

## Review

# Water Pollution and Human Health: An Integrated Risk Perspective

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## Abstract

Water resources are essential for human well-being. However, water pollution is a major global problem with significant implications for the environment and public health. To address these challenges, this study presents an integrated perspective on water pollution by correlating pollution sources, transport pathways, exposure routes, and associated risks to human health. The methodology combined a systematic review conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines with a bibliometric analysis performed by using VOSviewer version 1.6.19, a software tool for constructing and visualizing bibliometric networks. A total of 332 publications published between 2015 and 2025 were retrieved from the Scopus and Google Scholar databases and met the PRISMA eligibility criteria. The findings indicate that both natural and anthropogenic sources contribute to water contamination, introducing pollutants such as heavy metals, pesticides, pharmaceutical residues, microplastics, and pathogenic microorganisms with potential human health impacts. Bibliometric analysis revealed a transition from conventional water quality assessments toward integrated approaches emphasizing health risks and environmental interactions. The study further identified important knowledge gaps regarding contaminant mixture effects and synergistic toxicity, which remain insufficiently addressed in current scientific and regulatory frameworks. These findings highlight the need for strengthened regulatory strategies, advanced treatment technologies, and evidence-based water governance to support environmental sustainability and public health protection.

**Keywords:** water pollution; human health risk; emerging pollutants; risk assessment; remediation technologies



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## 1. Introduction

Water pollution is a major global environmental issue. This problem has been reported in numerous countries, both developed, such as China and regions of South America and Europe, and developing, including India and areas of Africa [1–3]. Under the influence of rapid urbanization and increasing anthropogenic pressures, water resources are becoming increasingly vulnerable to pollution, leading to the degradation of aquatic ecosystems and posing significant risks to human health and sustainable development [1,4].

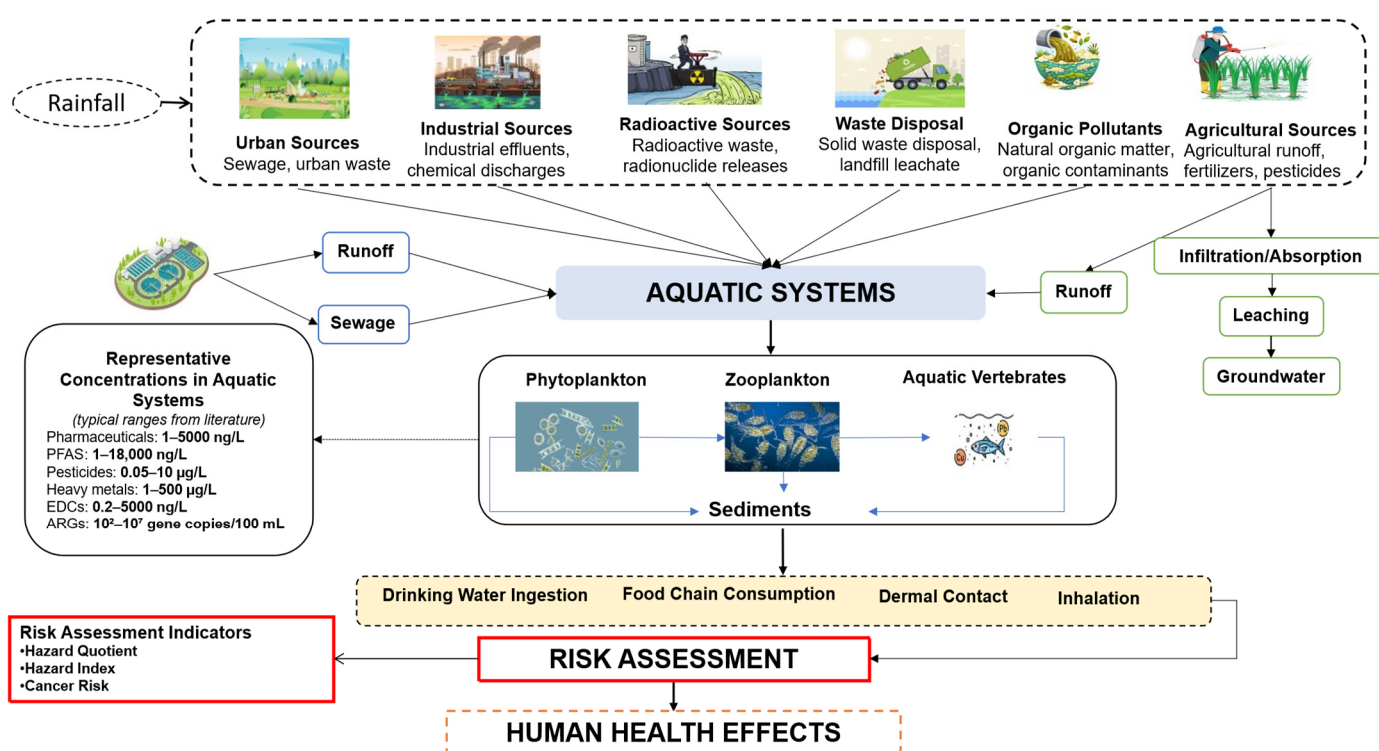
Water resource pollution is an intensively studied phenomenon that requires appropriate policies and techniques for monitoring, as well as the implementation of effective

strategies aimed at identifying viable remediation solutions [5,6]. This complex phenomenon results from the interaction between natural factors, such as climate change and geological processes, and anthropogenic activities, including agriculture, urban waste generation, the use and improper disposal of pharmaceuticals and personal care products, and the discharge of domestic and industrial wastewater [7]. In this context, increasing attention is being paid to emerging contaminants, defined as insufficiently regulated or newly identified compounds that are detected in aquatic environments and may cause adverse effects on ecosystems and human health, even at low concentrations [5,8–10]. These contaminants include both synthetic and natural chemical compounds that persist in the environment and pose risks to both aquatic and terrestrial environments, despite their often-low concentrations [11–14].

In addition, interactions between emerging contaminants and conventional pollutants remain insufficiently explored, particularly in the context of cumulative exposure [5,15,16].

As surface water and groundwater are important sources of drinking water supply, maintaining their quality is essential for safe use [4,17]. In this context, ensuring water quality is a key component of sustainable development, which is directly linked to global objectives related to public health and the responsible management of freshwater resources.

Nevertheless, water resources management and aging hydraulic infrastructure continue to pose significant challenges in many situations, mainly because of the complexity of factors influencing water quality and quantity, as well as limitations in the availability of relevant data (Figure 1) [10,18].



**Figure 1.** Sources, transport pathways, and effects of pollutants in the aquatic environment and on human health.

Thus, the relationship between pollution sources, transport processes, and their impacts on both human health and ecosystem integrity can be described using a cause–effect framework that includes the contamination source, transport medium, transformation processes, exposure pathways, and exposed human and ecological receptors.

Water contamination involves various pollutants, including pathogenic microorganisms, heavy metals, pesticides, pharmaceutical compounds, and emerging contaminants originating from domestic, agricultural, and industrial activities [6,19]. These contaminants may adversely affect human health and continue to pose significant challenges for water quality monitoring and management, particularly in the case of pesticides, pharmaceuticals, and emerging pollutants [20].

Human health risks associated with exposure to water contaminants are assessed by correlating the toxicological properties of pollutants with population exposure levels, following a structured methodology that includes hazard identification, exposure assessment, contaminant quantification, and application of dose–response mathematical models [21]. Exposure to polluted water can produce acute effects (gastrointestinal illness following short-term, high-concentration exposure) or chronic effects (cardiovascular disease, neurological disorders, and cancer resulting from prolonged low-level exposure) [12,22,23].

In risk assessment studies, this probability is evaluated by correlating the toxicological characteristics of contaminants with the level of population exposure [24–26]. Risk assessment methodology generally involves several sequential steps, including hazard identification, exposure assessment, determination of contaminant concentrations, and application of mathematical models to quantify human health risk based on dose–response relationships [27].

Heavy metals represent a major risk category, entering surface waters primarily through industrial processes [28–30] and accumulating in human organisms via drinking water ingestion, dermal absorption, and consumption of contaminated food products [31–33].

Studies from China have reported arsenic concentrations exceeding drinking water standards and carcinogenic risks above acceptable thresholds, highlighting the public health significance of groundwater contamination [34]. This study further showed that the health risks associated with oral exposure to arsenic are significantly higher than those resulting from dermal exposure. Additionally, the carcinogenic risk was higher in adults than in children, whereas the non-carcinogenic risk was more pronounced in children than in adults [34].

The consequences are significant, as poor water quality is associated with more than 50 waterborne diseases and is a major determinant of child mortality, responsible for approximately half of all global child deaths. Furthermore, it is estimated that approximately 80% of diseases in developing countries are linked to the consumption of contaminated water and inadequate sanitation conditions [1,31–33].

Similarly, elevated heavy metal concentrations in leachates and adjacent water bodies have been associated with increased carcinogenic risks, particularly through oral exposure pathways [35].

Economic development has intensified agricultural activities, leading to a significant increase in non-point source freshwater pollution [36]. Studies have shown that rural watersheds are predominantly contaminated with nitrogen-based fertilizers, nutrients, microorganisms, and pesticides, whereas urban watersheds exhibit elevated concentrations of petroleum hydrocarbons, heavy metals, pesticides, microbes, and organic nutrients [36–38]. This contributes to water quality degradation and adversely affects aquatic ecosystems and human health [36].

Beyond heavy metals, emerging contaminants including pharmaceutical residues, pesticides, and petroleum hydrocarbons further compound health risks [39–41]. Their persistence, bioactivity, and capacity to disrupt ecosystems and human health further amplify their environmental significance [40,42,43].

A study reported average concentrations of pharmaceutical compounds of 2068 ng/L during the dry season and 2860 ng/L during the rainy season, highlighting a significant increase in contaminant concentrations during periods with precipitation. This seasonal variation suggests that the input of pharmaceutical pollutants into surface water and groundwater is amplified during the rainy season, most likely due to runoff, mobilization, and diffuse transport processes from urban and agricultural areas [44]. These findings further demonstrate the complexity of contaminant transport and exposure scenarios in aquatic environments [42].

Thus, to reduce and prevent the pollution of surface and groundwater generated by processes of industrialization, urbanization, and intensification of agricultural activities, the European Union (EU) has established a comprehensive framework of policies and regulations dedicated to water resource management [45]. Initially, these directives were developed in a sectoral manner, but with the adoption of the Water Framework Directive, it was emphasized that challenges related to drinking water quality cannot be addressed solely through legislative instruments. This is because they are intrinsically linked to the specific characteristics of each river basin and require the development of governance mechanisms that facilitate intersectoral cooperation and the involvement of authorities both within member states and at the transboundary level [45–47].

Unlike previous reviews that focused on specific contaminant groups, water quality assessment methods, or individual health outcomes, this review simultaneously integrates pollution sources, environmental transport processes, exposure pathways, risk assessment frameworks, treatment limitations, and human health impacts within a single analytical perspective. By combining a systematic review conducted according to PRISMA guidelines with bibliometric analysis, this work not only synthesizes current scientific knowledge but also identifies structural research gaps and emerging trends within the field. In particular, the analysis reveals persistent limitations in understanding cumulative exposure patterns, multi-pathway exposure dynamics, and contaminant mixture interactions, despite their importance for accurate health risk assessment. The novelty of this approach lies in integrating evidence synthesis with bibliometric mapping to provide both a comprehensive overview of existing knowledge and a quantitative evaluation of research evolution.

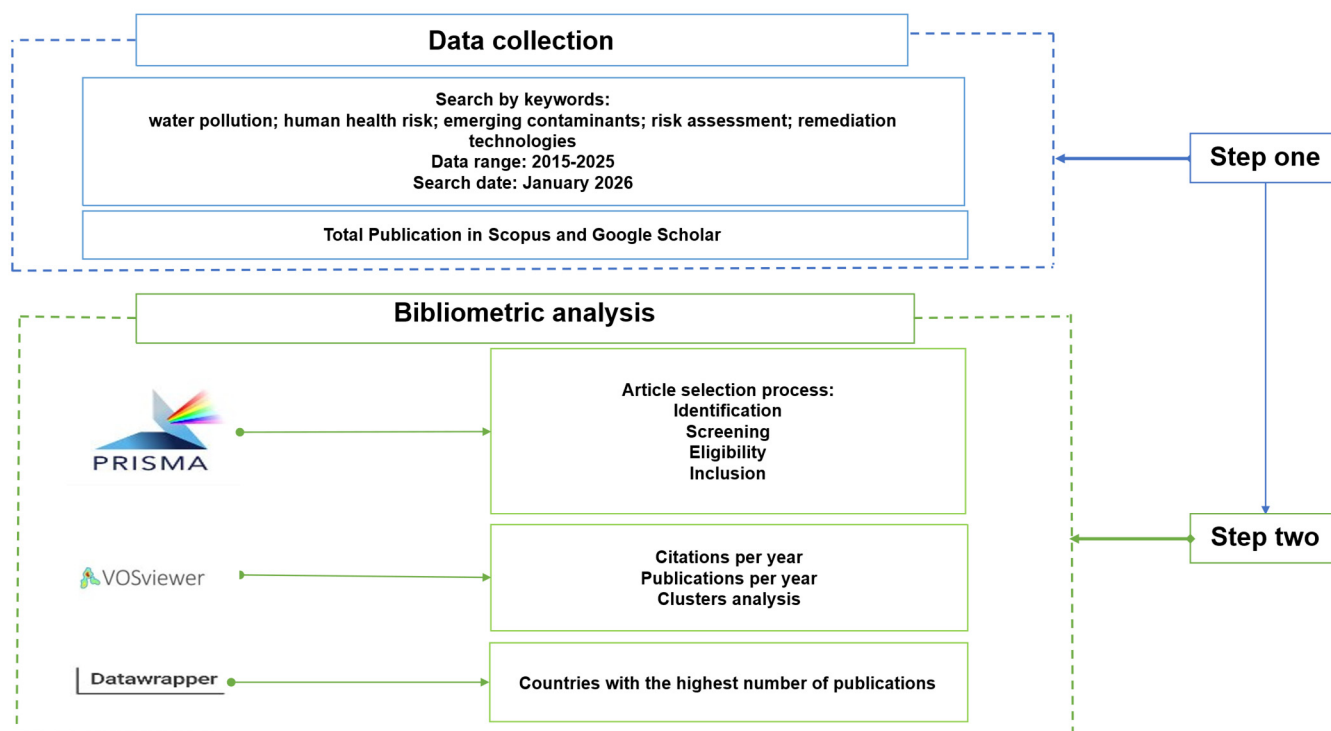
The findings also emphasize the importance of strengthening monitoring programs, advancing risk assessment methodologies, and addressing knowledge gaps related to emerging contaminants and long-term exposure effects. These efforts are critical for informing evidence-based environmental policies and enhancing the resilience of water management systems under changing environmental conditions.

## 2. Methodology

This study integrates a systematic literature review with bibliometric analysis using scientometric methods to obtain a comprehensive perspective on water pollution and its impact on human health (Figure 2). The integration of these approaches enables a comprehensive understanding of scientific development by combining evidence synthesis with quantitative mapping of research evolution.

The methodological workflow combined a systematic review and bibliometric analysis to provide both qualitative evidence synthesis and quantitative assessment of research trends and knowledge gaps [48]. PRISMA was selected to ensure methodological transparency, reproducibility, and traceability throughout study identification, screening, eligibility assessment, and inclusion processes [48,49]. In addition, bibliometric analysis based on specific scientometric methods has been used for the quantitative evaluation of scientific literature [50,51]. This approach allowed the investigation of publication dynamics,

identification of authors and high-impact papers, and analysis of relationships between concepts through keywords [52,53].



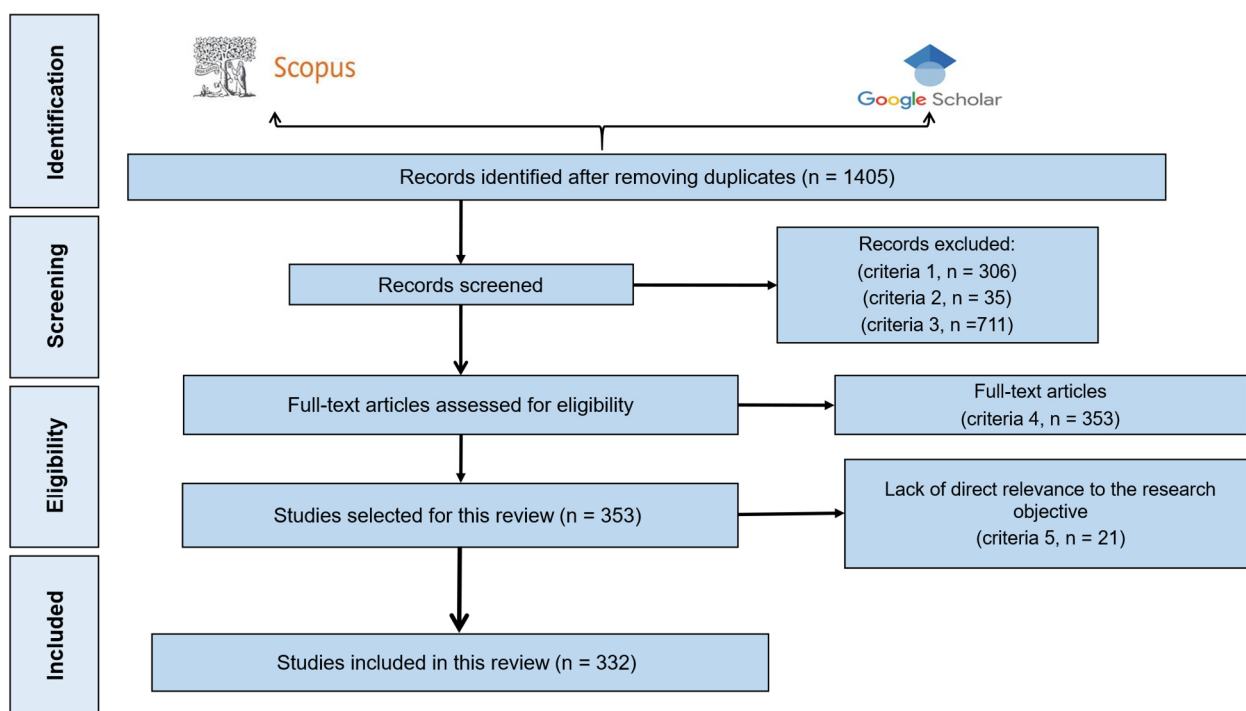
**Figure 2.** Data collection methodology and bibliometric analysis used in the study.

VOSviewer was used for the analysis and visualization of bibliometric data, which facilitates the construction and interpretation of scientific maps, including co-citation and keyword co-occurrence networks. This method highlights the conceptual structure of the field and identifies emerging research areas [54,55].

To analyze the geographical distribution of scientific publications, the web-based Data wrapper (Data wrapper GmbH, Berlin, Germany; <https://www.datawrapper.de>, accessed on 20 January 2026) platform was used to generate a thematic map reflecting the number of publications at the national level for the analyzed period. This approach enables the identification of countries with significant contributions to this field.

### 2.1. Systematic Review of Literature

This systematic review was conducted in accordance with the PRISMA guidelines, following a logical flow diagram and methodological protocol that included the steps of identification, screening, assessment of eligibility, and inclusion of relevant studies (Figure 3) [48,49]. A systematic literature search was performed in the electronic databases Scopus (<https://www.scopus.com/>, accessed on: 13 January 2026) and Google Scholar (<https://scholar.google.com>, accessed on: 17 January 2026). Queries were developed by combining keywords with Boolean operators (water pollution AND human health risk AND emerging contaminants AND risk assessment AND remediation technologies) to identify all relevant studies that met the scope and inclusion/exclusion criteria of this review.



**Figure 3.** Information flow using the PRISMA diagram applied in this study.

The inclusion and exclusion criteria were established to ensure the selection of studies directly related to water pollution, human health risks, contaminant exposure pathways, risk assessment approaches, and remediation technologies. Only English-language articles/reviews/reports published between 2015 and 2025 were considered. The search was restricted to the fields of environmental science, biochemistry, medical biology, and medicine, as these disciplines provide the most relevant evidence regarding water contamination and its impacts on human health.

Following the removal of duplicates, 1405 records were identified. Titles and abstracts were initially screened according to the predefined eligibility criteria. During this stage, 306 records were excluded under criterion 1 because they were published outside the selected time frame (2015–2025), 35 records were excluded under criterion 2 because they were not published in English, and 711 records were excluded under criterion 3 because they did not belong to the selected research fields (environmental science, biochemistry, medical biology, and medicine).

The eligibility assessment, and final study selection were conducted by the authors using the same predefined criteria throughout all stages of the review process to ensure consistency. The quality and relevance of the selected studies were evaluated based on their methodological clarity, availability of the full-text article, consistency of the reported findings, and relevance to the review objectives. A formal quality scoring system was not applied because the primary objective of this review was to provide a comprehensive synthesis of the available literature.

At this stage, only open-access publications were considered during the eligibility assessment (criterion 4), and all 353 records met this criterion. The dataset comprised 296 research articles, 8 conference papers, 40 review articles, 7 books, and 2 book chapters. A total of 18 records were excluded under criterion 5 because they did not directly address water pollution, human health risks, contaminants, or risk assessment.

This final screening step ensured that only studies providing direct evidence within the scope of the review were retained for the qualitative and bibliometric analyses. Consequently, the final dataset consisted of 332 publications.

