonitoring of environmental contaminants in the aquatic environment is especially useful due to their toxicity levels on organisms and their biomagnification. Among the BM implemented for the evaluation of aquatic contamination are invertebrates such as *Daphnia, Caenorhabditis elegans, Ceriodaphnia, Gammarus pulex,* among others, and vertebrates such as *Pimephales promelas,* although their reproduction rate, sensitivity, and handling are challenging to carry out bioassays (Vimalkumar et al., 2022; De la Parra-Guerra & Olivero-Verbel, 2020).

Within this systematic review, BM such as *Daphnia similis, Danio rerio, Crassostrea rhizophorae, Physalaemus cuvieri, Megalops atlanticus, Haliclona implexiformis, Halichondria melanadocia and Amorphinopsis atlantica* were found*,* BM used for toxicological studies exposed to contaminants such as ECs, including hormones, drugs, pesticides, insecticides, personal care products, metals, microplastics, and industrial compounds (Garcés-Ordóñez et al., 2022; Martini et al., 2021; Souza et al., 2021; Celis-Hernández et al., 2021; Cristale et al., 2021; da Costa Araújo et al., 2020; Acosta-Coley et al., 2019a; Hernández-Guzmán et al., 2017), nonylphenol and ethoxylated nonylphenols, in the nematode *Caenorhabditis elegans* (De la Parra-Guerra et al., 2020; De la Parra-Guerra & Olivero-Verbel, 2020). Toxic effects of cadmium chloride on fertilization, sperm quality, and mortality at 0-, 1-, 6-, and 7-days post-hatching (dph) in a vulnerable fish species, *Prochilodus magdalenae*, exposure to environmentally relevant Cd concentrations causes physiological changes in the early developmental stages of *P. magdalenae* (Sierra-Marquez et al., 2019).

3.4 Traditional pollutants: heavy metals case.

Metals are generally chemical elements with high electrical and thermal conductivity, malleability, ductility, and luster. They are usually found on the left side of the periodic table and include similar elements such as copper (Cu), iron (Fe), aluminum (Al), among others. They are typically solids at room temperature, and many have high melting and boiling points (Ghuge et al., 2023). On the other hand, heavy metals (HMs) have an atomic density greater than 5 g/cm^3. Examples include lead (Pb), nickel (Ni), mercury (Hg) (liquid at room temperature), cadmium (Cd), and metalloids such as arsenic (As) (Dey et al., 2021; Barakat, 2011).

HMs are not associated with biological functions, which is why they are considered toxic to living beings; additionally, they are persistent and have a high impact on the environment, so their study is especially relevant. HMs are associated with both natural (geogenic) and anthropogenic sources (Ulhassan et al., 2022). Human activities, such as manufacturing operations, fossil fuel burning, mining, electroplating, smelting, and sludge dumping (Amir et al., 2020; Klink, 2017) have led to an increase in their presence in soils, sediments, and water bodies (Pogrzeba et al., 2016). Additionally, the rise in world population has accelerated the growth of the industrial and agricultural sectors, increasing the use of synthetic fertilizers and biocidal agents, resulting in discharges with higher concentrations of HMs (Sarwar et al., 2017). Highlighting that more than 80% of global wastewater is discharged untreated into the environment (Liao et al., 2021). In developing countries, this proportion reaches 95% (Kataki et al., 2021). This situation increases the possibility of irrigation with wastewater with high HM contents (Khan et al., 2016; Sun et al., 2013). The mobility of these compounds in the environment is shown in Figure 2.

Once HMs reach aquatic ecosystems, they can accumulate, causing long-term impacts on their health (Jaiswal et al., 2018). HMs concentrate in various compartments, including water, sediment, and biota (Ghuge et al., 2023). Sediment acts as a reservoir for secondary contamination of the aquatic environment, as approximately 99% of the contaminants remain attached to it, while only 1% remains suspended in the water column. Consequently, the number of HMs in a river's lower reach is usually higher than in the upper reach due to sediment deposition and effluent inflow from adjacent areas. These conditions lead to bioaccumulation and biomagnification processes (Patel et al., 2018).

In some countries, there are already regulations for some of the metals. However, the increase in the presence and concentration of some has brought a new lack of knowledge and a growing concern. Highlighting also that HMs can combine with other elements forming inorganic or organic compounds that can further increase their toxicity and mobility in the ecosystem, reaching plants such as rice grown in flooded soils, modulating conditions of pH, dissolved oxygen, and redox potential, favoring this bioavailability and transfer. Plants can accumulate these HMs, given their similarity to other essential elements, using root transporters (Asati et al., 2016). This is the case of thioarsenial compounds using root phosphate transporters to reach these organisms' edible parts (Monroy-Licht, 2023).