## 2.2. Bibliometric Analysis

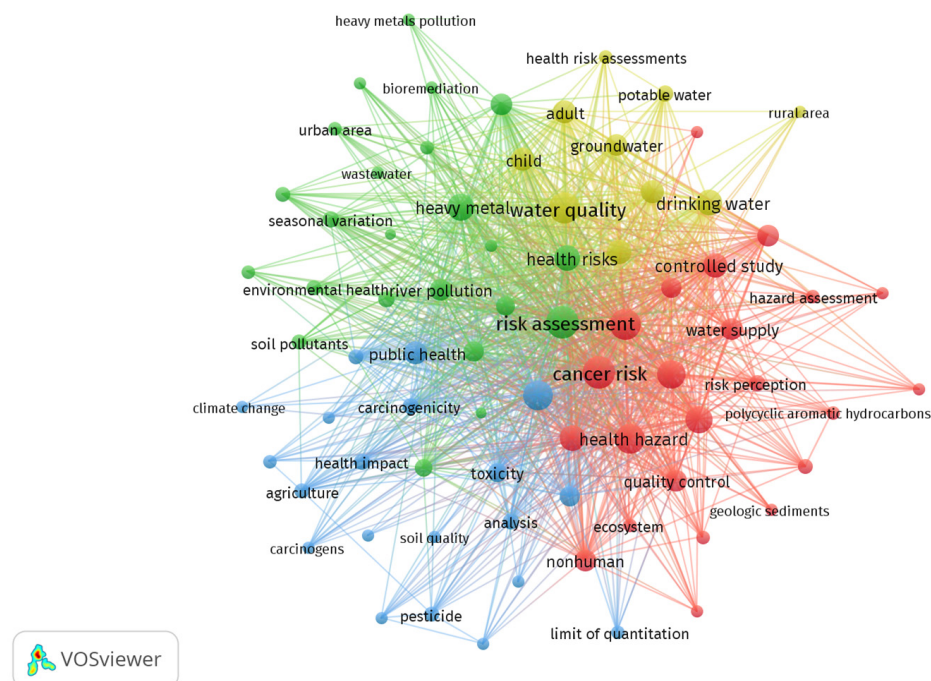
In this study, bibliometric analysis was performed using scientometric techniques implemented in VOSviewer software to visualize and interpret relationships among keywords within the scientific literature related to water pollution and human health risks [52,53]. Bibliometric analysis enables the results to be illustrated in the form of conceptual maps, facilitating the interpretation of relationships between different elements of the scientific literature [55,56]. In addition to its analytical capabilities and widespread application in bibliometric research, VOSviewer is a freely accessible and user-friendly platform that supports transparent and reproducible analytical workflow [54].

Bibliometric networks were constructed using bibliographic metadata extracted from the final dataset covering the period 2015–2025. Keyword co-occurrence analysis was selected because it enables the identification of dominant research themes and conceptual relationships within the scientific domain. To ensure a balance between thematic coverage and network interpretability, a minimum occurrence threshold keyword of three was applied. This threshold was chosen to retain both established and emerging research topics while minimizing the influence of isolated or infrequently used keywords. Only keywords meeting this criterion were included in the visualization and subsequent analysis. Network construction was performed using the association strength normalization method implemented in VOSviewer, which calculates similarities between terms based on their co-occurrence frequencies.

VOSviewer generates network visualizations, overlay maps, and density visualizations to facilitate interpretation of relationships between scientific elements [54,55]. Node size reflects keyword occurrence frequency, links indicate relationships between concepts, while total link strength (TLS) represents the cumulative intensity of associations between nodes. Higher TLS values indicate stronger conceptual connectivity within the scientific domain [55,56]. Clusters were generated automatically using the VOSviewer clustering algorithm, which groups keywords according to the strength of their co-occurrence relationships. Keywords exhibiting stronger internal associations were assigned to the same thematic cluster, allowing the identification of major research domains within the literature. The final network consisted of 4 clusters, each representing a distinct thematic area related to water pollution and human health.

Figure 4 presents the keyword co-occurrence network organized into four thematic clusters differentiated by color.

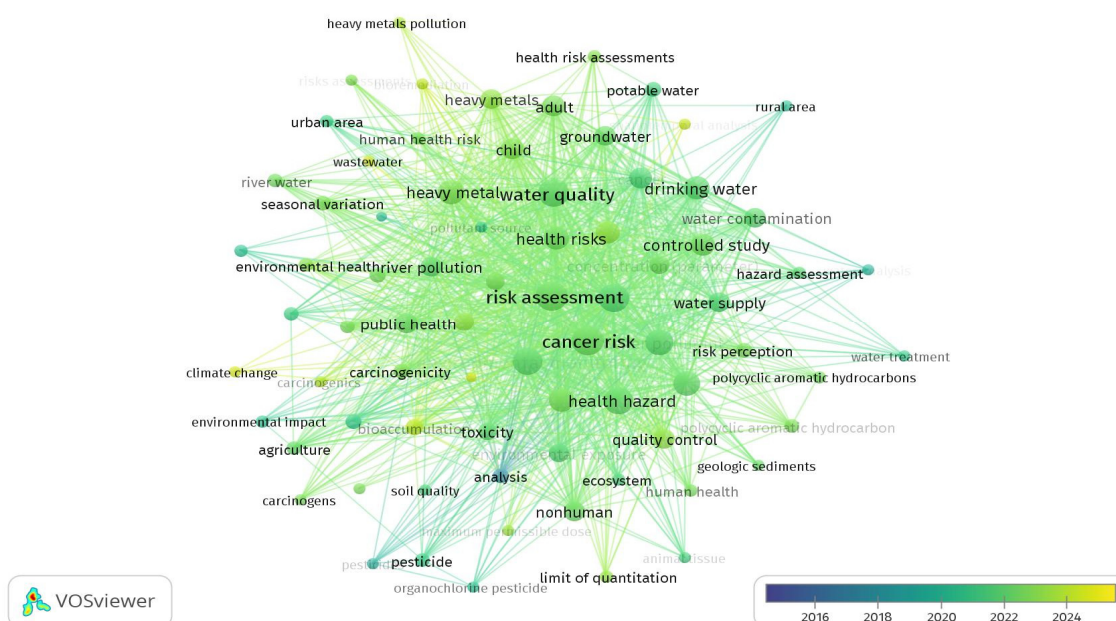
Cluster 1 (red) represents the most interconnected thematic domain focusing on human health risk assessment associated with water contamination. Cluster 2 (green) highlights environmental dimensions of water pollution, including pollution sources, water quality, and remediation processes. Cluster 3 (blue) emphasizes analytical and toxicological foundations supporting environmental and health-related investigations. Cluster 4 (yellow) focuses on water resources and population exposure pathways associated with human health risks. The strong interconnections among these clusters indicate that research in this field is increasingly evolving toward multidisciplinary and integrated approaches. In particular, the close relationships between environmental contamination, exposure pathways, toxicological assessment, and human health risk evaluation reflect a growing scientific interest in understanding the complete pathway from pollution sources to adverse health outcomes.



**Figure 4.** Keyword co-occurrence map on the analyzed topic showing cluster division.

Overall, the bibliometric structure demonstrates a clear transition from traditional water quality monitoring studies toward integrated research frameworks that combine environmental contamination, exposure assessment, toxicological evaluation, and human health risk assessment. This trend reflects the increasing recognition that water pollution should be addressed through multidisciplinary approaches capable of linking environmental processes with public health outcomes.

Figure 5 presents the overlay visualization bibliometric map generated using VOSviewer, highlighting the co-occurrence relationships of keywords and the temporal evolution of research in the field of water quality and health risk.



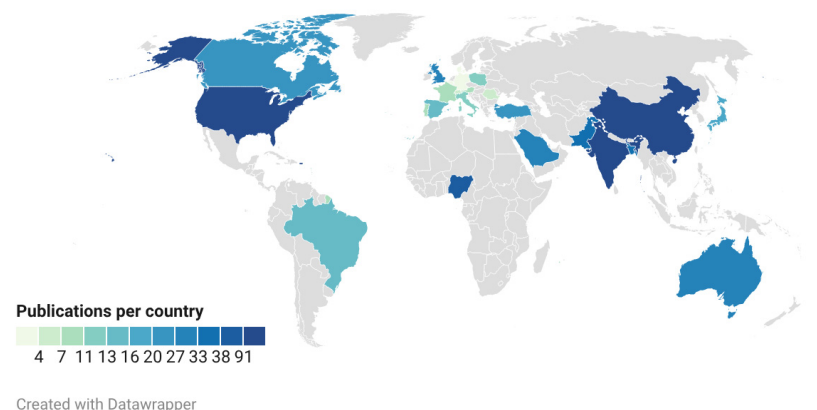
**Figure 5.** Overlay bibliometric map of keyword co-occurrence and temporal evolution of research in the field of water quality and health risks.



These findings highlight current research priorities and confirm the increasing importance of multidisciplinary frameworks for addressing water pollution challenges.

### 2.3. Data Visualization Using Data Wrapper

According to Figure 7, scientific activity is concentrated in China, the United States, and India, followed by European countries such as Germany and France. The predominance of these countries may be associated with greater research capacity, higher investments in scientific infrastructure, and stronger funding support for environmental and public health research. In addition, rapid industrialization, urban expansion, and increasing environmental pressures may contribute to prioritizing research related to water pollution and associated health risks.



**Figure 7.** Geographical distribution of scientific publications on water pollution and its impact on human health analyzed in this study.

Higher publication outputs may also reflect the existence of more developed regulatory frameworks and monitoring programs, which facilitate data collection, environmental assessment, and scientific reporting. In countries such as China and India, high research productivity may additionally be influenced by the substantial water pollution challenges associated with population growth, industrial activities, and agricultural intensification.

Countries with lower publication outputs, particularly in parts of Africa and South America, may face limitations related to research funding, institutional capacity, scientific infrastructure, and differences in national research priorities. In some regions, limited monitoring networks and reduced access to analytical facilities may further constrain scientific research and reporting activities, despite the presence of significant water quality challenges. The observed geographical distribution therefore highlights disparities in scientific productivity, regulatory capacity, and environmental monitoring systems, emphasizing the importance of strengthening international collaboration and expanding research efforts in underrepresented regions.

## 3. Water Pollution: Sources and Types of Pollutants

### 3.1. Classification of Pollution

Water pollution involves the enrichment of surface or groundwater with chemical compounds, substances, organisms, and/or pathogens through natural activities, leading to changes in the chemical, physical, and biological composition of water resources and negatively affecting the health of all forms of life [10,57,58].

According to the United States Environmental Protection Agency, water pollution is classified into two categories based on the mode of generation and the possibility of identifying the source.

Point-source pollution originates from sources that can be easily identified and monitored and is characterized by the direct discharge of pollutants at well-defined locations. Relevant examples include industrial facilities, oil extraction operations, wastewater treatment plants, and the maritime transportation of petroleum products [58–62]. Non-point source pollution is associated with diffuse sources that are difficult to spatially identify and control operationally because there is no single discharge point. It is mainly generated by agricultural activities, the use of fertilizers and pesticides, and other anthropogenic practices, with widespread impacts on river basins [57,58,63].

Thus, to better understand the origin and nature of pollutants, as well as to support pollution prevention, pollutants have been classified into three main categories according to their origin, chemical composition, and mode of action (Table 1) [57].

**Table 1.** Classification of water pollutants according to origin, chemical composition, and mode of action.

| Classification                    | Category                  | Characteristics                                                                   | Representative Examples                                           | Environmental and Health Implications                      |
|-----------------------------------|---------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------|------------------------------------------------------------|
| Classification by source          |                           |                                                                                   |                                                                   |                                                            |
| Source                            | Point-source pollutants   | Pollutants discharged from identifiable and localized sources                     | Industrial effluents, wastewater treatment plants, oil refineries | Easier monitoring and control, Localized exposure risks    |
|                                   | Diffuse-source pollutants | Pollutants originating from dispersed activities without a single discharge point | Agricultural runoff, urban stormwater, atmospheric deposition     | Complex monitoring, Widespread environmental contamination |
| Classification by chemical nature |                           |                                                                                   |                                                                   |                                                            |
| Chemical nature                   | Organic pollutants        | Carbon-based contaminants originating from anthropogenic activities               | Pesticides, hydrocarbons, pharmaceuticals, detergents             | Persistence, bioaccumulation, endocrine disruption         |
|                                   | Inorganic pollutants      | Non-carbon-based compounds including metals and nutrients                         | Heavy metals, nitrates, phosphates                                | Toxicity, eutrophication, carcinogenicity                  |
|                                   | Biological pollutants     | Living microorganisms capable of causing disease                                  | Bacteria, viruses, protozoa                                       | Waterborne diseases                                        |
|                                   | Physical pollutants       | Materials affecting physical properties of water                                  | Sediments, plastics, suspended solids                             | Turbidity, habitat degradation                             |

Table 1. Cont.

| Classification                            | Category                   | Characteristics                                           | Representative Examples                              | Environmental and Health Implications          |
|-------------------------------------------|----------------------------|-----------------------------------------------------------|------------------------------------------------------|------------------------------------------------|
| Classification by environmental behavior  |                            |                                                           |                                                      |                                                |
| Environmental behavior                    | Biodegradable pollutants   | Compounds susceptible to biological degradation           | Organic matter, biodegradable organic compounds      | Oxygen depletion and microbial proliferation   |
|                                           | Persistent pollutants      | Compounds resistant to degradation                        | Microplastics, persistent pesticides, heavy metals   | Long-term accumulation and chronic exposure    |
|                                           | Bioaccumulative pollutants | Compounds accumulating in organisms and food chains       | Mercury, PCBs, organochlorine pesticides             | Biomagnification and chronic toxicity          |
| Classification by toxicological relevance |                            |                                                           |                                                      |                                                |
| Toxicological relevance                   | Toxic pollutants           | Substances inducing toxic effects at low concentrations   | Heavy metals, pesticides                             | Neurotoxicity and carcinogenic effects         |
|                                           | Nutrient pollutants        | Compounds promoting eutrophication                        | Nitrogen, phosphorus                                 | Eutrophication and ecosystem imbalance         |
|                                           | Emerging contaminants      | Newly recognized or insufficiently regulated contaminants | Pharmaceuticals, microplastics, endocrine disruptors | Chronic low-dose exposure and mixture toxicity |

### 3.2. Pesticides and Diffuse Contamination Pathways

According to the specialized literature, a cause—effect relationship has been established between human activities and water pollution, as well as the associated health risks. Most anthropogenic activities, under the influence of urbanization and industrial development, result in the discharge of effluents into urban areas [60,61,64].

Recent studies have identified intensive agricultural practices as one of the major drivers of water resource contamination at the global scale. Unlike point-source pollution associated with industrial or municipal discharges, agricultural pollution is predominantly diffuse, which considerably complicates its monitoring, quantification, and regulatory control. Consequently, agricultural runoff represents a major transport pathway for contaminants into both surface water and groundwater systems [65–67]. Agricultural practices generate complex mixtures of pollutants, including pesticides, fertilizers, organic matter, sediments, pharmaceutical residues, microplastics, and pathogenic agents [68,69].

This diversity of contaminants reflects the transition of agriculture from a traditional activity to an intensive and chemically driven system, with increasing implications for environmental quality and human health.

From an integrated risk perspective, agricultural contamination should not be evaluated solely through the occurrence of individual pollutants but through cumulative exposure scenarios involving contaminant mixtures, environmental transport processes, treatment limitations, and long-term health implications. Agricultural runoff frequently contains multiple contaminants simultaneously, increasing the likelihood of additive or synergistic toxicological effects that remain insufficiently characterized within conventional pollutant-specific assessment frameworks [70,71].

In the EU, more than 150 distinct types of such substances are authorized and used in agriculture to increase crop yield and quality, as well as to optimize economic benefits [72]. However, the intensification of agricultural practices in recent decades has significantly increased the occurrence of pesticides, fertilizers, trace elements, salts, and pathogenic agents in both surface water and groundwater systems [73,74].

The environmental occurrence of pesticides is strongly influenced by hydrological processes, particularly surface runoff generated by precipitation, snowmelt, and irrigation. In addition, infiltration processes facilitate the transport of soluble compounds into groundwater, while adsorption to soil particles enables the mobilization of less soluble pesticides through erosion and sediment transport [75–78].

Owing to their environmental persistence, mobility, and resistance to degradation, many pesticides remain detectable in aquatic systems long after application, increasing the probability of chronic low-dose exposure and bioaccumulation within trophic chains [70,75,79,80]. Due to their persistence and physicochemical properties, many pesticides exhibit high environmental stability, allowing them to remain in aquatic systems long after application. A critical aspect highlighted in the literature is the ability of certain pesticides to bioaccumulate in aquatic organisms and biomagnified along trophic chains, resulting in elevated concentrations at higher trophic level [81,82].

From an integrated risk perspective, pesticide-related health risks depend not only on concentration levels but also on environmental persistence, transport mechanisms, physicochemical properties, cumulative exposure pathways, and treatment performance. Human exposure occurs through multiple pathways including contaminated drinking water consumption, irrigation-derived food products, dermal exposure, inhalation, and trophic transfer processes resulting from bioaccumulation [83].

Environmental risk is additionally influenced by climatic and hydrological drivers such as precipitation intensity, soil properties, irrigation practices, contaminant solubility, and degradation dynamics. Climate-related changes affecting runoff intensity and groundwater recharge may further increase contaminant mobility and exposure probability.

Human exposure to pesticide residues primarily occurs through the consumption of contaminated drinking water and agricultural products, although dermal contact and inhalation may also contribute under specific environmental or occupational conditions. Chronic exposure to pesticide residues has been associated with endocrine disruption, neurotoxicity, reproductive disorders, and increased carcinogenic risk. An analysis correlating pesticide use with longitudinal health data demonstrated that a 10% increase in pesticide application was associated with an approximately 1% increase in the medical disability index among the population aged over 65 years, highlighting significant public health implications [84].

Empirical evidence confirms the widespread presence of pesticides in aquatic environments. For example, studies conducted in the Gangetic river basin identified 39 pesticide compounds in groundwater, with 32% of samples containing multiple residues. Frequently detected substances, such as malathion, atrazine, and chlorpyrifos, were found at concentrations exceeding permissible limits by up to 46 times, indicating severe contamination levels [85].

Similar findings have been reported in other regions, including Southeast Asia and Europe, where both organochlorine and organophosphorus pesticides persist in surface waters despite regulatory restrictions [76].

A study conducted on the Selangor River (Malaysia) identified the presence of organochlorine pesticides (lindane, heptachlor, endosulfan, dieldrin, endosulfan sulphate) and organophosphorus pesticides (chlorpyrifos and diazinon) in surface water. The determined concentrations ranged from 10.1 ng/L (lindane) to 1848.7 ng/L (endosulfan),

indicating a significant level of pollution. The study associated water quality degradation with agricultural, urban, and industrial activities, as well as population growth, while also emphasizing that conventional treatment technologies do not ensure the complete removal of these compounds [86].

In addition to pesticides, fertilizers represent another major source of agricultural water pollution. Nitrogen and phosphorus based fertilizers can reach aquatic systems through surface runoff and infiltration processes, contributing to nutrient enrichment and groundwater contamination [78]. Excessive use of fertilizers leads to the accumulation of nitrates, which are formed by the biological transformation of nitrogen and are characterized by high solubility and mobility, facilitating their leaching into groundwater [78,87].

At the EU level, approximately 38% of water bodies are affected by significant pressure generated by nitrogen pollution of groundwater. This phenomenon reflects a major pollution trend observed mainly in high-income countries, where agriculture has become the main source of water quality degradation, surpassing the impact of urbanization and industrial activities [69,88,89].

In this context, agricultural practices are considered responsible for the eutrophication of inland and coastal waters, as well as for the accumulation of nitrates and salts in groundwater resources. Bisimwa et al., 2022, noted that massive runoff resulting from agricultural land-use practices has a negative influence on surface water quality, also constituting a cause of the eutrophication phenomenon [90].

Despite the extensive body of literature on agricultural pollution, several critical knowledge gaps remain. Most existing studies continue to focus on individual contaminants rather than complex contaminant mixtures, although real environmental exposure scenarios involve multiple interacting substances simultaneously [38,65,88]. In addition, cumulative exposure, chronic low-dose effects, transformation products, and long-term health implications remain insufficiently understood, particularly for vulnerable population groups.

Current treatment technologies also present limitations because conventional systems often demonstrate variable removal efficiencies for persistent pesticides and their transformation products, allowing residual contamination to persist within drinking water systems and increasing concerns regarding chronic exposure.

### 3.3. Heavy Metal Ions

Globally, it is estimated that approximately 40% of rivers and lakes are contaminated with heavy metals, highlighting the extent of this phenomenon [91]. Heavy metal contamination represents one of the most persistent and hazardous forms of water pollution because of the environmental persistence, non-biodegradability, toxicity, and bioaccumulation potential of these elements (Table 2) [92].

**Table 2.** Sources and types of heavy metal pollution reported in different regions.

| Metal                            | Source Category                     | Pollution Type | Location           | Reference |
|----------------------------------|-------------------------------------|----------------|--------------------|-----------|
| Aluminium<br>(Al <sup>3+</sup> ) | Natural (geogenic)                  | Natural        | Bulgaria           | [93]      |
|                                  | Drinking water treatment            | Anthropogenic  | Poland             | [94]      |
|                                  | Industrial activities               | Anthropogenic  | Multiple countries | [95]      |
| Arsenic<br>(As <sup>3+</sup> )   | Natural (geogenic)                  | Natural        | Southwest China    | [96]      |
|                                  | Industrial and wastewater discharge | Anthropogenic  | Nigeria            | [97]      |
|                                  | Mining activities                   | Anthropogenic  | Colombia           | [98,99]   |

Table 2. Cont.

| Metal                                              | Source Category                            | Pollution Type | Location                      | Reference |
|----------------------------------------------------|--------------------------------------------|----------------|-------------------------------|-----------|
| Copper<br>(Cu <sup>2+</sup> )                      | Mining activities                          | Anthropogenic  | Uganda                        | [100]     |
|                                                    | Natural (geogenic)                         | Natural        | China                         | [101,102] |
| Chromium<br>(Cr <sup>3+</sup> , Cr <sup>6+</sup> ) | Industrial activities                      | Anthropogenic  | China                         | [103]     |
|                                                    | Natural (geogenic)                         | Natural        | Europe                        | [104]     |
| Iron<br>(Fe <sup>2+</sup> , Fe <sup>3+</sup> )     | Industrial activities                      | Anthropogenic  | Vietnam                       | [105]     |
|                                                    | Natural (geogenic)                         | Natural        | Bangladesh                    | [106,107] |
| Manganese<br>(Mn <sup>2+</sup> )                   | Agricultural activities                    | Anthropogenic  | Egypt                         | [108]     |
|                                                    | Mining activities                          | Anthropogenic  | Kovdorsky District,<br>Russia | [109]     |
| Mercury<br>(Hg <sup>2+</sup> )                     | Industrial and wastewater<br>discharge     | Anthropogenic  | Germany                       | [110]     |
|                                                    | Natural (geogenic)                         | Natural        | France                        | [111]     |
| Nickel<br>(Ni <sup>2+</sup> )                      | Mixed (industrial and geogenic<br>sources) | Mixed          | Italy                         | [112]     |
|                                                    | Agricultural activities                    | Anthropogenic  | Romania                       | [113]     |
| Lead<br>(Pb <sup>2+</sup> )                        | Mining activities                          | Anthropogenic  | Mexico                        | [114]     |
|                                                    | Industrial and geogenic sources            | Mixed          | Pakistan                      | [115]     |
| Zinc<br>(Zn <sup>2+</sup> )                        | Natural (geogenic)                         | Natural        | China                         | [116]     |
|                                                    | Mining activities                          | Anthropogenic  | Japan                         | [117]     |

Unlike many organic contaminants, heavy metals cannot be degraded into harmless compounds and may persist in aquatic environments for prolonged periods, increasing the probability of chronic human exposure through drinking water consumption and food chain transfer.

Heavy metal ions originate from both natural and anthropogenic sources. Natural (geogenic) inputs include rock weathering, volcanic activity, and geochemical evolution processes, whereas anthropogenic contributions are associated with mining and smelting, industrial production, wastewater discharge, and agricultural practices [118].

The relative contribution of these sources varies significantly depending on geological conditions, hydrological characteristics, land use patterns, and the intensity of human activities. In addition, the environmental behavior and toxicity of heavy metals are strongly influenced by their chemical speciation, oxidation state, mobility, and bioavailability, which determine their persistence, transport, and uptake by aquatic organisms and humans.

From an integrated risk perspective, heavy metal contamination represents a multi-factorial environmental challenge requiring simultaneous consideration of contaminant sources, environmental transport processes, metal speciation, bioavailability, and cumulative exposure pathways. Unlike conventional pollutant-specific assessments, integrated risk frameworks recognize that metal toxicity is controlled not only by concentration levels but also by chemical form, oxidation state, environmental mobility, and interactions with co-occurring contaminants [119].

Environmental parameters including pH, redox potential, dissolved organic matter, salinity, and hydrological conditions strongly influence metal transport and bioavailability, thereby affecting exposure probability and toxicological outcomes. Furthermore, climate-related hydrological variability may alter contaminant mobilization dynamics and increase long-term exposure uncertainty.

Among heavy metals, As is considered one of the most critical contaminants due to its high toxicity and carcinogenic potential. Its presence in groundwater has been identified as a major public health concern worldwide [120–122]. A study conducted in the Murshidabad district (West Bengal, India) demonstrated that 54.6% of groundwater samples used for drinking exceeded the permissible limit of 10 µg/L, while 37.3% of samples used for irrigation exceeded recommended thresholds, indicating severe contamination linked to both natural and anthropogenic factors [123]. These findings suggest significant chronic exposure risks for populations dependent on untreated groundwater resources.

In a study conducted by Xu et al., 2017, high concentrations of Cd, Cu and Zn were reported in nine coastal rivers from the Laizhou Bay basin, with maximum values exceeding the permissible limits for drinking water and indicating a moderate ecological risk from these metals [124]. In two main rivers in Antalya (Turkey), elevated concentrations of heavy metals were identified, with strontium and Al values exceeding the permissible limits. These results indicate variable water quality, ranging from good to very poor in certain locations, and suggest the influence of anthropogenic factors and urbanization on pollution levels [125].

Another study assessed the presence and distribution of heavy metal ions in water resources from Pb–Zn mining areas in Abakaliki (Nigeria). A total of 106 water samples were analyzed across two seasons, and the results revealed high concentrations of heavy metals, most exceeding the limits recommended by the World Health Organization (WHO) for drinking water. Contamination was more pronounced near active mines and in surface waters, whereas seasonal variations indicated lower levels during the rainy season compared to the dry season [126].

Importantly, the simultaneous occurrence of multiple heavy metals represents an important challenge for integrated risk assessment because combined exposure may generate synergistic or additive toxicological effects that are insufficiently addressed within current regulatory and toxicological frameworks.

In recent years, wastewater reuse for agricultural irrigation has emerged as an additional pathway for heavy metal dispersion in the environment. Although wastewater reuse contributes to water conservation and nutrient recovery, insufficiently treated wastewater may promote the accumulation of metals in agricultural soils and facilitate their transfer into crops, groundwater, and food chains [127,128].

Consequently, human exposure may occur not only through drinking water consumption but also through indirect dietary pathways, increasing concerns regarding cumulative long-term exposure [129]. Despite extensive research on heavy metal contamination, several critical challenges remain. Current monitoring systems are frequently fragmented, particularly in developing regions with limited analytical and technical capacity.

In addition, conventional water treatment technologies often demonstrate limited efficiency for the complete removal of dissolved metal species under variable environmental conditions, especially in the presence of complex contaminant mixtures. Furthermore, most studies continue to focus on individual metals rather than cumulative exposure scenarios, although real environmental systems generally involve simultaneous exposure to multiple contaminants.

### 3.4. Emerging Contaminants in Water Pollution

Emerging pollutants encompass a broad range of chemical and biological substances, including pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals (EDCs), antibiotic resistance genes (ARGs), disinfection by-products, and persistent organic pollutants, which may pose risks to both environmental and human health [130–132].

The increasing occurrence of these contaminants in groundwater, surface waters, and drinking water resources has become a growing global concern because of their persistence, continuous release into the environment, and potential long-term ecological and health effects [130]. This situation highlights the urgent need to strengthen monitoring programs, improve risk assessment methodologies, and develop advanced treatment technologies capable of reducing their environmental and health impacts [133].

Although wastewater treatment plants are primarily designed to remove conventional pollutants, many pharmaceutical residues and other biologically active compounds are only partially removed during treatment processes [87,134,135]. Consequently, treated effluents represent an important pathway through which these substances are continuously released into aquatic environments, making wastewater treatment plants a significant source of emerging contaminants in surface waters.

Pharmaceutical compounds are generally classified as pseudo-persistent pollutants due to their continuous input into the environment, even if individual substances may exhibit moderate degradation rates [136]. The presence of active pharmaceutical ingredients (APIs) in aquatic environments, such as rivers, lakes, and oceans, because of their widespread use in the medical field, represents a global issue because of their persistence, bioactivity, and capacity to disrupt ecosystems and human health [137,138]. In addition, the simultaneous occurrence of multiple pharmaceutical classes in aquatic environments complicates environmental risk assessment because interactions between compounds may generate additive or synergistic toxicological effects.

APIs encompass a broad range of chemical classes, including antibiotics, anti-inflammatories, antiepileptics,  $\beta$ -blockers, hormones, cytostatic, and contrast agents [41,136]. The primary pathway for pharmaceutical contamination of freshwater systems is represented by effluents from wastewater treatment plants, which act as continuous point sources. Additional contributions originate from hospital discharges, pharmaceutical manufacturing, and domestic wastewater, reflecting the widespread use and disposal of medicinal products [136]. Human exposure to pharmaceutical residues may occur through drinking water consumption, recreational water contact, indirect dietary exposure, and food chain transfer, raising concerns regarding chronic low-dose exposure and cumulative toxicological effects.

Another important group of emerging contaminants of global concern is represented by per- and polyfluoroalkyl substances (PFAS). This class includes perfluoroalkyl sulfonates (PFSAs), such as perfluorooctane sulfonic acid (PFOS), perfluorobutane sulfonic acid (PFBS), and perfluorohexane sulfonic acid (PFHxS), as well as perfluoroalkyl carboxylic acids (PFCAs), including perfluorooctanoic acid (PFOA), perfluorohexanoic acid (PFHxA), and perfluorononanoic acid (PFNA). Due to their high environmental persistence, mobility, and resistance to conventional treatment processes, PFAS are frequently detected in surface waters, groundwater resources, and drinking water systems, raising increasing concerns regarding their potential impacts on environmental and human health [139,140].

Several studies have reported the widespread occurrence of perfluoroalkyl acids (PFAAs), including PFCAs and PFSAs, in aquatic environments. Concentrations of these compounds have been reported to reach up to 18,000 ng/L in river waters and 20,458 ng/L in wastewater effluents in China [141]. In addition, monitoring studies have detected PFOS in drinking water supplies, with concentrations reaching 2280 ng/L in Stockholm, highlighting the widespread distribution of PFAS and their potential implications for environmental and human health [142].

EDCs, including phthalate esters (PAEs) and bisphenol A (BPA), have received increasing attention due to their widespread occurrence in water resources and their potential impacts on human health and aquatic ecosystems [143]. Their presence in drinking water sources is of particular concern because these compounds may alter endocrine function

even at low concentrations. Furthermore, the occurrence of EDCs in water systems may increase the complexity and costs associated with water treatment and remediation processes aimed at ensuring safe drinking water supplies [143,144].

Several studies have confirmed the occurrence of EDCs in drinking water systems. Kumawat et al., 2020, reported the widespread presence of phthalates, including Di(2-ethylhexyl) phthalate (DEHP), Di-n-octyl phthalate (DNOP), and Dibutyl phthalate (DBP), in both source water and treated drinking water, indicating incomplete removal during treatment processes [145]. Wee et al., 2019, reported the occurrence of endocrine-disrupting chemicals in drinking water supplies worldwide, with concentrations in treated drinking water ranging from 0.2 ng/L to 5510 ng/L. The authors highlighted the widespread detection of EDCs in tap water and emphasized their potential implications for human exposure through drinking water consumption [146].

Emerging contaminants involve not only parent compounds but also transformation products, environmental persistence, and cumulative exposure scenarios, increasing the complexity of environmental and human health risk assessment.

Numerous studies have confirmed the global occurrence of pharmaceutical compounds in aquatic environments. Vålitalo et al., 2017, reported the widespread presence of pharmaceuticals in surface waters across Europe, Asia, and North America, with concentrations ranging from ng/L to µg/L and significant spatial and seasonal variability [147]. In Mexico, high concentrations of naproxen (732–4889 ng/L), acetaminophen (354–4460 ng/L), and diclofenac (258–1398 ng/L) were identified in both wastewater and surface waters, underscoring the limited efficiency of conventional treatment systems in removing biologically active compounds [148].

A large-scale monitoring study across 258 rivers in 104 countries detected 61 active pharmaceutical ingredients, with higher contamination levels in regions with inadequate wastewater infrastructure particularly Sub-Saharan Africa, South Asia, and South America and concentrations exceeding safe thresholds for aquatic organisms at 25.7% of sampling locations [149]. These results indicate not only ecological risks but also the potential for long-term human exposure through contaminated water resources.

Pharmaceutical residues have also been confirmed in river sediments, with diclofenac (9.53 ng/g), ibuprofen (134 ng/g), and naproxen (4.31 ng/g) detected in South African rivers [150]. Seasonal dynamics further amplify contamination, with mean pharmaceutical concentrations increasing from 2068 ng/L during the dry season to 2860 ng/L during the rainy season, reflecting enhanced mobilization and transport through surface runoff [44].

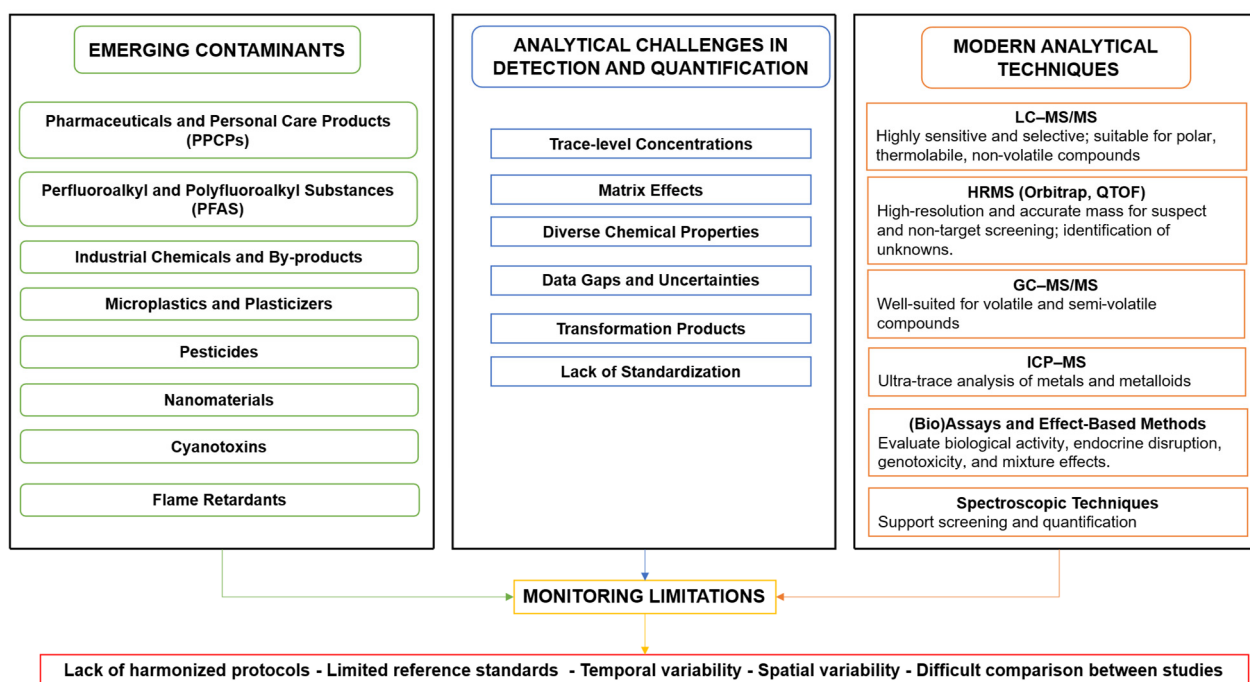
Importantly, the presence of pharmaceutical compounds is not limited to surface waters. Investigations of drinking water systems, such as those conducted in Lisbon, have identified multiple pharmaceutical residues in both raw and treated water, although generally at low concentrations (0.005–46 ng/L), raising concerns regarding chronic exposure [151].

Another important challenge is represented by pharmaceutical transformation products and metabolites generated during environmental degradation and wastewater treatment processes [152]. These compounds may exhibit different persistence, mobility, and toxicological profiles compared with parent compounds, further increasing uncertainty in environmental and human health risk assessment [133,153]. In addition, most existing studies continue to focus on individual compounds rather than realistic contaminant mixtures, although environmental exposure scenarios typically involve simultaneous exposure to multiple APIs and other contaminants.

Current evidence indicates that mixture toxicity, cumulative exposure, chronic low-dose effects, and integrated impact assessments remain insufficiently investigated. Furthermore, the absence of standardized monitoring protocols and harmonized regulatory

frameworks limits the comparability of studies and hinders the development of effective management strategies [154,155]. These challenges are further compounded by the limited ability of conventional wastewater treatment systems to effectively remove biologically active micropollutants, resulting in the continuous release of pharmaceutical residues and transformation products into aquatic environment.

An additional challenge associated with emerging pollutants is their detection and quantification in environmental matrices. Many compounds, including PFAS, pharmaceutical residues, endocrine-disrupting chemicals, and microplastics, occur at trace concentrations and require advanced analytical techniques such as liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS), high-resolution mass spectrometry (HRMS), gas chromatography-mass spectrometry (GC-MS), and spectroscopic methods for reliable identification and quantification (Figure 8) [156,157].



**Figure 8.** Emerging contaminants: analytical challenges, detection techniques, and implications for environmental monitoring.

Analytical limitations are related to detection limits, matrix effects, transformation products, and the lack of standardized monitoring protocols may contribute to uncertainties in exposure assessment and risk characterization.

Consequently, the advancement of analytical tools, harmonized monitoring protocols, and comprehensive surveillance strategies remains essential for improving contaminant assessment.

### 3.5. Water Pollution with Plastic Materials

Plastic materials, particularly microplastics, represent a relatively new category of emerging contaminants, and the identification of sources, characterization of composition, and assessment of environmental occurrence remain major challenges [68,158,159].

Owing to their persistence, mobility, and resistance to degradation, microplastics have attracted increasing scientific attention as potential vectors for contaminant transport and chronic human exposure. However, the identification of sources, characterization of polymer composition, environmental distribution, and assessment of toxicological impacts continue to represent major scientific and regulatory challenges.

To date, most studies on microplastics (MP) have focused on the marine environment, whereas freshwater systems remain insufficiently investigated, highlighting a significant knowledge gap in this field [68,160,161]. MP are mainly composed of synthetic polymers such as polyvinyl chloride, nylon, polyethylene terephthalate, polyethylene, polypropylene, polystyrene, polyvinyl alcohol, and polyamide [158,162]. Their environmental behavior is strongly influenced by polymer density, particle size, morphology, and physicochemical properties, which determine buoyancy, transport mechanisms, sedimentation, and potential bioavailability within aquatic systems.

MP can be classified into two main categories: primary MP, which are intentionally produced for industrial or domestic uses, such as plastic resin pellets or raw material granules used in industry and as abrasives in cosmetic products and secondary MP, which result from the fragmentation of larger plastic materials under the action of ultraviolet radiation and mechanical wear [163]. This distinction is important because secondary microplastics represent a continuously increasing source of diffuse contamination resulting from the degradation of plastic waste in the environment.

Recent studies have mainly focused on methods for the identification and quantification, toxicity, and monitoring of microplastics [164–166]. Nevertheless, substantial uncertainty persists regarding their long-term environmental fate, interactions with other pollutants, and associated human health risks. In addition to their intrinsic physical and chemical properties, microplastics may act as carriers for heavy metals, persistent organic pollutants, pharmaceutical compounds, and pathogenic microorganisms, thereby increasing the complexity of environmental exposure scenarios and integrated risk assessment.

From an integrated risk perspective, MP contamination involves both direct particle toxicity and indirect environmental risks associated with contaminant transport mechanisms. Beyond their intrinsic physicochemical properties, microplastics may function as environmental vectors facilitating the transport of heavy metals, pesticides, pharmaceutical compounds, and pathogenic microorganisms across environmental compartments.

Particle characteristics including polymer composition, size distribution, morphology, density, and surface properties strongly influence environmental mobility, adsorption capacity, and biological interactions, thereby determining exposure probability and toxicological relevance.

Empirical evidence confirms the widespread occurrence of MP in freshwater ecosystems. A study conducted on the Ciwalengke River (Indonesia) identified the presence of microplastics at all 10 sampling points, both in surface water and sediments. The mean concentrations were  $5.85 \pm 3.28$  particles/L in water and  $3.03 \pm 1.59$  particles/100 g dry sediment, with fibers being the predominant form. The sources of contamination were mainly associated with industrial activities and domestic use, particularly washing processes [167]. Another study on the Karstic Yulong River (China) confirmed the presence of MP in both water and sediments, with higher concentrations in inhabited areas. Their distribution in groundwater is mainly influenced by hydraulic exchanges with surface water [168]. The study further highlighted the role of hydraulic interactions between groundwater and surface water in controlling microplastic distribution within aquatic environments [168].

Recent research indicates that MP are present not only in surface aquatic environments but also in soils and aquifers, suggesting the existence of transfer processes between environmental compartments.

However, the mechanisms of migration from soil to groundwater remain insufficiently understood. In this context, Cheng et al., 2024, analyzed integrated soil groundwater river water sections and highlighted the presence of microplastics in all investigated matrices. Concentrations ranged between 392–836 n/kg in soil (mean:  $655 \pm 177$  n/kg), 0.58–2.48 n/L in groundwater (mean:  $1.23 \pm 0.42$  n/L), and 0.38–1.80 n/L in river water

(mean:  $0.86 \pm 0.41$  n/L) [159]. These findings highlight the mobility of MP across interconnected environmental systems and suggest the potential for widespread human exposure through multiple pathways.

In parallel, recent studies have reported the presence of fine MP particles in bottled drinking water, attributing contamination mainly to packaging materials [169]. These findings raise concerns regarding chronic human exposure through drinking water consumption and support the need for integrated risk assessment approaches capable of evaluating cumulative exposure and long-term toxicological effects.

Although the health implications of MP exposure remain incompletely understood, recent studies suggest potential associations with oxidative stress, inflammatory responses, endocrine disruption, and the transport of adsorbed contaminants into biological systems.

However, the analysis of specialized literature indicates that research on MP in freshwater ecosystems remains limited and fragmented, given that most studies have focused on the marine environment, resulting in a significant knowledge deficit in this field [68]. Most investigations continue to focus on urban pollution sources, whereas agricultural contributions, despite the extensive use of plastic materials in modern agriculture, remain insufficiently investigated [68,170].

These limitations highlight the inadequacy of conventional pollutant-specific assessment approaches and support the development of integrated risk-based frameworks capable of simultaneously addressing contaminant interactions, environmental transport mechanisms, cumulative exposure pathways, and residual health risks.

### 3.6. Microbiological Water Pollution

Microbiological pollution of surface water and groundwater resources represents one of the most significant water-related public health challenges worldwide because of its direct association with waterborne diseases, fecal contamination, and the dissemination of pathogenic microorganisms [171,172].

This form of contamination is primarily caused by bacteria, viruses, protozoa, and helminths originating from human and animal fecal sources, with substantial implications for both public health and aquatic ecosystem stability [172]. This type of pollution is closely linked to anthropogenic activities, particularly the discharge of insufficiently treated wastewater, the use of organic fertilizers in agriculture, leakage from septic systems, and surface runoff generated by precipitation [173].

Both point and diffuse pollution sources contribute significantly to pathogen dissemination within aquatic systems. Point sources include effluents from wastewater treatment plants, healthcare facilities, and industrial discharges, for which strong correlations have been identified between pathogen concentrations and urbanization intensity [174]. At the same time, significant contributions may also arise from diffuse sources, including the application of sewage sludge and manure on agricultural land [88].

Several studies have demonstrated that the discharge of untreated wastewater into rivers and lakes, together with inadequately designed septic systems, contributes substantially to groundwater contamination in numerous regions worldwide [175,176].

This issue is particularly critical in low- and middle-income regions lacking efficient sanitation infrastructure, where shallow groundwater resources are frequently used for drinking water supply, increasing the risk of direct human exposure to pathogenic microorganisms.

Microbiological indicators used to assess fecal contamination include coliform bacteria, *Escherichia coli*, and intestinal enterococci, which are considered reliable markers of recent pollution. In addition, the use of bacteriophages and viral indicators enables a more precise characterization of microbiological risk, particularly in cases of persistent

contamination. Recent studies have confirmed the widespread occurrence of potentially pathogenic microorganisms in surface waters, especially in urban areas and regions with inadequate sanitation infrastructure, emphasizing the need for continuous monitoring and effective risk management strategies to protect public health [177,178].