Taking into account the high mobility of HMs, there have been several works where their presence has been identified in water sources, as is the case of the Biobío River basin in Chile, where inorganic substances such as Al, Cu, non-ionized ammonia, and Hg were detected, the latter being the most dangerous substance found in the sediments of this basin (Alonso et al., 2017). Likewise, studies in other countries, such as Brazil, found the presence of heavy metals of the emerging type in surface water, groundwater, and rainwater bodies, such as those detected by Souza et al. (2021) in two Neotropical mangrove estuarine ecosystems, where 10 emerging metal contaminants (Bi, Ce, La, Nb, Sn, Ta, Ti, W, Y, and Zr) were determined. As well as those identified in a bibliographic review conducted by Zini and Gutterres (2021) which had as a study area about 18 cities in six states in Brazil in which about 15 metals were identified, of which 11 (Al, As, Fe, Cd, Mn, Pb, Ni, Cu, Hg, Cr, and Zn) are listed and regulated in the Brazilian drinking water quality standard, and 4 (beryllium, cobalt, tin and vanadium) are not regulated.

The high presence of Hg in South America is associated with the widespread use of mercury in artisanal mining, with Colombia, Peru, Ecuador, and Brazil being the main users of this metal. In

Colombia, this element is used for gold (78%) and silver (22%) beneficiation (Artisanal Gold Council, 2014). The presence of Hg and other HM in Colombian aquatic ecosystems is not a minor issue, especially in those of economic importance, such as the Magdalena River basin, Atrato River, San Jorge River, Amazon River, where they have been identified, and in some points in concentrations that have caused the deterioration of the resource and therefore imbalance of its ecosystem services and alterations in the aquatic communities present (Monroy-Licht et al., 2023; Alcala-Orozco et al., 2020; Palacios-Torres et al., 2020; Tejeda-Benitez et al., 2016). Table 3 presents some reported effects on different organisms from exposure to mercury chemical species. El conocimiento de las especies químicas de mercurio en los recursos hídricos es fundamental para evaluar su toxicidad, movilidad y persistencia en los ecosistemas acuáticos. Diferentes formas de mercurio, como el metilmercurio, representan un alto riesgo para la salud humana y la biodiversidad debido a su bioacumulación en la cadena trófica. Comprender su especiación permite desarrollar estrategias eficaces de monitoreo y mitigación para reducir su impacto ambiental.

4. CONCLUSION

This review identified that the presence of ECs is mainly associated with human activities, emphasizing the high potential mobility of these compounds and their high persistence in aquatic ecosystems, highlighting that the level of toxicity is associated with the environmental matrices where they accumulate, and to the action of factors such as light, pH, dissolved oxygen, redox potential (external factors) that could increase their bioavailability, leading to the generation of a series of critical ecotoxic effects at different levels that account for their high permanence in these areas.

This scoping review was carried out to generate a systematic and holistic view of the behavior of some groups of ECs regarding environmental trends in water resources on the American continent, selecting articles containing concentrations in aquatic matrices. ECs are found in all continents, even in concentrations above the toxicity threshold for some species. Additional efforts should be made to assess the presence and impact of these chemicals in groundwater worldwide, due to the limited information available. Pharmaceuticals, illicit drugs, and personal care products are the most monitored contaminants, while preservatives, antioxidants, and flavorings in cosmetics and cleaning products have been less studied in water bodies. Polycyclic musks HHCB, AHTN, and the endocrine disruptor TCS were the most frequently found compounds, so their evaluation is suggested.

Encouraging the formulation of local and international regulations to reduce and control production and subsequent release of ECs and TPs into ecosystems, as well as strengthening the analytical capacity of developing countries such as those in South America to massify the identification and quantification of these compounds, leading to more effective actions proposed to address this global problem. The establishment of education policies and strategies focused on the preservation and sustainable use of water systems, including coastal areas and maritime spaces, to effectively advance in the international commitments associated with the Convention on Biological Diversity (CBD), the Minamata Convention on Mercury, the 2030 Agenda for Sustainable Development, and the Paris Agreement on Climate Change, is also recommended. Protecting these ecosystems is not only an environmental issue, but also essential to ensure a healthy and sustainable future for humanity, which also points to the fulfillment of the Sustainable Development Goals in its 2030 Agenda.

Despite advances in research on TPs, gaps in knowledge hinder the formulation of more robust and effective environmental plans. Although numerous studies have shown the different sources and types of heavy metal pollution, information on the dynamics of these pollutants in various ecosystems and their interaction with other environmental factors is still limited. In addition, current technologies, although useful for detection and monitoring, have revealed new dispersion routes for heavy metals. This highlights the need to continue researching and developing innovative strategies for their control and mitigation.

FIGURE CAPTIONS

Figure 1: Possible routes of entry of ECs from human activities into water bodies: Production, Use, and Environmental Release. Source: own elaboration.