A recent study conducted in China highlighted the ubiquitous presence of potentially pathogenic bacteria in all 16 analyzed urban surface water samples, with microbial communities dominated by the phyla *Proteobacteria* (21.9–78.5%) and *Bacteroidetes* (19.1–74.7%) of total sequences [178]. These findings indicate the substantial influence of urban wastewater discharges on microbial water quality and highlight the potential for increased exposure to pathogenic microorganisms in densely populated areas.

Similarly, investigations conducted in Porto Velho (Brazil) revealed high levels of faecal contamination in groundwater, with a predominance of bacterial genera such as *Escherichia*, *Enterobacter*, *Cronobacter*, and *Citrobacter*, highlighting the vulnerability of shallow groundwater sources and the increased risk of exposure to waterborne pathogens in areas lacking adequate sanitation services [179].

Furthermore, studies conducted in the Swist River basin (Germany) demonstrated that land use significantly influences microbiological contamination, with maximum values associated with intensive agriculture and episodic events, such as manure application, whereas surface runoff plays a more important role than infiltration [180]. These findings illustrate the complex interactions between hydrological processes, agricultural practices, and pathogen transport within aquatic systems.

An emerging issue is the role of contaminated waters as reservoirs for antimicrobial resistance genes (ARGs), which can be transferred between microorganisms, thereby amplifying public health risks and reducing the effectiveness of medical treatments. These mechanisms facilitate the spread of antimicrobial resistance through environmental pathways and increase the complexity of microbiological risk assessment and management [181,182]. Zhang et al., 2021, identified over 150 distinct ARGs in river water samples collected from urban and rural environments. Through metagenomic analyses, the study revealed a broad diversity of antibiotic-resistant bacteria and resistance determinants, emphasizing the role of aquatic ecosystems as in Recent evidence indicates that aquatic environments may act as important reservoirs and transmission pathways for ARGs [183].

Recent evidence indicates that aquatic environments may act as important reservoirs and transmission pathways for ARGs. Singh et al., 2022, reported that wastewater treatment plants and receiving water bodies frequently contain ARGs and antimicrobial-resistant bacteria, highlighting the limited capacity of conventional treatment processes to completely eliminate these contaminants and prevent their dissemination in the environment [184].

Integrated risk perspective, the microbiological contamination of water necessitates a holistic assessment that encompasses the occurrence of pathogenic agents, environmental transport pathways, exposure probability, susceptible population subgroups, and the spread of antimicrobial resistance.

Accordingly, climate related stressors such as elevated temperatures, recurrent flooding events, and hydrological variability may also alter pathogen transport patterns and amplify contamination risks. Furthermore, comprehensive microbiological risk assessment frameworks should incorporate cumulative exposure scenarios involving diverse pathogenic microorganisms, along with antimicrobial resistance determinants that have the potential to escalate public health risks.

The transfer of resistance genes between microorganisms may amplify public health risks and reduce the effectiveness of antimicrobial therapies. Interactions between microbiological contaminants and chemical pollutants may further alter pathogen survival, virulence, and environmental persistence, increasing uncertainty in integrated

risk assessment. Climate change and the increasing frequency of extreme hydrological events may additionally intensify pathogen mobilization, transport, and environmental persistence, thereby increasing the vulnerability of water resources to microbiological contamination [181,185,186].

Human exposure to microbiological contaminants primarily occurs through drinking water consumption recreational water use, irrigation practices, and food chain transfer. Vulnerable population groups, including children, elderly individuals, and immunocompromised persons, may experience disproportionately higher risks associated with pathogen exposure. Furthermore, cumulative exposure to multiple pathogenic microorganisms and antimicrobial resistance determinants remains insufficiently addressed within current monitoring and regulatory frameworks.

Although conventional water treatment processes can substantially reduce microbiological loads, certain pathogens, particularly protozoa resistant to conventional disinfection, may persist in water systems. In addition, existing monitoring approaches are generally based on indicator organisms and may not accurately reflect the presence of all pathogenic microorganisms, contributing to uncertainty in public health risk assessment [187,188]. This highlights the need for implementing advanced treatment technologies and efficient monitoring systems. In this context, microbiological water pollution should be addressed through integrated strategies based on risk assessment, continuous monitoring, and source control to protect public health and water resources.

Microbiological water pollution represents a complex and dynamic environmental and public health challenge characterized by multiple contamination sources, diffuse transport pathways, pathogen persistence, cumulative exposure scenarios, and substantial uncertainty regarding antimicrobial resistance dissemination and long-term health implications.

Although pesticides, heavy metals, emerging contaminants, microplastics, and microbiological pollutants differ in terms of origin, environmental behavior, and toxicological properties, they share several common characteristics that contribute to water quality degradation and human health risks. A comparative overview of the major pollutant groups discussed in this review is presented in Table 3, highlighting differences and similarities regarding pollution sources, environmental persistence, exposure pathways, health effects, monitoring challenges, and treatment limitations. This comparison supports a more integrated understanding of water pollution and facilitates the identification of common challenges and research priorities across contaminant categories.

**Table 3.** Comparative characteristics of major water pollutant groups and associated human health risks.

| Pollutant Group | Main Sources                                                            | Environmental Persistence                         | Environmental Transport Pathways                                 | Main Human Exposure Routes                                                  | Principal Health Effects                                                      | Monitoring Challenges                                                    | Treatment Challenges                                                                   |
|-----------------|-------------------------------------------------------------------------|---------------------------------------------------|------------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Pesticides      | Agricultural runoff, pesticide application, irrigation return flows     | Moderate to high, depending on chemical structure | Surface runoff, leaching to groundwater, sediment transport      | Drinking water consumption, food-chain transfer, dermal contact, inhalation | Neurotoxicity, endocrine disruption, reproductive disorders, carcinogenicity  | Large number of compounds, seasonal variability, transformation products | Conventional treatment may not completely remove persistent pesticides and metabolites |
| Heavy Metals    | Mining, metallurgy, industrial discharges, wastewater, geogenic sources | Very high                                         | Dissolved transport, sediment association, groundwater migration | Drinking water, food-chain transfer, crop uptake                            | Neurological, renal, cardiovascular disorders, developmental toxicity, cancer | Speciation-dependent toxicity and mobility                               | Removal efficiency depends on pH, speciation, and treatment conditions                 |

Table 3. *Cont.*

| Pollutant Group              | Main Sources                                                                       | Environmental Persistence                                      | Environmental Transport Pathways                                         | Main Human Exposure Routes                                 | Principal Health Effects                                                    | Monitoring Challenges                                    | Treatment Challenges                                                |
|------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------------------|
| Pharmaceutical compounds     | Municipal wastewater, hospitals, pharmaceutical industries                         | Moderate to high (pseudo-persistent due to continuous release) | Wastewater discharge, river transport, groundwater infiltration          | Drinking water, recreational exposure, dietary exposure    | Endocrine disruption, antimicrobial resistance, chronic toxicity            | Detection of metabolites and transformation products     | Conventional wastewater treatment often provides incomplete removal |
| PFAS                         | Industrial activities, firefighting foams, consumer products, wastewater effluents | Extremely high                                                 | Surface water transport, groundwater migration, atmospheric deposition   | Drinking water, food consumption, occupational exposure    | Endocrine, immune, hepatic, developmental effects; possible carcinogenicity | Large number of PFAS compounds and analytical complexity | Highly resistant to conventional treatment processes                |
| EDCs                         | Wastewater effluents, plastics, personal care products, industrial discharges      | Moderate to high                                               | Wastewater discharge, surface water transport, groundwater contamination | Drinking water, food-chain transfer                        | Hormonal imbalance, reproductive disorders, developmental effects           | Biological effects may occur at very low concentrations  | Incomplete removal by conventional treatment systems                |
| MP                           | Plastic waste degradation, wastewater, industrial and domestic sources             | Very high                                                      | Surface runoff, river transport, groundwater–surface water interactions  | Drinking water, food consumption, inhalation               | Oxidative stress, inflammation, contaminant vector effects                  | Lack of standardized sampling and analytical methods     | Conventional treatment may not completely remove smaller particles  |
| Microbiological Contaminants | Wastewater, septic systems, agricultural runoff, animal waste                      | Variable                                                       | Surface runoff, groundwater infiltration, direct discharge               | Drinking water, recreational exposure, food-chain transfer | Diarrheal diseases, cholera, hepatitis, giardiasis, cryptosporidiosis       | Pathogen diversity and temporal variability              | Resistant microorganisms may survive conventional disinfection      |

The comparison demonstrates that, despite important differences among pollutant groups, most contaminants originate from multiple anthropogenic sources, are transported through interconnected environmental pathways, and contribute to human exposure through several routes simultaneously. Consequently, health risks are determined not only by the properties of individual contaminants but also by the interactions between pollution sources, environmental transport processes, exposure pathways, and toxicological effects. This highlights the need for integrated risk assessment approaches capable of addressing cumulative exposures and mixture effects.

#### 4. Integrated Assessment of Water Pollution Risks to Human Health

Traditional approaches for water pollution assessment have predominantly focused on individual contaminants and isolated exposure scenarios. Although these methods have substantially improved understanding of pollutant occurrence, transport mechanisms, and toxicological effects, they frequently underestimate real environmental risks because aquatic systems are characterized by the simultaneous presence of multiple chemical and biological contaminants interacting across interconnected environmental compartments [189–191].

Consequently, integrated risk assessment (IRA) frameworks have emerged as an essential transition from conventional contaminant-specific approaches toward more realistic evaluations of environmental and public health risks [192].

Humans and ecosystems are continuously exposed to complex contaminant mixtures rather than isolated substances, increasing concerns regarding cumulative exposure, mixture toxicity, chronic low dose effects, and long term ecological and health impacts [193–197]. Consequently, the evaluation of potential health risks should not rely solely on contaminant identification but also on the comparison of measured concentrations with health-based guideline values and regulatory standards [129,198,199].

Recent studies have demonstrated that contaminant mixtures occurring in aquatic environments may generate additive or synergistic effects that cannot be determined from assessments of individual contaminants alone [200,201].

Pesticide mixtures commonly detected in rivers and agricultural runoff have been shown to produce combined toxic effects on aquatic organisms that frequently exceed those expected from individual compounds, highlighting the importance of concentration-addition mechanisms in aquatic ecosystems [72,195,197].

Pharmaceutical compounds are rarely present as individual substances in wastewater and surface waters, being frequently identified together with other contaminants, including heavy metals [194]. Numerous studies have highlighted the coexistence of pharmaceutical compounds and heavy metals both in wastewater treatment plant effluents and in natural aquatic ecosystems [193,202].

Experimental research on the formation and presence of pharmaceutical-metal complexes has demonstrated that they can generate significant negative effects on the environment [194]. Thus, these complexes can amplify the toxicity on microorganisms, leading to the diminution of bacterial communities and, implicitly, to the reduction in the efficiency of biological wastewater treatment processes [203]. They can also manifest an increased toxicity towards aquatic plants and organisms, increasing the ecological risks associated with their presence in the aquatic environment [204].

Environmental contamination with PFAS and MP is an increasingly important environmental problem at a global level, with the concentrations of these pollutants continuously increasing in aquatic ecosystems [205]. Available research indicates that mixtures of PFAS compounds can generate cumulative toxic effects, and simultaneous exposure to PFAS and MP can amplify the negative impact on aquatic organisms and, implicitly, humans [206].

Recent studies have highlighted the existence of significant interactions between PFAS and microplastics, PFAS and heavy metals, PFAS and pharmaceuticals, and PFAS and pesticides, suggesting that their concomitant presence may amplify adverse biological effects [205–209]. For instance, Dai et al., 2022, demonstrated that microplastics can adsorb PFAS and enhance their transport and bioavailability in aquatic environments [206]. Experimental evidence provided by Soltanighias et al., 2024, showed that simultaneous exposure of *Daphnia magna* to PFOS, PFOA and microplastics resulted in reduced growth, delayed maturation, decreased fecundity and increased mortality compared with single-contaminant exposures. Approximately 40% of the observed toxicity was attributed to synergistic interactions among contaminants [210].

From an ecotoxicological perspective, numerous investigations have analyzed the behavior, bioavailability and effects of these contaminants in aquatic environments, highlighting the risks associated with the exposure of organisms to such complex mixtures of pollutants.

In this context, the assessment of potential risks to human health requires not only the identification of contaminants and exposure routes, but also the comparison of measured concentrations with health-based guideline values and regulatory standards. Such reference values, established by international organizations and national regulatory authorities, provide an essential basis for evaluating contaminant significance, assessing compliance, and supporting evidence-based risk management decisions.

The regulation of heavy metals demonstrates both scientific consensus and regulatory variability across international frameworks.  $\text{As}^{3+}$  is consistently limited to 10  $\mu\text{g/L}$  by the WHO, U.S. Environmental Protection Agency (U.S. EPA), EU, Health Canada, and Australian guidelines due to its well-established carcinogenicity. Nevertheless, ongoing discussions regarding lower health-based targets reflect growing concerns about adverse effects at low exposure levels [211,212].

Similarly,  $\text{Ni}^{2+}$  standards vary considerably, ranging from 20  $\mu\text{g/L}$  in the EU and Australia to higher guideline values in other jurisdictions. Such differences often reflect regional exposure conditions, local hydrogeological characteristics, and the methodologies used in deriving health-based guideline values [213,214].

$\text{Pb}^{2+}$  exhibits greater regulatory divergence. The EU and Health Canada have adopted a limit of 5  $\mu\text{g/L}$ , reflecting increasing evidence of neurodevelopmental effects in children, whereas the USEPA and Australia apply higher values or alternative implementation mechanisms. These differences illustrate variations in precautionary approaches and risk management strategies among jurisdictions [214,215].

PFAS regulation represents one of the most rapidly evolving areas of drinking water policy. Due to their high persistence, widespread occurrence, and potential adverse health effects, regulatory authorities have adopted different management approaches. The EU applies a group-based strategy by establishing limits for the sum of selected PFAS compounds, whereas the USEPA has introduced highly stringent standards for specific substances such as PFOA and PFOS. Similar guideline values have also been developed in Canada and Australia, although differences remain regarding the compounds included and the threshold concentrations applied. These variations reflect ongoing scientific uncertainties and highlight the need for harmonized regulatory frameworks capable of addressing the complexity of PFAS contamination and cumulative exposure [211,216]. Although regulatory standards provide essential benchmarks for evaluating water quality and compliance, a comprehensive assessment of human health impacts also requires the application of quantitative risk assessment tools. These approaches allow the estimation of both non-carcinogenic and carcinogenic risks associated with contaminant exposure and complement the interpretation of regulatory guideline values.

In addition to guideline values and regulatory limits, quantitative risk assessment commonly relies on indicators such as the Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR). HQ is used to assess non-carcinogenic risks associated with individual contaminants, whereas HI evaluates the cumulative effects of exposure to multiple contaminants or exposure pathways [217]. For carcinogenic contaminants, CR estimates the probability of developing cancer over a lifetime of exposure. These indicators are widely used to support the interpretation of exposure data and the characterization of potential human health risks in water quality assessment studies.

The application of these indicators is integrated within established human health risk assessment frameworks. Risk assessment approaches recommended by the U.S. EPA and the WHO are generally structured around four principal stages: hazard identification, exposure assessment, dose–response assessment, and risk characterization [217–219]. Within the context of water pollution, integrated assessment includes heavy metals, pesticides, pharmaceutical compounds, microplastics, nutrients, and pathogenic microorganisms occurring across surface waters, groundwater resources, sediments, and drinking water systems.

This framework additionally incorporates contaminant persistence, environmental transport mechanisms, transformation processes, treatment performance, mixture interactions, and residual risks remaining after conventional treatment processes. Consequently, IRA provides a more realistic estimation of actual human and ecosystem risks compared to

traditional single-contaminant approaches and constitutes the analytical backbone of the present review [220,221].

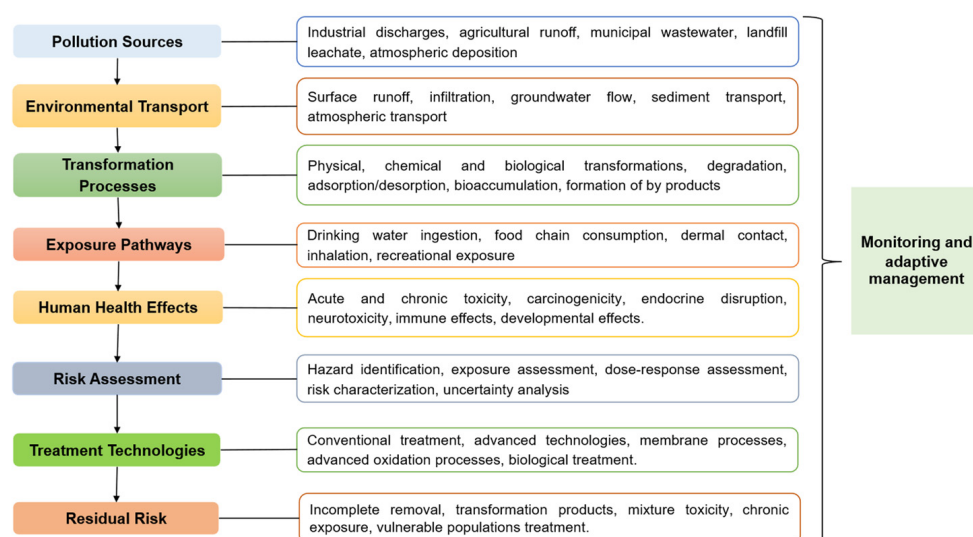
Hazard identification involves determining contaminants capable of inducing adverse ecological and human health effects, including heavy metals, pesticides, pharmaceutical compounds, endocrine-disrupting chemicals, pathogenic microorganisms, and microplastics [222,223].

Exposure assessment evaluates contaminant concentration, frequency, duration, and pathways of human contact, including drinking water ingestion, dermal exposure, inhalation, and food-chain transfer [224–227].

Water pollutants are interconnected through environmental transport, transformation, and exposure processes. Consequently, human health outcomes often result from cumulative exposure to multiple contaminants, highlighting the importance of integrated risk assessment frameworks [192,221].

During their environmental transfer, contaminants can undergo physical, chemical, and biological transformations that influence their persistence, mobility, bioavailability, and toxicity. Human exposure subsequently occurs through multiple pathways, including drinking water consumption, food-chain transfer, dermal contact, and inhalation. Consequently, adverse health outcomes are often the result of cumulative and simultaneous exposure to multiple contaminants rather than isolated substances, highlighting the importance of integrated risk assessment frameworks capable of addressing real-world exposure scenarios.

An integrated perspective on water pollution requires consideration of the complex interactions among pollution sources, environmental transport processes, contaminant transformation pathways, exposure routes, health effects, treatment technologies, and residual risks. As illustrated in Figure 9, contaminants belonging to different classes may follow similar environmental pathways and contribute to cumulative human exposure and adverse health outcomes. This conceptual framework facilitates a more comprehensive understanding of water pollution and its associated risks than conventional pollutant-specific assessment approaches [228–231].



**Figure 9.** Integrated Water Pollution Risk Framework.

Despite increasing scientific advances, uncertainty remains an important challenge in integrated risk assessment because contaminant interactions, environmental variability, and long-term low-dose exposure may substantially influence risk estimation and public health evaluation [83,190].

#### 4.1. Integrated Risk Assessment Across Major Water Pollutant Classes

Exposure assessment quantifies the magnitude, frequency, and duration of human contact with identified hazardous substances through all relevant pathways. In the context of water pollution, the primary exposure routes include ingestion of contaminated drinking water, dermal contact during recreational or domestic water use, and inhalation of aerosols with individual [226,232].

Human health risk characterization in water pollution studies frequently integrates carcinogenic and non-carcinogenic endpoints to estimate adverse effects associated with contaminant exposure.

Acceptable carcinogenic risk is generally defined within the range of  $10^{-6}$  (negligible risk) to  $10^{-4}$  (upper acceptable threshold), as established by the U.S. EPA [218,219]. Integrated assessment therefore extends beyond individual contaminant concentration measurements by incorporating long-term exposure patterns and combined environmental pressures.

Studies reviewed in this work reported carcinogenic risks exceeding this threshold for arsenic in groundwater from China ( $3.50 \times 10^{-4}$ ) contaminants [34] and for heavy metals in landfill leachates (up to  $9.09 \times 10^{-5}$  for infants via oral exposure) [35], confirming the public health significance of these pollutants even at concentrations that conventional [70,233]. Integrated assessment of pesticide contamination must consider agricultural runoff dynamics, contaminant persistence, groundwater infiltration, trophic transfer processes, and chronic exposure via drinking water and food consumption [234].

A landmark global-scale study integrating meta-analysis, ecotoxicological testing, and explainable machine learning mapped the mixture hazard of 311 pesticides to aquatic invertebrates and algae across surface waters worldwide, identifying high-hazard agricultural regions and practical recommendations for sustainable land management [235].

Despite their widespread application, conventional risk assessment approaches are subject to important limitations when applied to real environments [168]. The study further highlighted the role of hydraulic interactions between groundwater and surface water in controlling microplastic distribution within aquatic environments [162]. However, environmental exposure frequently involves simultaneous interactions between heavy metals, pesticides, pharmaceutical residues, nutrients, pathogenic microorganisms, and microplastics, which may generate additive, synergistic, or antagonistic toxicological effects [108,158,236–239].

A fundamental challenge in integrated risk assessment is the characterization of mixture toxicity, defined as the combined effects resulting from simultaneous exposure to multiple contaminants. Real-world water contamination scenarios rarely involve isolated substances. Instead, aquatic environments are characterized by the co-occurrence of diverse chemical and biological agents interacting through shared, additive, synergistic, or antagonistic toxicological mechanisms [218,232,240].

A nationwide study of drinking water treatment plants detected 30 pharmaceuticals and personal care products compounds in treated water at mean concentrations reaching 131 ng/L, with biologically active compounds present at concentrations capable of posing significant threats to water quality [241].

Incomplete removal during wastewater treatment represents a critical pathway for pharmaceutical entry into surface waters. A European multi-site study detecting 97 pharmaceuticals in wastewater and receiving waters found that approximately 40% of tested compounds were quantified, with several including carbamazepine, citalopram, and venlafaxine subsequently incorporated into Group I of the EU Urban Wastewater Directive (2024/3019) owing to their documented environmental risk [242].