Figure 2: Mobility of metals/metalloids in the environment. HMs: heavy metals/metalloids. (The figure was adapted from (S. Kumar et al., 2019).

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De la Parra-Guerra Ana C.: Conceptialization; Data curation; Formal analysis; Investigation; Supervision; Validation; Visualization; Writing – original draft Writing – review & editing.
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Data Availability

All data and information related to this review article are included in the manuscript, but if readers require additional information, the authors are happy to provide it.

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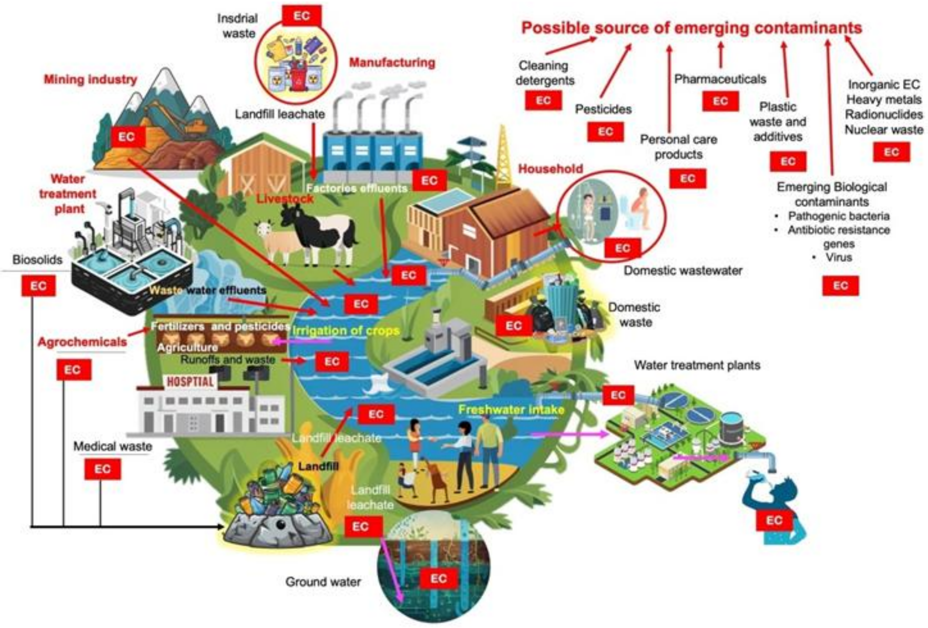

Figure 1. Possible routes of entry of ECs from human activities into water bodies: Production, Use, and Environmental Release. Source: own elaboration.

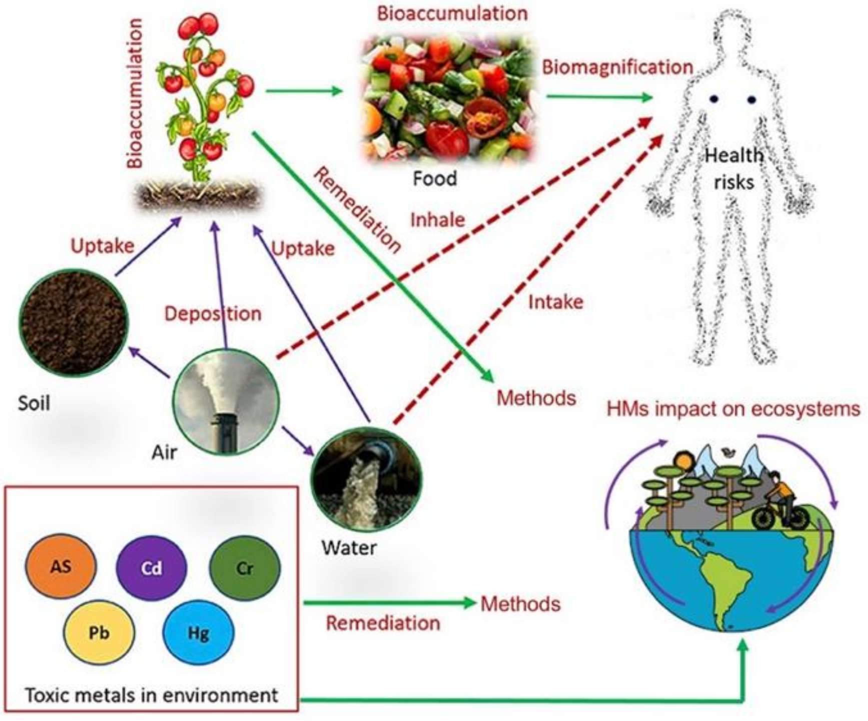

Figure 2. Mobility of metals/metalloids in the environment. HMs: heavy metals/metalloids. (The figure was adapted from (S. Kumar et al., 2019).