Conventional mixture assessment approaches are frequently based on additive toxicity models. However, deviations from these models, particularly synergism (greater-than-additive effects) and antagonism (less-than-additive effects), represent major sources of uncertainty in environmental risk assessment [243].

As highlighted throughout this review, synergistic interactions between heavy metals and organic pollutants, as well as between pharmaceutical compounds and microplastics, may substantially amplify health risks beyond those predicted by individual-compound assessments [27,33,148,222].

Compound-specific ecological risk assessments continue to document acute and chronic risks in river lake systems. A study in a representative Chinese river–lake continuum detected 52 pesticides at a mean total surface-water concentration of 203 ng/L, with ecological risks rising along trophic levels [244].

Recent studies demonstrated that interactions between microplastics and heavy metals may enhance bioavailability and bioaccumulation in aquatic organisms [245]. Recent studies further demonstrated that interactions between microplastics and heavy metals may enhance bioavailability, oxidative stress, inflammatory responses, and bioaccumulation in aquatic organisms, supporting the so-called “Trojan Horse Effect” hypothesis [200,246].

Microbiological risk assessment requires integration of pathogen occurrence, environmental transport dynamics, climate-related variability, and vulnerability of sensitive sub-populations to improve estimation of infection probability and public health risks [247,248].

Despite considerable advances in risk assessment methodologies, significant uncertainties remain regarding the combined effects of contaminant interactions, environmental variability, and chronic low-dose exposure. These factors may influence risk estimates and hinder accurate public health evaluations.

#### *4.2. Residual Risks and Treatment Limitations*

An additional dimension of the integrated risk perspective concerns the residual risks that persist after conventional water treatment. As documented in the preceding sections, physical treatment processes including sedimentation, filtration, and aeration demonstrate limited efficiency in removing dissolved heavy metal species, pharmaceutical compounds, and microplastics under variable environmental conditions [249–252]. Advanced oxidation processes, membrane filtration, and biological treatment technologies offer improved removal efficiencies for specific contaminant classes, but their application remains constrained by operational costs, energy requirements, and the generation of transformation products whose toxicological profiles may differ substantially from parent compounds [43,253–260].

Pharmaceutical transformation products and metabolites generated during environmental degradation or wastewater treatment represent a particularly poorly characterized source of residual risk. These compounds may exhibit greater environmental persistence, mobility, and bioactivity than their precursors, yet they are not systematically monitored or regulated in most countries [261–263]. Similarly, the fragmentation of larger plastic items into microplastics and nanoplastics during treatment processes may redistribute rather than eliminate plastic contamination from water systems [158,200,201].

The continuous discharge of incompletely treated effluents into receiving water bodies, combined with the pseudo-persistent nature of pharmaceutical compounds and the environmental mobility of heavy metals and pesticide residues, creates conditions of chronic, low-dose, multi-contaminant exposure for populations dependent on surface water or groundwater as drinking water sources [264].

## 5. Impact of Water Pollution on Human Health

Water resource pollution represents a major global concern, driven by environmental changes and intensification of anthropogenic activities, with significant implications for human health [57,265]. Water contamination is associated with the occurrence of waterborne diseases, episodes of acute and chronic intoxication, as well as adverse effects on physical and mental health [59].

Numerous studies have highlighted correlations between poor water quality and the incidence of acute waterborne diseases, such as hepatitis A, cholera, dysentery, cryptosporidiosis, giardiasis, diarrhea, and typhoid fever. These conditions are primarily caused by pathogenic microorganisms (bacteria, viruses, and protozoa) originating from fecal sources, particularly in the context of inadequate water treatment and distribution infrastructure [178,265–267].

In addition to microbiological risks, chemical contaminants present in drinking water represent a major public health issue. These adverse effects are primarily mediated through oxidative stress, enzyme inhibition, disruption of cellular homeostasis, and interactions with proteins and nucleic acids, leading to cellular dysfunction and tissue damage [265,268]. For example, arsenic exposure has been linked to skin, lung, and bladder cancers, while lead is recognized for its neurotoxic effects, particularly during early-life development [229]. In addition, hexavalent chromium is classified as a human carcinogen and has been associated with an increased risk of lung cancer following long-term exposure [129].

The presence of emerging pollutants, such as pharmaceutical residues, pesticides, and endocrine disruptors, has been associated with hormonal imbalances, reproductive disorders, and potential effects on fertility. Some studies have suggested a possible link between exposure to these compounds and an increased incidence of chronic diseases, including certain types of cancer and gynecological conditions. However, the exact mechanisms underlying these effects are still under investigation and require further validation [87,134,259,269]. Endocrine-disrupting compounds may interfere with hormone synthesis, transport, metabolism, and receptor signaling pathways, thereby affecting reproductive, developmental, metabolic, and thyroid functions.

Human exposure to water pollutants frequently occurs through multiple pathways, including drinking water consumption, food chain transfer, dermal contact, and indirect environmental exposure [9,12,22,57,270].

Furthermore, susceptibility to water pollution health effects varies across population groups, with children, elderly individuals, pregnant women, and immunocompromised populations presenting increased vulnerability to cumulative contaminant exposure.

Recent studies increasingly emphasize that chronic low-dose exposure to emerging contaminants, including pharmaceutical residues, endocrine disruptors, pesticides, and microplastics, may induce oxidative stress, endocrine disruption, immune dysregulation, and epigenetic alterations even at concentrations previously considered environmentally safe [151,199,271–275]. Oxidative stress resulting from excessive production of reactive oxygen species may promote lipid peroxidation, mitochondrial dysfunction, and chronic inflammation, contributing to the development of cardiovascular, metabolic, neurodegenerative, and oncological diseases [1,18,174,200,268,270,276,277].

In addition, neurotoxic contaminants may alter neurotransmitter signaling, impair neuronal development, and induce neuroinflammation, potentially leading to cognitive deficits and developmental disorders [143,151,269,277]. These mechanisms provide biologically plausible pathways linking long-term contaminant exposure to adverse human health outcomes (Table 4).

Although global estimates indicate a substantial health burden associated with unsafe water and water pollution, these figures should be interpreted with caution. Consider-

able regional variability exists due to differences in sanitation coverage, drinking water infrastructure, monitoring capacity, socioeconomic conditions, and healthcare access [278]. Countries with lower socio-demographic development generally experience a disproportionately higher burden of water-related diseases compared with high-income regions, where advanced treatment technologies, regulatory frameworks, and surveillance systems contribute to reduced exposure risks [279–281]. Furthermore, uncertainties associated with disease reporting, exposure assessment, data availability, and attribution methodologies may influence the accuracy of global estimates and limit direct comparisons between regions [279]. Recent analyses based on the Global Burden of Disease database have shown that the highest mortality and disability-adjusted life year rates attributable to unsafe water, sanitation, and hygiene remain concentrated in low-income regions, particularly Sub-Saharan Africa and South Asia, highlighting substantial geographical disparities in health outcomes associated with water pollution and inadequate water services [278,280].

**Table 4.** Impact of water pollutants on human health.

| Pollutant Type                             | Examples                                                                                                                                                                                    | Exposure Pathways                            | Mechanisms of Toxicity                                                                                                                                      | Target Organs/Systems                                                             | Health Effects                                                                                                                                                           | References                |
|--------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| Heavy metals                               | Pb <sup>2+</sup> , Hg <sup>2+</sup> , Cr <sup>3+</sup> , Cr <sup>6+</sup> , As <sup>3+</sup> , Cd <sup>2+</sup> , Zn <sup>2+</sup> , Al <sup>3+</sup> , Fe <sup>2+</sup> , Fe <sup>3+</sup> | Ingestion<br>Inhalation<br>Dermal contact    | Oxidative stress<br>binding to proteins and nucleic acids<br>Enzyme inhibition<br>Interference with ion transport<br>Epigenetic alterations                 | Nervous system<br>Kidneys<br>Liver<br>Hematological system<br>Reproductive system | Neurotoxicity<br>Renal failure<br>Anemia<br>Carcinogenesis<br>Hepatotoxicity<br>Developmental disorders                                                                  | [230,282–285]             |
| Nutrients                                  | Nitrates, Phosphates                                                                                                                                                                        | Ingestion                                    | Conversion of nitrates to nitrites;<br>Interference with oxygen transport (methemoglobin formation)<br>Endocrine disruption                                 | Circulatory system<br>Digestive system<br>Endocrine system                        | Methemoglobinemia<br>Gastrointestinal Disorders<br>Thyroid dysfunction<br>Potential carcinogenic risk                                                                    | [224,225,272,286–289]     |
| Persistent organic compounds               | Organophosphates<br>Carbamates<br>Herbicides<br>Polycyclic aromatic hydrocarbons<br>Solvents                                                                                                | Ingestion<br>Dermal contact<br>Inhalation    | Acetylcholinesterase inhibition<br>Endocrine disruption<br>Bioaccumulation and biomagnification<br>Toxic metabolic activation<br>Receptor-mediated toxicity | Nervous system<br>Endocrine system<br>Liver<br>Immune system                      | Neurological disorders<br>Hormonal imbalance<br>Chronic toxicity<br>Hepatotoxicity<br>Carcinogenicity<br>Immunotoxicity<br>Non-Hodgkin's lymphoma<br>Parkinson's disease | [70,290–295]              |
| Pathogenic microorganisms                  | Bacteria<br>Viruses<br>Protozoa                                                                                                                                                             | Ingestion                                    | Direct infection;<br>Toxin production<br>Immune system activation                                                                                           | Digestive system<br>Liver<br>Immune system                                        | Cholera<br>Dysentery<br>Hepatitis<br>Diarrhea<br>Gastrointestinal infections                                                                                             | [270,271,296,297]         |
| Pharmaceuticals and personal care products | Antibiotics<br>Hormones<br>Analgesics<br>Antidepressants                                                                                                                                    | Ingestion<br>Indirect environmental exposure | Interference with biochemical pathways<br>Endocrine disruption<br>Antimicrobial resistance selection<br>Chronic low-dose toxicity                           | Endocrine system<br>Gut microbiota<br>Liver                                       | Antimicrobial resistance<br>Hormonal imbalances<br>Reproductive effects<br>Metabolic disturbances                                                                        | [40,136,138,149, 151,199] |

## 6. Water and Wastewater Treatment and Remediation Technologies

Water and wastewater treatment technologies represent a critical component of integrated water pollution risk management because they directly influence contaminant removal efficiency, residual exposure levels, and the protection of human health and aquatic ecosystems. From an integrated risk perspective, treatment technologies should not be evaluated solely according to pollutant removal performance but also considering their capacity to reduce cumulative exposure scenarios, mitigate contaminant interactions, minimize residual risks, and improve long-term water safety [298].

The effectiveness of water and wastewater treatment technologies varies considerably depending on contaminant characteristics and treatment objectives. Conventional processes, including sedimentation, filtration, aeration, and coagulation-flocculation, are generally effective for the removal of suspended solids, pathogens, and particulate matter, but often exhibit limited performance for dissolved micropollutants, pharmaceutical residues, PFAS, and transformation products [130].

They are currently classified into three main categories: physical, chemical, and biological or advanced technologies, each with specific mechanisms of action and distinct areas of applicability [198,299].

Physical water treatment is one of the most widely used categories of technologies in the field of water resources purification and remediation. It is based on simple physical processes, such as sieving, sedimentation, aeration, and filtration, through which suspended solids and certain contaminants are removed without the use of chemicals [252,300,301]. These processes are frequently applied as preliminary or complementary steps in treatment schemes, due to their operational simplicity, low costs and efficiency in reducing pollutant loads (Table 5) [302].

**Table 5.** Physical Water Treatment Technologies.

| Technology                   | Target Pollutants                                            | Advantages                                                  | Major Limitations                                                          | Contribution to Risk Reduction               | References |
|------------------------------|--------------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------|------------|
| Dredging                     | Sediment-associated pollutants, nutrients, heavy metals      | Rapid pollutant removal<br>Improves water quality           | Sediment resuspension;<br>Ecosystem disturbance;<br>High operational costs | Moderate to high for localized contamination | [303,304]  |
| Aeration                     | Organic pollutants, reduced compounds, cyanobacterial blooms | Improves dissolved oxygen<br>Enhances microbial degradation | Limited effectiveness for persistent pollutants<br>Energy-intensive        | Moderate                                     | [305,306]  |
| Mechanical algae removal     | Cyanobacteria and algal biomass                              | Rapid bloom reduction;<br>Immediate aesthetic improvement   | Temporary effectiveness;<br>Biomass disposal required                      | Low to moderate                              | [307,308]  |
| Water diversion              | Nutrients, stagnant pollutants                               | Reduces stagnation;<br>improves circulation                 | Dependent on hydrological conditions                                       | Moderate                                     | [309]      |
| Filtration and sedimentation | Suspended solids, particulate contaminants                   | Simple and cost-effective pre-treatment                     | Inefficient for dissolved contaminants and emerging pollutants             | Low to moderate                              | [310]      |

Although physical treatment technologies contribute significantly to pollutant load reduction, their capacity to address complex contaminant mixtures remains limited. Persistent pollutants including pharmaceutical residues, dissolved heavy metals, pesticide

transformation products, and microplastics frequently require advanced treatment solutions capable of reducing residual risks associated with chronic low-dose exposure and cumulative contaminant interactions.

Advanced treatment technologies generally provide higher removal efficiencies for emerging contaminants and complex contaminant mixtures. Membrane filtration has demonstrated high effectiveness for the removal of dissolved contaminants, pathogens, microplastics, and PFAS. However, its application is often constrained by membrane fouling, energy consumption, and operational costs [252,311–314].

Adsorption-based technologies, including activated carbon and biochar, have shown promising performance for trace organic contaminants and certain PFAS compounds, but their efficiency depends on adsorbent properties and regeneration requirements [30,142,207,312].

Biological treatment technologies, including bioremediation, bioaugmentation, and biostimulation, offer environmentally sustainable solutions for biodegradable organic contaminants and nutrient removal [315–319]. Nevertheless, their performance may be influenced by environmental conditions and is generally less effective for persistent pollutants such as PFAS and certain pharmaceutical compounds.

Advanced oxidation processes and ozonation are particularly suitable for degrading pharmaceuticals, pesticides, and other organic micropollutants, although the formation of transformation products remains an important limitation requiring further evaluation [130,198,314].

Nevertheless, treatment technologies themselves may introduce additional challenges including energy requirements, operational costs, transformation product generation, and incomplete contaminant mineralization, highlighting the importance of treatment optimization within integrated risk management strategies (as presented in Table 6).

**Table 6.** Water treatment technologies and key characteristics.

| Technology                          | Target Contaminants                                  | Advantages                                                        | Major Limitations                        | Contribution to Risk Reduction                            | References |
|-------------------------------------|------------------------------------------------------|-------------------------------------------------------------------|------------------------------------------|-----------------------------------------------------------|------------|
| Advanced oxidation processes (AOPs) | Pharmaceuticals, pesticides, organic micropollutants | High degradation efficiency<br>Suitable for emerging contaminants | Energy demand<br>Transformation products | Reduces chronic exposure to persistent contaminants       | [320–322]  |
| Fenton oxidation                    | Organic pollutants, microorganisms                   | Efficient degradation<br>Microbial inactivation                   | Sludge generation<br>Reagent consumption | Improves contaminant removal and lowers residual exposure | [260]      |
| Electrochemical oxidation           | Refractory organic pollutants                        | Effective for persistent contaminants                             | Operational complexity<br>Energy demand  | Reduces residual contamination                            | [254–257]  |
| Ozonation                           | Organic pollutants, pathogens                        | Broad applicability;<br>Strong oxidation capacity                 | Transformation product formation         | Supports pathogen control and micropollutant reduction    | [258]      |
| Chemical precipitation              | Nutrients, dissolved metals                          | Effective nutrient and metal removal                              | Sludge generation                        | Limits eutrophication and contaminant mobility            | [323]      |

Table 6. Cont.

| Technology                         | Target Contaminants                                | Advantages                                | Major Limitations                                 | Contribution to Risk Reduction                   | References    |
|------------------------------------|----------------------------------------------------|-------------------------------------------|---------------------------------------------------|--------------------------------------------------|---------------|
| Photocatalysis                     | Organic micropollutants                            | Potential mineralization of pollutants    | Operational limitations<br>Incomplete degradation | Supports reduction in persistent contaminants    | [324]         |
| Coagulation–floculation            | Colloids, suspended contaminants                   | Established and cost-effective technology | Limited removal of dissolved micropollutants      | Improves bulk contaminant removal                | [249,250,325] |
| Ion exchange                       | Heavy metals, nitrates                             | High selectivity<br>Effective ion removal | Resin regeneration requirements                   | Reduces exposure to toxic inorganic contaminants | [326,327]     |
| Bioremediation                     | Organic contaminants                               | Sustainable and environmentally friendly  | Slow treatment kinetics                           | Supports long-term contaminant reduction         | [318,319]     |
| Bioaugmentation/<br>Biostimulation | Organic pollutants, nutrients                      | Enhances biodegradation efficiency        | Performance depends on environmental conditions   | Improves contaminant attenuation capacity        | [327–330]     |
| Phytoremediation                   | Metals, nutrients, organic contaminants            | Low-cost and sustainable                  | Long remediation periods                          | Reduces contaminant bioavailability              | [331]         |
| Membrane filtration                | Micropollutants, pathogens, dissolved contaminants | High removal efficiency                   | Fouling<br>Energy-intensive operation             | Minimizes residual exposure pathways             | [187,252]     |
| Biochar adsorption                 | Organic and inorganic contaminants                 | Sustainable and low-cost adsorbent        | Regeneration requirements                         | Reduces trace contaminant persistence            | [332]         |

Integrated treatment strategies combining multiple technologies may provide superior performance compared to single-process approaches, particularly under multi-contaminant environmental scenarios.

Future treatment development should prioritize technologies capable of simultaneously addressing chemical pollutants, microbiological contamination, microplastics, transformation products, and antimicrobial resistance determinants while minimizing energy consumption and operational complexity.

## 7. Conclusions

This study provides an integrated analysis of major water pollution sources and contaminant categories, highlighting the increasing complexity of contamination patterns driven by anthropogenic activities. The results demonstrate that water pollution is no longer a single-contaminant issue but a multi-contaminant and multi-pathway phenomenon involving pesticides, heavy metals, pharmaceutical compounds, microplastics, and microbiological agents, with cumulative implications for the environment and human health.

The findings confirm that these contaminants are characterized by persistence, mobility, bioaccumulation potential, and diverse mechanisms of toxicity. Exposure occurs through multiple pathways, including ingestion, dermal contact, and inhalation, and may result in both acute and chronic health effects.

Microbiological contamination is primarily associated with acute diseases, whereas long-term exposure to chemical pollutants contributes to neurological, endocrine, renal, and oncological disorders.

A key outcome of this work is the recognition that interactions between contaminants represent a critical but insufficiently understood aspect of water pollution. Emerging contaminants, particularly microplastics and pharmaceutical compounds, may influence the transport, bioavailability, and toxicity of other pollutants, leading to cumulative and potentially synergistic effects. However, these processes remain poorly characterized because of the lack of standardized methodologies and limited data on mixture toxicity and long-term exposure.

The analysis also highlights significant knowledge gaps related to transformation products, chronic low-dose exposure, and the behavior of contaminants under real environmental conditions. In addition, current monitoring systems are often fragmented, and conventional water treatment processes do not ensure the complete removal of emerging contaminants, thereby limiting their effectiveness in protecting drinking water quality.

The impact of water pollution is not uniformly distributed, and vulnerable populations, such as children, the elderly, and communities with limited access to safe water, are disproportionately affected. This underscores the need for risk-based approaches that integrate environmental exposure with public health considerations.

From a practical perspective, reducing water pollution requires the implementation of integrated management strategies that combine source control, optimization of treatment technologies, and continuous monitoring. Attention should be given to the development of advanced and cost-effective treatment solutions capable of addressing complex contaminant mixtures.

Future research should prioritize the development of integrated assessment frameworks capable of simultaneously addressing multiple contaminant classes, cumulative exposure scenarios, environmental transport dynamics, and limitations associated with water treatment technologies. Particular attention should be directed toward improving the understanding of mixture toxicity resulting from simultaneous exposure to pesticides, heavy metals, pharmaceutical compounds, microplastics, and pathogenic microorganisms, considering that current knowledge remains predominantly based on assessments of individual contaminants.

Additional studies are needed to characterize the effects of chronic low-dose exposure, long-term human health implications, ecosystem-level responses, and the susceptibility of vulnerable populations under cumulative exposure conditions. Long-term epidemiological studies and integrated exposure models are particularly needed to improve understanding of cumulative risks associated with multiple contaminant classes. Future investigations should also focus on pharmaceutical transformation products, antimicrobial resistance dissemination, and emerging contaminants that remain insufficiently characterized within current European monitoring and regulatory frameworks.

Another important research priority involves the development of harmonized monitoring and integrated surveillance systems that combine chemical, microbiological, and ecological indicators to support comprehensive risk characterization across interconnected environmental compartments. Emerging monitoring technologies, including real-time sensor networks, remote sensing platforms, and advanced analytical tools, may significantly improve contaminant detection and early-warning capabilities. In addition, advances in predictive modelling, artificial intelligence, machine learning methods, and probabilistic risk assessment tools may contribute to improved water quality forecasting, uncertainty characterization, and decision support for environmental and public health management.

Finally, future studies should evaluate the long-term efficiency of advanced treatment technologies under multi-contaminant conditions and support integrated water management strategies spanning the entire pathway from source to consumer. Such approaches should combine source control measures, optimized treatment technologies, standardized monitoring systems, and science-based regulatory frameworks capable of reducing cumulative environmental and human health risks. Based on these findings, the need to strengthen public policies is highlighted by updating the legislative framework and including emerging contaminants, in accordance with the European Commission initiatives, as well as by harmonizing standards between states. In parallel, the implementation of integrated and standardized monitoring systems, supported by advanced analytical techniques, is essential for the real assessment of contamination and cumulative effects, in the context of a significant gap between the number of existing substances and those evaluated toxicologically.

Reducing pollution at the source, by promoting sustainable agriculture and controlling industrial discharges, must be correlated with the modernization of treatment technologies, in particular by adopting advanced processes capable of eliminating persistent contaminants. At the same time, the application of the “polluter pays” principle, promoted by the Organization for Economic Co-operation and Development, can financially support these measures and stimulate pollution reduction. Finally, the substantiation of effective policies requires the intensification of research on cumulative effects, long-term exposure, and interactions between contaminants to support evidence-based decisions.

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## Abbreviations

The following abbreviations are used in this manuscript:

|                  |                                                                    |
|------------------|--------------------------------------------------------------------|
| PRISMA           | Preferred Reporting Items for Systematic Reviews and Meta-Analyses |
| APIs             | Active Pharmaceutical Ingredients                                  |
| AOPs             | Advanced oxidation processes                                       |
| TLS              | Total Link Strength                                                |
| US EPA           | United States Environmental Protection Agency                      |
| WHO              | World Health Organization                                          |
| EU               | European Union                                                     |
| MP               | Microplastics                                                      |
| IRA              | Integrated risk assessment                                         |
| Al <sup>3+</sup> | Aluminium                                                          |
| As <sup>3+</sup> | Arsenic                                                            |
| Cd <sup>2+</sup> | Cadmium                                                            |
| Cu <sup>2+</sup> | Copper                                                             |
| Fe <sup>2+</sup> | Iron                                                               |

|                  |                                                             |
|------------------|-------------------------------------------------------------|
| Hg <sup>2+</sup> | Mercury                                                     |
| Mn <sup>2+</sup> | Manganese                                                   |
| Ni <sup>2+</sup> | Nickel                                                      |
| Pb <sup>2+</sup> | Lead                                                        |
| Zn <sup>2+</sup> | Zinc                                                        |
| ng/L             | Nanograms per litre                                         |
| µg/L             | Micrograms per litre                                        |
| E. coli          | Escherichia coli                                            |
| PPCPs            | Pharmaceuticals and personal care products                  |
| PFAS             | Per- and polyfluoroalkyl substances                         |
| EDCs             | Endocrine-disrupting chemicals                              |
| ARGs             | Antibiotic resistance genes                                 |
| PFSAs            | Perfluoroalkyl sulfonates                                   |
| PFOS             | Perfluorooctane sulfonic acid                               |
| PFBS             | Perfluorobutane sulfonic acid                               |
| PFHxS            | Perfluorohexane sulfonic acid                               |
| PFCAs            | Perfluoroalkyl carboxylic acids                             |
| PFOA             | Perfluorooctanoic acid                                      |
| PFHxA            | Perfluorohexanoic acid                                      |
| PFNA             | Perfluorononanoic acid                                      |
| PFAAs            | Perfluoroalkyl acids PFAAs                                  |
| PAEs             | Phthalate esters                                            |
| BPA              | Bisphenol A                                                 |
| DEHP             | Di(2-ethylhexyl) phthalate                                  |
| DNOP             | Di-n-octyl phthalate                                        |
| DBP              | Dibutyl phthalate                                           |
| LC-MS/MS         | Liquid chromatography coupled with tandem mass spectrometry |
| HRMS             | High-resolution mass spectrometry                           |
| GC-MS            | Gas chromatography-mass spectrometry                        |
| HQ               | Hazard Quotient Cancer Risk (CR).                           |
| HI               | Hazard Index                                                |
| CR               | Cancer Risk                                                 |

## References

1. Jayaswal, K.; Sahu, V.; Gurjar, B.R. Water Pollution, Human Health and Remediation. In *Energy, Environment, and Sustainability*; Springer: Singapore, 2018; pp. 11–27. [\[CrossRef\]](#)
2. du Plessis, A. Persistent Degradation: Global Water Quality Challenges and Required Actions. *One Earth* **2022**, *5*, 129–131. [\[CrossRef\]](#)
3. United Nations World Enters Era of ‘Global Water Bankruptcy’ | UN News. Available online: <https://news.un.org/en/story/2026/01/1166800> (accessed on 13 March 2026).
4. Ameen, R.F.M.; Mourshed, M. Influences of Key Factors on River Water Quality in Urban and Rural Areas: A Review. *Case Stud. Chem. Environ. Eng.* **2023**, *8*, 100424. [\[CrossRef\]](#)
5. Sarker, B.; Keya, K.N.; Mahir, F.I.; Nahiun, K.M.; Shahida, S.; Khan, R.A. Surface and Ground Water Pollution: Causes and Effects of Urbanization and Industrialization in South Asia. *Sci. Rev.* **2021**, *7*, 32–41. [\[CrossRef\]](#)
6. Rodriguez-Narvaez, O.M.; Peralta-Hernandez, J.M.; Goonetilleke, A.; Bandala, E.R. Treatment Technologies for Emerging Contaminants in Water: A Review. *Chem. Eng. J.* **2017**, *323*, 361–380. [\[CrossRef\]](#)
7. Morin-Crini, N.; Lichtfouse, E.; Liu, G.; Balaram, V.; Ribeiro, A.R.L.; Lu, Z.; Stock, F.; Carmona, E.; Teixeira, M.R.; Picos-Corrales, L.A.; et al. Worldwide Cases of Water Pollution by Emerging Contaminants: A Review. *Environ. Chem. Lett.* **2022**, *20*, 2311–2338. [\[CrossRef\]](#)
8. Xiao, J.; Wang, L.; Deng, L.; Jin, Z. Characteristics, Sources, Water Quality and Health Risk Assessment of Trace Elements in River Water and Well Water in the Chinese Loess Plateau. *Sci. Total Environ.* **2019**, *650*, 2004–2012. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Lin, L.; Yang, H.; Xu, X. Effects of Water Pollution on Human Health and Disease Heterogeneity: A Review. *Front. Environ. Sci.* **2022**, *10*, 880246. [\[CrossRef\]](#)

10. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. *Water* **2021**, *13*, 2660. [\[CrossRef\]](#)
11. Li, X.; Shen, X.; Jiang, W.; Xi, Y.; Li, S. Comprehensive Review of Emerging Contaminants: Detection Technologies, Environmental Impact, and Management Strategies. *Ecotoxicol. Environ. Saf.* **2024**, *278*, 116420. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Aziz, F.; Wang, X.; Mahmood, M.Q.; Juliette, O.K. Assessing Human Health Risks Associated with Wastewater Flooding. *Environ. Impact Assess. Rev.* **2025**, *115*, 108031. [\[CrossRef\]](#)
13. Teodosiu, C.; Gilca, A.F.; Barjoveanu, G.; Fiore, S. Emerging Pollutants Removal through Advanced Drinking Water Treatment: A Review on Processes and Environmental Performances Assessment. *J. Clean. Prod.* **2018**, *197*, 1210–1221. [\[CrossRef\]](#)
14. Tremblay, L.; Stewart, M.; Northcott, G. Emerging Contaminants: Should We Be Worried? *Revolve*, August 2016; pp. 19–21.
15. Shetty, S.S.; Deepthi, D.; Harshitha, S.; Sonkusare, S.; Naik, P.B.; Madhyastha, H. Environmental Pollutants and Their Effects on Human Health. *Heliyon* **2023**, *9*, e19496. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Lu, X. Environmental Transport and Transformation of Pollutants. *Toxics* **2025**, *13*, 1028. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Khatri, N.; Tyagi, S. Influences of Natural and Anthropogenic Factors on Surface and Groundwater Quality in Rural and Urban Areas. *Front. Life Sci.* **2015**, *8*, 23–39. [\[CrossRef\]](#)
18. Boelee, E.; Geerling, G.; van der Zaan, B.; Blauw, A.; Vethaak, A.D. Water and Health: From Environmental Pressures to Integrated Responses. *Acta Trop.* **2019**, *193*, 217–226. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Kumar, R.; Qureshi, M.; Vishwakarma, D.K.; Al-Ansari, N.; Kuriqi, A.; Elbeltagi, A.; Saraswat, A. A Review on Emerging Water Contaminants and the Application of Sustainable Removal Technologies. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100219. [\[CrossRef\]](#)
20. Majid, S.; Reus, A.; Hoondert, R.; Blokker, M.; Dash, A.; Houtman, C.; Schriks, M.; Dingemans, M.M.L. A Framework for Evaluating Less-than-Lifetime Exposures: Advancing Toxicological Risk Assessment for Drinking Water Quality. *Arch. Toxicol.* **2025**, *99*, 3147–3168. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Kamrin, M.A. Hazard Identification. In *Encyclopedia of Toxicology*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2014; pp. 818–820. [\[CrossRef\]](#)
22. Babuji, P.; Thirumalaisamy, S.; Duraisamy, K.; Periyasamy, G. Human Health Risks Due to Exposure to Water Pollution: A Review. *Water* **2023**, *15*, 2532. [\[CrossRef\]](#)
23. Kumar, M.; Borah, P.; Devi, P. Priority and Emerging Pollutants in Water. *Inorg. Pollut. Water* **2020**, 33–49. [\[CrossRef\]](#)
24. Banerjee, A.; Singh, P.; Pratap, K. Hydrogeological Component Assessment for Water Resources Management of Semi-Arid Region: A Case Study of Gwalior M.P., India. *Arab. J. Geosci.* **2016**, *9*, 711. [\[CrossRef\]](#)
25. Ahmed, N.; Bodrud-Doza, M.; Towfiqul Islam, A.R.M.; Hossain, S.; Moniruzzaman, M.; Deb, N.; Bhuiyan, M.A.Q. Appraising Spatial Variations of As, Fe, Mn and NO<sub>3</sub> Contaminations Associated Health Risks of Drinking Water from Surma Basin, Bangladesh. *Chemosphere* **2019**, *218*, 726–740. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Guo, W.; Li, P.; Du, Q.; Zhou, Y.; Xu, D.; Zhang, Z. Hydrogeochemical Processes Regulating the Groundwater Geochemistry and Human Health Risk of Groundwater in the Rural Areas of the Wei River Basin, China. *Expo. Health* **2023**, *16*, 291–306. [\[CrossRef\]](#)
27. Xu, D.; Li, P.; Chen, X.; Yang, S.; Zhang, P.; Guo, F. Major Ion Hydrogeochemistry and Health Risk of Groundwater Nitrate in Selected Rural Areas of the Guanzhong Basin, China. *Hum. Ecol. Risk Assess.* **2023**, *29*, 701–727. [\[CrossRef\]](#)
28. Fighir, D.; Paduraru, C.; Ciobanu, R.; Bucatariu, F.; Plavan, O.; Gherghel, A.; Barjoveanu, G.; Mihai, M.; Teodosiu, C. Removal of Diclofenac and Heavy Metal Ions from Aqueous Media Using Composite Sorbents in Dynamic Conditions. *Nanomaterials* **2024**, *14*, 33. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Morosanu, I.; Bucatariu, F.; Fighir, D.; Paduraru, C.; Mihai, M.; Teodosiu, C. Optimization of Lead and Diclofenac Removal from Aqueous Media Using a Composite Sorbent of Silica Core and Polyelectrolyte Coacervate Shell. *Polymers* **2023**, *15*, 1948. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Morosanu, I.; Paduraru, C.; Bucatariu, F.; Fighir, D.; Mihai, M.; Teodosiu, C. Shaping Polyelectrolyte Composites for Heavy Metals Adsorption from Wastewater: Experimental Assessment and Equilibrium Studies. *J. Environ. Manag.* **2022**, *321*, 115999. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Acarer Arat, S. Health Risk Assessment of Oral and Dermal Exposure to Metal-Contaminated Groundwater: A Case Study from Hatay, Türkiye. *Sci. Total Environ.* **2025**, *1006*, 180932. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Alhagri, I.A.; Albadri, A.E.A.E.; Alghriby, F.; Al-Saqabi, F.; Alharbi, T.S.; Alglfs, S. Determination of Heavy Metals and Health Risk Assessment in Drinking Water in Bukayriyah City, Saudi Arabia. *Open Chem.* **2024**, *22*, 20240105. [\[CrossRef\]](#)
33. Xu, H.; Newton, R.; Love, D.C.; Zhao, Y.; Toppe, J.; Zhang, W. Heavy Metal Risks in Aquatic Foods. *Environ. Int.* **2025**, *205*, 109831. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Zhang, Y.; Xu, B.; Guo, Z.; Han, J.; Li, H.; Jin, L.; Chen, F.; Xiong, Y. Human Health Risk Assessment of Groundwater Arsenic Contamination in Jinghui Irrigation District, China. *J. Environ. Manag.* **2019**, *237*, 163–169.

35. Essien, J.P.; Ikpe, D.I.; Inam, E.D.; Okon, A.O.; Ebong, G.A.; Benson, N.U. Occurrence and Spatial Distribution of Heavy Metals in Landfill Leachates and Impacted Freshwater Ecosystem: An Environmental and Human Health Threat. *PLoS ONE* **2022**, *17*, e0263279. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Hussain, F.; Ahmed, S.; Muhammad Zaigham Abbas Naqvi, S.; Awais, M.; Zhang, Y.; Zhang, H.; Raghavan, V.; Zang, Y.; Zhao, G.; Hu, J. Agricultural Non-Point Source Pollution: Comprehensive Analysis of Sources and Assessment Methods. *Agriculture* **2025**, *15*, 531. [\[CrossRef\]](#)
37. Dragun, Z.; Fiket, Ž.; Tepić, N.; Kiralj, Z.; Kralj, T.; Šoštarić Vulić, Z.; Ivanković, D.; Lučić, M.; Puljko, A.; Udiković-Kolić, N.; et al. The Problem of Diffuse Pollution of a Major River Running through Predominantly Rural Area: The Case of Potentially Detrimental Levels of Tungsten, Silver, and Manganese in the Mura River. *Environ. Chem. Ecotoxicol.* **2025**, *7*, 2043–2066. [\[CrossRef\]](#)
38. Tudi, M.; Ruan, H.D.; Wang, L.; Lyu, J.; Sadler, R.; Connell, D.; Chu, C.; Phung, D.T. Agriculture Development, Pesticide Application and Its Impact on the Environment. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1112. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Bodor, A.; Feigl, G.; Kolossa, B.; Mészáros, E.; Laczi, K.; Kovács, E.; Perei, K.; Rákhely, G. Soils in Distress: The Impacts and Ecological Risks of (Micro)Plastic Pollution in the Terrestrial Environment. *Ecotoxicol. Environ. Saf.* **2024**, *269*, 115807. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Karishma, S.; Yaashikaa, P.R.; Kumar, P.S.; Kamalesh, R.; Saravanan, A.; Rangasamy, G. Promising Approaches and Kinetic Prospects of the Microbial Degradation of Pharmaceutical Contaminants. *Environ. Sci. Adv.* **2023**, *2*, 1488–1504. [\[CrossRef\]](#)
41. Jagadeesan, K.K.; Proctor, K.; Standerwick, R.; Barden, R.; Kasprzyk-Hordern, B. Predicting Pharmaceutical Concentrations and Assessing Risks in the Aquatic Environment Using PERK: A Case Study of a Catchment Area in South-West England. *Water Res.* **2025**, *268*, 122643. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Pirvu, F.; Pascu, L.F.; Paun, I.; Stoica, C.; Iancu, V.I.; Niculescu, M.; Stinga, M.V.; Chiriac, F.L. Sorption of PAHs onto Microplastics in Romanian Surface Waters and Sediments: Environmental Toxicity and Human Health Risk with Emphasis on Pediatric Exposure. *Water Res.* **2025**, *287*, 124483. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Jeong, C.B.; Won, E.J.; Kang, H.M.; Lee, M.C.; Hwang, D.S.; Hwang, U.K.; Zhou, B.; Souissi, S.; Lee, S.J.; Lee, J.S. Microplastic Size-Dependent Toxicity, Oxidative Stress Induction, and p-JNK and p-P38 Activation in the Monogonont Rotifer (*Brachionus koreanus*). *Environ. Sci. Technol.* **2016**, *50*, 8849–8857. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Ebele, A.; Oluseyi, T.; Drage, D.; Harrad, S.; Abou-Elwafa Abdallah, M. Occurrence, Seasonal Variation and Human Exposure to Pharmaceuticals and Personal Care Products in Surface Water, Groundwater and Drinking Water In. *Emerg. Contam.* **2020**, *6*, 124–134. [\[CrossRef\]](#)
45. Wuijts, S.; Claessens, J.; Farrow, L.; Doody, D.G.; Klages, S.; Christophoridis, C.; Cvejić, R.; Glavan, M.; Nesheim, I.; Platjouw, F.; et al. Protection of Drinking Water Resources from Agricultural Pressures: Effectiveness of EU Regulations in the Context of Local Realities. *J. Environ. Manag.* **2021**, *287*, 112270. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Makanda, K.; Nzama, S.; Kanyerere, T. Assessing the Role of Water Resources Protection Practice for Sustainable Water Resources Management: A Review. *Water* **2022**, *14*, 3153. [\[CrossRef\]](#)
47. Giakoumis, T.; Voulvoulis, N. The Transition of EU Water Policy towards the Water Framework Directive's Integrated River Basin Management Paradigm. *Environ. Manag.* **2018**, *62*, 819–831. [\[CrossRef\]](#) [\[PubMed\]](#)
48. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 Explanation and Elaboration: Updated Guidance and Exemplars for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n160. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Int. J. Surg.* **2010**, *8*, 336–341. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Ahmad, T.; Shaban, I.A.; Zayed, T. A Review of Climatic Impacts on Water Main Deterioration. *Urban Clim.* **2023**, *49*, 101552. [\[CrossRef\]](#)
51. Brignardello-Petersen, R.; Santesso, N.; Guyatt, G.H. Systematic Reviews of the Literature: An Introduction to Current Methods. *Am. J. Epidemiol.* **2025**, *194*, 536–542. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Ganasegeran, K.; Hor, C.P.; Jamil, M.F.A.; Suppiah, P.D.; Noor, J.M.; Hamid, N.A.; Chuan, D.R.; Manaf, M.R.A.; Ch'ng, A.S.H.; Looi, I. Mapping the Scientific Landscape of Diabetes Research in Malaysia (2000–2018): A Systematic Scientometrics Study. *Int. J. Environ. Res. Public Health* **2021**, *18*, 318. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Chen, C.; Song, M. Visualizing a Field of Research: A Methodology of Systematic Scientometric Reviews. *PLoS ONE* **2019**, *14*, e0223994. [\[CrossRef\]](#) [\[PubMed\]](#)
54. van Eck, N.J.; Waltman, L. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics* **2009**, *84*, 523–538. [\[CrossRef\]](#) [\[PubMed\]](#)
55. van Eck, N.J.; Waltman, L. Citation-Based Clustering of Publications Using CitNetExplorer and VOSviewer. *Scientometrics* **2017**, *111*, 1053–1070. [\[CrossRef\]](#) [\[PubMed\]](#)

56. Hemati, G.; Irandoost, K.; Alizadeh, H. Exploring the Research Evolution and Global Perspectives of Water-Sensitive Cities: A Comprehensive Bibliometric Analysis Using CiteSpace and VOSviewer. *Environ. Dev. Sustain.* **2025**, *2025*, 1–20. [\[CrossRef\]](#)
57. Madhav, S.; Ahamad, A.; Singh, A.K.; Kushawaha, J.; Chauhan, J.S.; Sharma, S.; Singh, P. Water Pollutants: Sources and Impact on the Environment and Human Health. In *Sensors in Water Pollutants Monitoring: Role of Material. Advanced Functional Materials and Sensors*; Springer: Singapore, 2020; pp. 43–62. [\[CrossRef\]](#)
58. Patterson, J.J.; Smith, C.; Bellamy, J. Understanding Enabling Capacities for Managing the “wicked Problem” of Nonpoint Source Water Pollution in Catchments: A Conceptual Framework. *J. Environ. Manag.* **2013**, *128*, 441–452. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Wang, Q.; Yang, Z. Industrial Water Pollution, Water Environment Treatment, and Health Risks in China. *Environ. Pollut.* **2016**, *218*, 358–365. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Danilov-Danilyan, V.I.; Venitsianov, E.V.; Belyaev, S.D. Some Problems of Reducing the Pollution of Water Bodies from Diffuse Sources. *Water Resour.* **2020**, *47*, 682–690. [\[CrossRef\]](#)
61. Li, Y.; Wang, H.; Deng, Y.; Liang, D.; Li, Y.; Gu, Q. Applying Water Environment Capacity to Assess the Non-Point Source Pollution Risks in Watersheds. *Water Res.* **2023**, *240*, 120092. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Hou, L.; Zhou, Z.; Wang, R.; Li, J.; Dong, F.; Liu, J. Research on the Non-Point Source Pollution Characteristics of Important Drinking Water Sources. *Water* **2022**, *14*, 211. [\[CrossRef\]](#)
63. Basic Information about Nonpoint Source (NPS) Pollution. Available online: <https://www.epa.gov/nps/basic-information-about-nonpoint-source-nps-pollution> (accessed on 7 April 2026).
64. Geissen, V.; Mol, H.; Klumpp, E.; Umlauf, G.; Nadal, M.; van der Ploeg, M.; van de Zee, S.E.A.T.M.; Ritsema, C.J. Emerging Pollutants in the Environment: A Challenge for Water Resource Management. *Int. Soil Water Conserv. Res.* **2015**, *3*, 57–65. [\[CrossRef\]](#)
65. Sharpley, A.N.; Bergström, L.; Aronsson, H.; Bechmann, M.; Bolster, C.H.; Börling, K.; Djodjic, F.; Jarvie, H.P.; Schoumans, O.F.; Stamm, C.; et al. Future Agriculture with Minimized Phosphorus Losses to Waters: Research Needs and Direction. *AMBIO* **2015**, *44*, 163–179. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Wen, Y.; Schoups, G.; Van De Giesen, N. Organic Pollution of Rivers: Combined Threats of Urbanization, Livestock Farming and Global Climate Change. *Nature* **2017**, *7*, 43289. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Navarro-Ortega, A.; Acuna, V.; Bellin, A.; Burek, P.; Cassiani, G.; Choukr-Allah, R.; Dolédec, S. Managing the Effects of Multiple Stressors on Aquatic Ecosystems under Water Scarcity. The GLOBAQUA Project. *Sci. Total Environ.* **2015**, *503*, 3–9. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Horton, A.A.; Walton, A.; Spurgeon, D.J.; Lahive, E.; Svendsen, C. Microplastics in Freshwater and Terrestrial Environments: Evaluating the Current Understanding to Identify the Knowledge Gaps and Future Research Priorities. *Sci. Total Environ.* **2017**, *586*, 127–141. [\[CrossRef\]](#) [\[PubMed\]](#)
69. Bonsch, M.; Popp, A.; Biewald, A.; Högner, K.; Rolinski, S.; Schmitz, C.; Weindl, I.; Stevanovic, M. Environmental Flow Provision: Implications for Agricultural Water and Land-Use at the Global Scale. *Glob. Environ. Change* **2015**, *30*, 113–132. [\[CrossRef\]](#)
70. Garud, A.; Pawar, S.; Patil, M.S.; Kale, S.R.; Patil, S. A Scientific Review of Pesticides: Classification, Toxicity, Health Effects, Sustainability, and Environmental Impact. *Cureus* **2024**, *16*, e67945. [\[CrossRef\]](#) [\[PubMed\]](#)
71. Eddleston, M. Poisoning by Pesticides. *Medicine* **2020**, *48*, 214–217. [\[CrossRef\]](#)
72. European Commission Pesticides—Agriculture and Rural Development. Available online: [https://agriculture.ec.europa.eu/cap-my-country/sustainability/environmental-sustainability/low-input-farming/pesticides\\_en](https://agriculture.ec.europa.eu/cap-my-country/sustainability/environmental-sustainability/low-input-farming/pesticides_en) (accessed on 8 February 2026).
73. Yang, W.; Schmidt, C.; Wu, S.; Zhao, Z.; Li, R.; Wang, Z.; Wang, H.; Hua, P.; Krebs, P.; Zhang, J. Exacerbated Anthropogenic Water Pollution under Climate Change and Urbanization. *Water Res.* **2025**, *280*, 123449. [\[CrossRef\]](#) [\[PubMed\]](#)
74. Fan, G.; Lin, R.; Wei, Z.; Xiao, Y.; Shangguan, H.; Song, Y. Effects of Low Impact Development on the Stormwater Runoff and Pollution Control. *Sci. Total Environ.* **2022**, *805*, 150404. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Syafrudin, M.; Kristanti, R.A.; Yuniarto, A.; Hadibarata, T.; Rhee, J.; Al-Onazi, W.A.; Algarni, T.S.; Almarri, A.H.; Al-Mohaimeed, A.M. Pesticides in Drinking Water—A Review. *Int. J. Environ. Res. Public Health* **2021**, *18*, 468. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Agarwal, A.; Prajapati, R.; Singh, O.P.; Raza, S.K.; Thakur, L.K. Pesticide Residue in Water—A Challenging Task in India. *Environ. Monit. Assess.* **2015**, *187*, 54. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Lammoglia, S.K.; Kennedy, M.C.; Barriuso, E.; Alletto, L.; Justes, E.; Munier-Jolain, N.; Mamy, L. Assessing Human Health Risks from Pesticide Use in Conventional and Innovative Cropping Systems with the BROWSE Model. *Environ. Int.* **2017**, *105*, 66–78. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Bhakkan-Mambir, B.; Deloumeaux, J.; Luce, D. Geographical Variations of Cancer Incidence in Guadeloupe, French West Indies. *BMC Cancer* **2022**, *22*, 783. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Sharma, A.; Kumar, V.; Shahzad, B.; Tanveer, M.; Sidhu, G.P.S.; Handa, N.; Kohli, S.K.; Yadav, P.; Bali, A.S.; Parihar, R.D.; et al. Worldwide Pesticide Usage and Its Impacts on Ecosystem. *SN Appl. Sci.* **2019**, *1*, 1446. [\[CrossRef\]](#)
80. Maggi, F.; Tang, F.H.M.; Tubiello, F.N. Agricultural Pesticide Land Budget and River Discharge to Oceans. *Nature* **2023**, *620*, 1013–1017. [\[CrossRef\]](#) [\[PubMed\]](#)

81. Pawlak, F.; Koziol, K.; Polkowska, Z. Chemical Hazard in Glacial Melt? The Glacial System as a Secondary Source of POPs (in the Northern Hemisphere). A Systematic Review. *Sci. Total Environ.* **2021**, *778*, 145244. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Corsolini, S.; Sarà, G. The Trophic Transfer of Persistent Pollutants (HCB, DDTs, PCBs) within Polar Marine Food Webs. *Chemosphere* **2017**, *177*, 189–199. [\[CrossRef\]](#) [\[PubMed\]](#)
83. Zeng, H.; Fu, X.; Liang, Y.; Qin, L.; Mo, L. Risk Assessment of an Organochlorine Pesticide Mixture in the Surface Waters of Qingshitan Reservoir in Southwest China. *RSC Adv.* **2018**, *32*, 17797–17805. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Lai, W. Pesticide Use and Health Outcomes: Evidence from Agricultural Water Pollution in China. *J. Environ. Econ. Manag.* **2017**, *86*, 93–120. [\[CrossRef\]](#)
85. Duttagupta, S.; Mukherjee, A.; Bhattacharya, A.; Bhattacharya, J. Wide Exposure of Persistent Organic Pollutants (PoPs) in Natural Waters and Sediments of the Densely Populated Western Bengal Basin, India. *Sci. Total Environ.* **2020**, *717*, 137187. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Leong, K.H.; Benjamin Tan, L.L.; Mustafa, A.M. Contamination Levels of Selected Organochlorine and Organophosphate Pesticides in the Selangor River, Malaysia between 2002 and 2003. *Chemosphere* **2007**, *66*, 1153–1159. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Li, Y.; Piao, Z.; Ge, X.; Feng, J.; Sun, D.; Zhang, J. Environmental Pollutants and Rectal Cancer: The Impact of Water Contamination. *Ecotoxicol. Environ. Saf.* **2025**, *294*, 118072. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Mateo-Sagasta, J.; Zadeh, S.; Turrall, H.; Burke, J. *Water Pollution from Agriculture: A Global Review. Executive Summary*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2017.
89. Evans, A.E.; Mateo-Sagasta, J.; Qadir, M.; Boelee, E.; Ippolito, A. Agricultural Water Pollution: Key Knowledge Gaps and Research Needs. *Curr. Opin. Environ. Sustain.* **2019**, *36*, 20–27. [\[CrossRef\]](#)
90. Bisimwa, A.M.; Amisi, F.M.; Bamawa, C.M.; Muhaya, B.B.; Kankonda, A.B. Water Quality Assessment and Pollution Source Analysis in Bukavu Urban Rivers of the Lake Kivu Basin (Eastern Democratic Republic of Congo). *Environ. Sustain. Indic.* **2022**, *14*, 100183. [\[CrossRef\]](#)
91. Zhou, Q.; Yang, N.; Li, Y.; Ren, B.; Ding, X.; Bian, H.; Yao, X. Total Concentrations and Sources of Heavy Metal Pollution in Global River and Lake Water Bodies from 1972 to 2017. *Glob. Ecol. Conserv.* **2020**, *22*, e00925. [\[CrossRef\]](#)
92. Ali, H.; Khan, E. Trophic Transfer, Bioaccumulation, and Biomagnification of Non-Essential Hazardous Heavy Metals and Metalloids in Food Chains/Webs—Concepts and Implications for Wildlife and Human Health. *Hum. Ecol. Risk Assess. Int. J.* **2019**, *25*, 1353–1376. [\[CrossRef\]](#)
93. Angelova, I.; Ivanov, I.; Venelinov, T. Origin of Aluminium in the Raw Drinking Water of Sofia City, Bulgaria. *Water Air Soil Pollut.* **2020**, *231*, 455. [\[CrossRef\]](#)
94. Krupiniska, I. Aluminium Drinking Water Treatment Residuals and Their Toxic Impact on Human Health. *Molecules* **2020**, *25*, 641. [\[CrossRef\]](#) [\[PubMed\]](#)
95. Paraskevas, D.; Kellens, K.; Van De Voorde, A.; Dewulf, W.; Duflou, J.R. Environmental Impact Analysis of Primary Aluminium Production at Country Level. *Procedia CIRP* **2016**, *40*, 209–213. [\[CrossRef\]](#)
96. Zhang, L.; Qin, X.; Tang, J.; Liu, W.; Yang, H. Review of Arsenic Geochemical Characteristics and Its Significance on Arsenic Pollution Studies in Karst Groundwater, Southwest China. *Appl. Geochem.* **2017**, *77*, 80–88. [\[CrossRef\]](#)
97. Fashae, O.A.; Obateru, R.O. *Geospatial Assessment of Surface Water Pollution and Industrial Activities in Ibadan, Nigeria*; Springer International Publishing: Cham, Switzerland, 2021; pp. 189–211. [\[CrossRef\]](#)
98. Chandio, T.A.; Khan, M.N.; Muhammad, M.T.; Yalcinkaya, O.; Wasim, A.A.; Kayis, A.F. Fluoride and Arsenic Contamination in Drinking Water Due to Mining Activities and Its Impact on Local Area Population. *Environ. Sci. Pollut. Res.* **2021**, *28*, 2355–2368. [\[CrossRef\]](#) [\[PubMed\]](#)
99. Alonso, D.L.; Pérez, R.; Okio, C.K.Y.A.; Castillo, E. Assessment of Mining Activity on Arsenic Contamination in Surface Water and Sediments in Southwestern Area of Santurbán Paramo, Colombia. *J. Environ. Manag.* **2020**, *264*, 110478. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Abraham, M.R.; Susan, T.B. Water Contamination with Heavy Metals and Trace Elements from Kilembe Copper Mine and Tailing Sites in Western Uganda; Implications for Domestic Water Quality. *Chemosphere* **2017**, *169*, 281–287. [\[CrossRef\]](#) [\[PubMed\]](#)
101. Chen, M.; Li, F.; Tao, M.; Hu, L.; Shi, Y.; Liu, Y. Distribution and Ecological Risks of Heavy Metals in River Sediments and Overlying Water in Typical Mining Areas of China. *Mar. Pollut. Bull.* **2019**, *146*, 893–899. [\[CrossRef\]](#) [\[PubMed\]](#)
102. Luo, Y.; Rao, J.; Jia, Q. Heavy Metal Pollution and Environmental Risks in the Water of Rongna River Caused by Natural AMD around Tiegelongnan Copper Deposit, Northern Tibet, China. *PLoS ONE* **2022**, *17*, e0266700. [\[CrossRef\]](#) [\[PubMed\]](#)
103. Sui, S.; Wang, M.; Wang, M.; Ma, W.; Yang, S.; Zhang, F.; Jia, L.; Liu, T. Pronounced Transition of Heavy Metal Pollution Sources in Chinese Agricultural Surface Waters: The Rising Prominence of Non-Point Source Pollution. *iScience* **2025**, *28*, 112524. [\[CrossRef\]](#) [\[PubMed\]](#)
104. Tumolo, M.; Ancona, V.; De Paola, D.; Losacco, D.; Campanale, C.; Massarelli, C.; Uricchio, V.F. Chromium Pollution in European Water, Sources, Health Risk, and Remediation Strategies: An Overview. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5438. [\[CrossRef\]](#) [\[PubMed\]](#)

105. Le, T.V.; Nguyen, B.T. Heavy Metal Pollution in Surface Water Bodies in Provincial Khanh Hoa, Vietnam: Pollution and Human Health Risk Assessment, Source Quantification, and Implications for Sustainable Management and Development. *Environ. Pollut.* **2024**, *343*, 123216. [[CrossRef](#)] [[PubMed](#)]
106. Neelotpol, S.; Raj, A.; Nabila, A.A.; Kamal, L.; Noha, S.M.; Moniruzzaman, M. Heavy Metal Pollution and Health Risk Assessment in Surface Waters Impacted by Pharmaceutical Effluents in Gazipur and Narayanganj, Bangladesh. *Sci. Rep.* **2026**, *16*, 11972. [[CrossRef](#)] [[PubMed](#)]
107. Sarker, M.N.I.; Wu, M.; Alam, G.M.M.; Shouse, R.C. Livelihood Vulnerability of Riverine-Island Dwellers in the Face of Natural Disasters in Bangladesh. *Sustainability* **2019**, *11*, 1623. [[CrossRef](#)]
108. Hagage, M.; Hewaidy, A.G.A.; Abdulaziz, A.M.; Shetaia, S.A. Nutrient and Manganese Pollution in Groundwater of the Northeastern Nile Delta: Distribution, Sources, and Health Risks. *Appl. Water Sci.* **2025**, *15*, 151. [[CrossRef](#)]
109. Matveeva, V.A.; Alekseenko, A.V.; Karthe, D.; Puzanov, A.V. Manganese Pollution in Mining-Influenced Rivers and Lakes: Current State and Forecast under Climate Change in the Russian Arctic. *Water* **2022**, *14*, 1091. [[CrossRef](#)]
110. Fricke, I.; Götz, R.; Schleyer, R.; Püttmann, W. Analysis of Sources and Sinks of Mercury in the Urban Water Cycle of Frankfurt Am Main, Germany. *Water* **2015**, *7*, 6097–6116. [[CrossRef](#)]
111. Zouhri, L.; Delépine, J.; Zouhri, L. Assessment of Mercury Contamination in the Chalk Aquifer of the Pays de Caux and Its Implications for Public Health (France). *Water* **2025**, *17*, 1087. [[CrossRef](#)]
112. Cangemi, M.; Madonia, P.; Albano, L.; Bonfardecì, A.; Di Figlia, M.G.; Di Martino, R.M.R.; Nicolosi, M.; Favara, R. Heavy Metal Concentrations in the Groundwater of the Barcellona-Milazzo Plain (Italy): Contributions from Geogenic and Anthropogenic Sources. *Int. J. Environ. Res. Public Health* **2019**, *16*, 285. [[CrossRef](#)] [[PubMed](#)]
113. Moldovan, A.; Török, A.I.; Kovacs, E.; Cadar, O.; Mirea, I.C.; Micle, V. Metal Contents and Pollution Indices Assessment of Surface Water, Soil, and Sediment from the Arieș River Basin Mining Area, Romania. *Sustainability* **2022**, *14*, 8024. [[CrossRef](#)]
114. Romo-Morales, D.; Moreno-Rodríguez, V.; Molina-Freaner, F.; Valencia-Moreno, M.; Ruiz, J.; Minjárez-Osorio, C.; Hernández-Mendiola, E.; del Rio-Salas, R. Assessment of Geogenic and Anthropogenic Pollution Sources Using an Aquatic Plant Along the Sonora River Basin: Insights from Elemental Concentrations and Pb Isotope Signatures. *Nat. Resour. Res.* **2020**, *29*, 2773–2786. [[CrossRef](#)]
115. Waseem, K.; Akhtar, A.S.; Nawaz, A. Assessment of Lead Contamination in Drinking Water in Zone I and Zone III of Islamabad, Pakistan. *Discov. Water* **2025**, *5*, 38. [[CrossRef](#)]
116. Chen, M.; Wang, D.; Ding, S.; Fan, X.; Jin, Z.; Wu, Y.; Wang, Y.; Zhang, C. Zinc Pollution in Zones Dominated by Algae and Submerged Macrophytes in Lake Taihu. *Sci. Total Environ.* **2019**, *670*, 361–368. [[CrossRef](#)] [[PubMed](#)]
117. Wardhani, W.K.; Ariesyady, H.D.; Andarani, P.; Nguyen, M.N.; Yokota, K.; Inoue, T. Assessment of Zinc Concentrations in Surface Sediment from Urban and Industrial Sites of Umeda River, Japan. *Water Supply* **2022**, *22*, 3941–3950. [[CrossRef](#)]
118. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K.; Sutton, D.J. Heavy Metals Toxicity and the Environment. *EXS* **2012**, *101*, 133. [[CrossRef](#)] [[PubMed](#)]
119. Meng, L.; Zhao, L.; Liu, W.; Lian, J.; Chao, L. Risk Assessment of Bioavailable Heavy Metals in the Water and Sediments in the Yongding New River, North China. *Environ. Monit. Assess.* **2021**, *193*, 589. [[CrossRef](#)] [[PubMed](#)]
120. Fatoki, J.O.; Badmus, J.A. Arsenic as an Environmental and Human Health Antagonist: A Review of Its Toxicity and Disease Initiation. *J. Hazard. Mater. Adv.* **2022**, *5*, 100052. [[CrossRef](#)]
121. Mohammed Abdul, K.S.; Jayasinghe, S.S.; Chandana, E.P.S.; Jayasumana, C.; De Silva, P.M.C.S. Arsenic and Human Health Effects: A Review. *Environ. Toxicol. Pharmacol.* **2015**, *40*, 828–846. [[CrossRef](#)] [[PubMed](#)]
122. Varol, S.; Köse, İ. Effect on Human Health of the Arsenic Pollution and Hydrogeochemistry of the Yazır Lake Wetland (Çavdır-Burdur/Turkey). *Environ. Sci. Pollut. Res.* **2018**, *25*, 16217–16235. [[CrossRef](#)] [[PubMed](#)]
123. Das, A.; Joardar, M.; De, A.; Mridha, D.; Chowdhury, N.R.; Bin Kashim Khan, M.T.; Chakrabartty, P.; Roychowdhury, T. Pollution Index and Health Risk Assessment of Arsenic through Different Groundwater Sources and Its Load on Soil-Paddy-Rice System in a Part of Murshidabad District of West Bengal, India. *Groundw. Sustain. Dev.* **2021**, *15*, 100652. [[CrossRef](#)]
124. Xu, L.; Wang, T.; Wang, J.; Lu, A. Occurrence, Speciation and Transportation of Heavy Metals in 9 Coastal Rivers from Watershed of Laizhou Bay, China. *Chemosphere* **2017**, *173*, 61–68. [[CrossRef](#)] [[PubMed](#)]
125. Leventeli, Y.; Yalcin, F.; Kilic, M. An Investigation about Heavy Metal Pollution of Duden and Goksu Streams (Antalya, Turkey). *Appl. Ecol. Environ.* **2019**, *17*, 2423–2436. [[CrossRef](#)]
126. Obasi, P.N.; Akudinobi, B.E.B. Heavy Metals Occurrence, Assessment and Distribution in Water Resources of the Lead–Zinc Mining Areas of Abakaliki, Southeastern Nigeria. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 8617–8638. [[CrossRef](#)]
127. Jaramillo, M.F.; Restrepo, I. Wastewater Reuse in Agriculture: A Review about Its Limitations and Benefits. *Sustainability* **2017**, *9*, 1734. [[CrossRef](#)]
128. Trotta, V.; Baaloudj, O.; Brienza, M. Risks Associated with Wastewater Reuse in Agriculture: Investigating the Effects of Contaminants in Soil, Plants, and Insects. *Front. Environ. Sci.* **2024**, *12*, 1358842. [[CrossRef](#)]

129. Jomova, K.; Alomar, S.Y.; Nepovimova, E.; Kuca, K.; Valko, M. Heavy Metals: Toxicity and Human Health Effects. *Arch. Toxicol.* **2024**, *99*, 153–209. [[CrossRef](#)] [[PubMed](#)]
130. Nishmitha, P.S.; Akhilghosh, K.A.; Aiswriya, V.P.; Ramesh, A.; Muthuchamy, M.; Muthukumar, A. Understanding Emerging Contaminants in Water and Wastewater: A Comprehensive Review on Detection, Impacts, and Solutions. *J. Hazard. Mater. Adv.* **2025**, *18*, 100755. [[CrossRef](#)]
131. Alam, M.S.; Tahriri, F.; Chen, G. Trends, Challenges, and Research Pathways in Emerging Contaminants: A Comprehensive Bibliometric Analysis. *Integr. Environ. Assess. Manag.* **2025**, *21*, 496–506. [[CrossRef](#)] [[PubMed](#)]
132. Ahrens, L.; Rakovic, J.; Ekdahl, S.; Kallenborn, R. Environmental Distribution of Per- and Polyfluoroalkyl Substances (PFAS) on Svalbard: Local Sources and Long-Range Transport to the Arctic. *Chemosphere* **2023**, *345*, 491–505. [[CrossRef](#)] [[PubMed](#)]
133. Boahen, E.; Owusu, L.; Adjei-Anim, S.O. A Comprehensive Review of Emerging Environmental Contaminants of Global Concern. *Discov. Environ.* **2025**, *3*, 144. [[CrossRef](#)]
134. Bochynska, S.; Duszewska, A.; Maciejewska-Jeske, M.; Wrona, M.; Szeliga, A.; Budzik, M.; Szczesnowicz, A.; Bala, G.; Trzcinski, M.; Meczekalski, B.; et al. The Impact of Water Pollution on the Health of Older People. *Maturitas* **2024**, *185*, 107981. [[CrossRef](#)] [[PubMed](#)]
135. aus der Beek, T.; Weber, F.A.; Bergmann, A.; Hickmann, S.; Ebert, I.; Hein, A.; Küster, A. Pharmaceuticals in the Environment—Global Occurrences and Perspectives. *Environ. Toxicol. Chem.* **2016**, *35*, 823–835. [[CrossRef](#)] [[PubMed](#)]
136. Desbiolles, F.; Malleret, L.; Tiliacos, C.; Wong-Wah-Chung, P.; Laffont-Schwob, I. Occurrence and Ecotoxicological Assessment of Pharmaceuticals: Is There a Risk for the Mediterranean Aquatic Environment? *Sci. Total Environ.* **2018**, *639*, 1334–1348. [[CrossRef](#)] [[PubMed](#)]
137. Hossain, M.S.; Debi, S.; Islam, R.; Ahmed, M.; Siddique, M.A.M. Prevalence of Pharmaceutical Compounds and Heavy Metals in Municipal Wastewater and River Waters of Gazipur District of Bangladesh: Ecological Risk Assessment. *Heliyon* **2026**, *12*, e44578. [[CrossRef](#)]
138. Rayan, R.A. Pharmaceutical Effluent Evokes Superbugs in the Environment: A Call to Action. *Biosaf. Health* **2023**, *5*, 363–371. [[CrossRef](#)] [[PubMed](#)]
139. Polychronidou, V.; Nag, R. Human Health Risk Assessment of Per- and Polyfluoroalkyl Substances (PFAS). *Sci. Total Environ.* **2025**, *1000*, 180428. [[CrossRef](#)] [[PubMed](#)]
140. Alsadik, A.; Akintunde, O.O.; Habibi, H.R.; Achari, G. PFAS in Water Environments: Recent Progress and Challenges in Monitoring, Toxicity, Treatment Technologies, and Post-Treatment Toxicity. *Environ. Syst. Res.* **2025**, *14*, 18. [[CrossRef](#)] [[PubMed](#)]
141. Li, X.Q.; Hua, Z.L.; Wu, J.Y.; Gu, L. Removal of Perfluoroalkyl Acids (PFAAs) in Constructed Wetlands: Considerable Contributions of Submerged Macrophytes and the Microbial Community. *Water Res.* **2021**, *197*, 117080. [[CrossRef](#)] [[PubMed](#)]
142. Pauletto, P.S.; Florent, M.; Bandoz, T.J. Insight into the Mechanism of Perfluorooctanesulfonic Acid Adsorption on Highly Porous Media: Sizes of Hydrophobic Pores and the Extent of Multilayer Formation. *Carbon N. Y.* **2022**, *191*, 535–545. [[CrossRef](#)]
143. Wee, S.Y.; Aris, A.Z. Endocrine Disrupting Compounds in Drinking Water Supply System and Human Health Risk Implication. *Environ. Int.* **2017**, *106*, 207–233. [[CrossRef](#)] [[PubMed](#)]
144. Cai, M.Q.; Wang, R.; Feng, L.; Zhang, L.Q. Determination of Selected Pharmaceuticals in Tap Water and Drinking Water Treatment Plant by High-Performance Liquid Chromatography-Triple Quadrupole Mass Spectrometer in Beijing, China. *Environ. Sci. Pollut. Res.* **2015**, *22*, 1854–1867. [[CrossRef](#)] [[PubMed](#)]
145. Kumawat, M.; Sharma, P.; Pal, N.; James, M.M.; Verma, V.; Tiwari, R.R.; Shubham, S.; Sarma, D.K.; Kumar, M. Occurrence and Seasonal Disparity of Emerging Endocrine Disrupting Chemicals in a Drinking Water Supply System and Associated Health Risk. *Sci. Rep.* **2022**, *12*, 9252. [[CrossRef](#)] [[PubMed](#)]
146. Wee, S.Y.; Aris, A.Z. Occurrence and Public-Perceived Risk of Endocrine Disrupting Compounds in Drinking Water. *Clean Water* **2019**, *2*, 4. [[CrossRef](#)]
147. Vălitalo, P.; Kruglova, A.; Mikola, A.; Vahala, R. Toxicological Impacts of Antibiotics on Aquatic Micro-Organisms: A Mini-Review. *Int. J. Hyg. Environ. Health* **2017**, *220*, 558–569. [[CrossRef](#)] [[PubMed](#)]
148. Rivera-Jaimes, J.A.; Postigo, C.; Melgoza-Alemán, R.M.; Aceña, J.; Barceló, D.; López de Alda, M. Study of Pharmaceuticals in Surface and Wastewater from Cuernavaca, Morelos, Mexico: Occurrence and Environmental Risk Assessment. *Sci. Total Environ.* **2018**, *613–614*, 1263–1274. [[CrossRef](#)] [[PubMed](#)]
149. Wilkinson, J.L.; Boxall, A.B.A.; Kolpin, D.W.; Leung, K.M.Y.; Lai, R.W.S.; Galban-Malag, C.; Adell, A.D.; Mondon, J.; Metian, M.; Marchant, R.A.; et al. Pharmaceutical Pollution of the World's Rivers. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2113947119. [[CrossRef](#)] [[PubMed](#)]
150. Gumbi, B.P.; Moodley, B.; Birungi, G.; Ndungu, P.G. Assessment of Nonsteroidal Anti-Inflammatory Drugs by Ultrasonic-Assisted Extraction and GC-MS in Mgeni and Msunduzi River Sediments, KwaZulu-Natal, South Africa. *Environ. Sci. Pollut. Res.* **2017**, *24*, 20015–20028. [[CrossRef](#)] [[PubMed](#)]
151. de Jesus Gaffney, V.; Almeida, C.M.M.; Rodrigues, A.; Ferreira, E.; Benoliel, M.J.; Cardoso, V.V. Occurrence of Pharmaceuticals in a Water Supply System and Related Human Health Risk Assessment. *Water Res.* **2015**, *72*, 199–208. [[CrossRef](#)] [[PubMed](#)]

152. Sefali, S.; Ruby, R.; Dimple, D.; Giri, A. Toxicological Implications of Emerging Pollutants on Aquatic Organisms. *Discov. Environ.* **2026**, *4*, 43. [CrossRef]
153. Mazhandu, Z.; Mashifana, T. Active Pharmaceutical Contaminants in Drinking Water: Myth or Fact? *DARU J. Pharm. Sci.* **2024**, *32*, 925–945. [CrossRef] [PubMed]
154. Pelkonen, O.; Abass, K.; Parra Morte, J.M.; Panzarea, M.; Testai, E.; Rudaz, S.; Louisse, J.; Gundert-Remy, U.; Wolterink, G.; Jean-Lou CM, D.; et al. Metabolites in the Regulatory Risk Assessment of Pesticides in the EU. *Front. Toxicol.* **2023**, *5*, 1304885. [CrossRef] [PubMed]
155. Alvarez, F.; Arena, M.; Auteri, D.; Binaglia, M.; Castoldi, A.F.; Chiusolo, A.; Colagiorgi, A.; Colas, M.; Crivellente, F.; De Lentdecker, C.; et al. Peer Review of the Pesticide Risk Assessment of the Active Substance Isoflucypram. *EFSA J.* **2022**, *20*, e07328. [CrossRef] [PubMed]
156. Meher, A.K.; Zarouri, A. Environmental Applications of Mass Spectrometry for Emerging Contaminants. *Molecules* **2025**, *30*, 364. [CrossRef] [PubMed]
157. Dolling, S.; Reis-Santos, P.; Williams, M.; Gillanders, B.M. Pharmaceuticals, Pesticides, and PFAS: Quantifying Endocrine Disrupting Compounds in Plastics and Fish Tissues Using Solvent Extraction and LC-MS/MS. *J. Sep. Sci.* **2025**, *48*, e70084. [CrossRef] [PubMed]
158. Carr, S.A.; Liu, J.; Tesoro, A.G. Transport and Fate of Microplastic Particles in Wastewater Treatment Plants. *Water Res.* **2016**, *91*, 174–182. [CrossRef] [PubMed]
159. Cheng, D.; Liu, H.; Qian, W.; Yao, R.; Wang, X. Migration Characteristics of Microplastics in Riparian Soils and Groundwater. *Environ. Monit. Assess.* **2024**, *196*, 796. [CrossRef] [PubMed]
160. Bergmann, M.; Gutow, L.; Klages, M. *Marine Anthropogenic Litter*; Springer: Berlin/Heidelberg, Germany, 2015; pp. 1–447. [CrossRef]
161. Auta, H.S.; Emenike, C.U.; Fauziah, S.H. Distribution and Importance of Microplastics in the Marine Environment: A Review of the Sources, Fate, Effects, and Potential Solutions. *Environ. Int.* **2017**, *102*, 165–176. [CrossRef] [PubMed]
162. Das, B.K.; Das, S.; Kumar, V.; Roy, S.; Mitra, A.; Mandal, B. Microplastics in Ecosystems: Ecotoxicological Threats and Strategies for Mitigation and Governance. *Front. Mar. Sci.* **2025**, *12*, 1672484. [CrossRef]
163. International Maritime Organization. Plastic Particles in the Ocean May Be as Harmful as Plastic Bags, Report Says. Available online: <https://www.imo.org/en/mediacentre/pressbriefings/pages/15-microplastics.aspx> (accessed on 14 April 2026).
164. Estahbanati, S.; Fahrenfeld, N.L. Influence of Wastewater Treatment Plant Discharges on Microplastic Concentrations in Surface Water. *Chemosphere* **2016**, *162*, 277–284. [CrossRef] [PubMed]
165. Triebkorn, R.; Braunbeck, T.; Grummt, T.; Hanslik, L. Relevance of Nano- and Microplastics for Freshwater Ecosystems: A Critical Review. *TrAC Trends Anal. Chem.* **2019**, *110*, 375–392.
166. Koelmans, A.A.; Nor, N.H.M.; Hermesen, E.; Kooi, M.; Mintenig, S.M.; De France, J. Microplastics in Freshwaters and Drinking Water: Critical Review and Assessment of Data Quality. *Water Res.* **2019**, *155*, 410–422. [CrossRef] [PubMed]
167. Alam, F.C.; Sembiring, E.; Muntalif, B.S.; Suendo, V. Microplastic Distribution in Surface Water and Sediment River around Slum and Industrial Area (Case Study: Ciwalengke River, Majalaya District, Indonesia). *Chemosphere* **2019**, *224*, 637–645. [CrossRef] [PubMed]
168. Shu, X.; Xu, L.; Yang, M.; Qin, Z.; Zhang, Q.; Zhang, L. Spatial Distribution Characteristics and Migration of Microplastics in Surface Water, Groundwater and Sediment in Karst Areas: The Case of Yulong River in Guilin, Southwest China. *Sci. Total Environ.* **2023**, *868*, 161578. [CrossRef] [PubMed]
169. Schymanski, D.; Goldbeck, C.; Humpf, H.U.; Fürst, P. Analysis of Microplastics in Water by Micro-Raman Spectroscopy: Release of Plastic Particles from Different Packaging into Mineral Water. *Water Res.* **2018**, *129*, 154–162. [CrossRef] [PubMed]
170. Vaughan, R.; Turner, S.D.; Rose, N.L. Microplastics in the Sediments of a UK Urban Lake. *Environ. Pollut.* **2017**, *229*, 10–18. [CrossRef] [PubMed]
171. Stupar, Z.; Levei, E.A.; Neag, E.; Baricz, A.; Szekeres, E.; Moldovan, O.T. Microbial Water Quality and Health Risk Assessment in Karst Springs from Apuseni Mountains, Romania. *Front. Environ. Sci.* **2022**, *10*, 931893. [CrossRef]
172. Afonso, A.C.; Saavedra, M.J.; Gomes, I.B.; Simões, M.; Simões, L.C. Current Microbiological Challenges in Drinking Water. *J. Water Process Eng.* **2025**, *72*, 107614. [CrossRef]
173. Digaletos, M.; Ptacek, C.J.; Thomas, J.; Liu, Y.Y. Chemical and Biological Tracers to Identify Source and Transport Pathways of Septic System Contamination to Streams in Areas with Low Permeability Soils. *Sci. Total Environ.* **2023**, *870*, 161866. [CrossRef] [PubMed]
174. Wang, F.; Xiang, L.; Sze-Yin Leung, K.; Elsner, M.; Zhang, Y.; Guo, Y.; Pan, B.; Sun, H.; An, T.; Ying, G.; et al. Emerging Contaminants: A One Health Perspective. *Innovation* **2024**, *5*, 100612. [CrossRef] [PubMed]
175. Ramos, C.F.; de Jesus Laureano, J.; da Rosa, A.L.D.; Gomes, B.M.; de Oliveira Gomes, J.P.; Oliveira, G.A.; Mendonça, A.P.; Bastos, W.R.; do Nascimento, E.L. Evaluation of the Quality of Groundwater in the Municipality of Ji-Paraná, Rondônia, in the Brazilian Amazon Region. *Rev. Ibero-Am. DE Ciênc. Ambient.* **2021**, *12*, 225–235. [CrossRef]

176. Li, P.; Wu, J.; Qian, H.; Zhang, Y.; Yang, N.; Jing, L.; Yu, P. Hydrogeochemical Characterization of Groundwater in and Around a Wastewater Irrigated Forest in the Southeastern Edge of the Tengger Desert, Northwest China. *Expo. Health* **2016**, *8*, 331–348. [\[CrossRef\]](#)
177. Bivins, A.W.; Sumner, T.; Kumpel, E.; Howard, G.; Cumming, O.; Ross, I.; Nelson, K.; Brown, J. Estimating Infection Risks and the Global Burden of Diarrheal Disease Attributable to Intermittent Water Supply Using QMRA. *Environ. Sci. Technol.* **2017**, *51*, 7542–7551. [\[CrossRef\]](#) [\[PubMed\]](#)
178. Jin, D.; Kong, X.; Cui, B.; Jin, S.; Xie, Y.; Wang, X.; Deng, Y. Bacterial Communities and Potential Waterborne Pathogens within the Typical Urban Surface Waters. *Sci. Rep.* **2018**, *8*, 13368. [\[CrossRef\]](#) [\[PubMed\]](#)
179. Baia, C.C.; Vargas, T.F.; Ribeiro, V.A.; Laureano, J.d.J.; Boyer, R.; Dórea, C.C.; Bastos, W.R. Microbiological Contamination of Urban Groundwater in the Brazilian Western Amazon. *Water* **2022**, *14*, 4023. [\[CrossRef\]](#)
180. Schreiber, C.; Rechenburg, A.; Rind, E.; Kistemann, T. The Impact of Land Use on Microbial Surface Water Pollution. *Int. J. Hyg. Environ. Health* **2015**, *218*, 181–187. [\[CrossRef\]](#) [\[PubMed\]](#)
181. Kusi, J.; Ojewole, C.O.; Ojewole, A.E.; Nwi-Mozu, I. Antimicrobial Resistance Development Pathways in Surface Waters and Public Health Implications. *Antibiotics* **2022**, *11*, 821. [\[CrossRef\]](#) [\[PubMed\]](#)
182. Sassi, A.; Basher, N.S.; Kirat, H.; Meradji, S.; Ibrahim, N.A.; Idres, T.; Touati, A. The Role of the Environment (Water, Air, Soil) in the Emergence and Dissemination of Antimicrobial Resistance: A One Health Perspective. *Antibiotics* **2025**, *14*, 764. [\[CrossRef\]](#) [\[PubMed\]](#)
183. Zhang, T.; Lv, K.; Lu, Q.; Wang, L.; Liu, X. Removal of Antibiotic-Resistant Genes during Drinking Water Treatment: A Review. *J. Environ. Sci.* **2021**, *104*, 415–429. [\[CrossRef\]](#)
184. Singh, A.K.; Kaur, R.; Verma, S.; Singh, S. Antimicrobials and Antibiotic Resistance Genes in Water Bodies: Pollution, Risk, and Control. *Front. Environ. Sci.* **2022**, *10*, 830861. [\[CrossRef\]](#)
185. Bartley, P.S.; Domitrovic, T.N.; Moretto, V.T.; Santos, C.S.; Ponce-Terashima, R.; Reis, M.G.; Barbosa, L.M.; Blanton, R.E.; Bonomo, R.A.; Perez, F. Antibiotic Resistance in Enterobacteriaceae from Surface Waters in Urban Brazil Highlights the Risks of Poor Sanitation. *Am. J. Trop. Med. Hyg.* **2019**, *100*, 1369–1377. [\[CrossRef\]](#) [\[PubMed\]](#)
186. Meradji, S.; Basher, N.S.; Sassi, A.; Ibrahim, N.A.; Idres, T.; Touati, A. The Role of Water as a Reservoir for Antibiotic-Resistant Bacteria. *Antibiotics* **2025**, *14*, 763. [\[CrossRef\]](#) [\[PubMed\]](#)
187. Nasir, A.M.; Adam, M.R.; Mohamad Kamal, S.N.E.A.; Jaafar, J.; Othman, M.H.D.; Ismail, A.F.; Aziz, F.; Yusof, N.; Bilad, M.R.; Mohamud, R.; et al. A Review of the Potential of Conventional and Advanced Membrane Technology in the Removal of Pathogens from Wastewater. *Sep. Purif. Technol.* **2022**, *286*, 120454. [\[CrossRef\]](#) [\[PubMed\]](#)
188. Teng, M.; Huo, Z.Y.; Zhang, Z.; Xie, M.; Wang, X.; Wu, Q.; Yang, Z.; Bowen, C.R.; Zhang, W.; Liu, G.; et al. Waterborne Pathogen Mitigation: Decoding Techno-Ecological Synergies in Multiscale Transmission Networks. *Innovation* **2025**, *7*, 101145. [\[CrossRef\]](#) [\[PubMed\]](#)
189. Aghaei, M.; Khoshnamvand, N.; Janjani, H.; Dehghani, M.H.; Karri, R.R. Exposure to Environmental Pollutants: A Mini-Review on the Application of Wastewater-Based Epidemiology Approach. *J. Environ. Health Sci. Eng.* **2024**, *22*, 65. [\[CrossRef\]](#) [\[PubMed\]](#)
190. Alengebawy, A.; Abdelkhalek, S.T.; Qureshi, S.R.; Wang, M.Q. Heavy Metals and Pesticides Toxicity in Agricultural Soil and Plants: Ecological Risks and Human Health Implications. *Toxics* **2021**, *9*, 42. [\[CrossRef\]](#) [\[PubMed\]](#)
191. Zolkefli, N.; Sharuddin, S.S.; Yusoff, M.Z.M.; Hassan, M.A.; Maeda, T.; Ramli, N. A Review of Current and Emerging Approaches for Water Pollution Monitoring. *Water* **2020**, *12*, 3417. [\[CrossRef\]](#)
192. Belle, G.; Moodley, B.; Moodley, R.; Omotola, E.O.; Truter, C.; Olatunji, O.; Oberholster, P. Occurrence and Detection of Selected Pharmaceuticals of Emerging Concern: Potential Risks for Aquatic Ecosystems and Human Health. *Discov. Appl. Sci.* **2025**, *7*, 1078. [\[CrossRef\]](#)
193. Han, Q.F.; Song, C.; Sun, X.; Zhao, S.; Wang, S.G. Spatiotemporal Distribution, Source Apportionment and Combined Pollution of Antibiotics in Natural Waters Adjacent to Mariculture Areas in the Laizhou Bay, Bohai Sea. *Chemosphere* **2021**, *279*, 130381. [\[CrossRef\]](#) [\[PubMed\]](#)
194. Zhai, M.; Fu, B.; Zhai, Y.; Wang, W.; Maroney, A.; Keller, A.A.; Wang, H.; Chovelon, J.M. Simultaneous Removal of Pharmaceuticals and Heavy Metals from Aqueous Phase via Adsorptive Strategy: A Critical Review. *Water Res.* **2023**, *236*, 119924. [\[CrossRef\]](#) [\[PubMed\]](#)
195. Nowell, L.H.; Moran, P.W.; Schmidt, T.S.; Norman, J.E.; Nakagaki, N.; Shoda, M.E.; Mahler, B.J.; Van Metre, P.C.; Stone, W.W.; Sandstrom, M.W.; et al. Complex Mixtures of Dissolved Pesticides Show Potential Aquatic Toxicity in a Synoptic Study of Midwestern U.S. Streams. *Sci. Total Environ.* **2018**, *613–614*, 1469–1488. [\[CrossRef\]](#) [\[PubMed\]](#)
196. Kidd, K.A.; Backhaus, T.; Brodin, T.; Inostroza, P.A.; McCallum, E.S. Environmental Risks of Pharmaceutical Mixtures in Aquatic Ecosystems: Reflections on a Decade of Research. *Environ. Toxicol. Chem.* **2024**, *43*, 549–558. [\[CrossRef\]](#) [\[PubMed\]](#)
197. Singh, N.; Gupta, V.K.; Kumar, A.; Sharma, B. Synergistic Effects of Heavy Metals and Pesticides in Living Systems. *Front. Chem.* **2017**, *5*, 70. [\[CrossRef\]](#) [\[PubMed\]](#)

198. Nyabadza, A.; McCarthy, É.; Makhesana, M.; Heidarinassab, S.; Plouze, A.; Vazquez, M.; Brabazon, D. A Review of Physical, Chemical and Biological Synthesis Methods of Bimetallic Nanoparticles and Applications in Sensing, Water Treatment, Biomedicine, Catalysis and Hydrogen Storage. *Adv. Colloid Interface Sci.* **2023**, *321*, 103010. [CrossRef] [PubMed]
199. Manole, F.; Marian, P.; Mekeres, G.M.; Csep, A.N. A Review of the Effects of Pharmaceutical Waste on the Environment and Human Health. *Pharmacophore* **2023**, *14*, 106–110. [CrossRef]
200. Abbas, G.; Ahmed, U.; Ahmad, M.A. Impact of Microplastics on Human Health: Risks, Diseases, and Affected Body Systems. *Microplastics* **2025**, *4*, 23. [CrossRef]
201. Wang, P.; Shi, Y.Z.; Guan, Q. The Microplastic–PFAS Nexus: From Co-Occurrence to Combined Toxicity in Aquatic Environments. *Toxics* **2025**, *13*, 1041. [CrossRef] [PubMed]
202. Andreu, V.; Gimeno-García, E.; Pascual, J.A.; Vazquez-Roig, P.; Picó, Y. Presence of Pharmaceuticals and Heavy Metals in the Waters of a Mediterranean Coastal Wetland: Potential Interactions and the Influence of the Environment. *Sci. Total Environ.* **2016**, *540*, 278–286. [CrossRef] [PubMed]
203. Zhang, Q.Q.; Ji, X.M.; Tian, G.M.; Jin, R.C. Evolution of Microbial Community and Antibiotic Resistance Genes in Anammox Process Stressed by Oxytetracycline and Copper. *Bioresour. Technol.* **2021**, *319*, 124106. [CrossRef] [PubMed]
204. Wang, Q.; He, X.; Xiong, H.; Chen, Y.; Huang, L. Structure, Mechanism, and Toxicity in Antibiotics Metal Complexation: Recent Advances and Perspectives. *Sci. Total Environ.* **2022**, *848*, 157778. [CrossRef] [PubMed]
205. Sands, M.; Sachdeva, A.; Bukavina, L.; Irudayaraj, J. Synergistic Toxicity of PFAS and Microplastic Mixtures across Five Human Cell Lines. *Environ. Pollut.* **2025**, *386*, 127256. [CrossRef] [PubMed]
206. Dai, Y.; Zhao, J.; Sun, C.; Li, D.; Liu, X.; Wang, Z.; Yue, T.; Xing, B. Interaction and Combined Toxicity of Microplastics and Per- and Polyfluoroalkyl Substances in Aquatic Environment. *Front. Environ. Sci. Eng.* **2022**, *16*, 136. [CrossRef]
207. Liu, Q.; Wu, H.; Chen, J.; Guo, B.; Zhao, X.; Lin, H.; Li, W. Adsorption Mechanism of Trace Heavy Metals on Microplastics and Simulating Their Effect on Microalgae in River. *Environ. Sci. Water Res. Technol.* **2022**, *214*, 113777. [CrossRef]
208. Libenson, A.; Karasaki, S.; Cushing, L.J.; Tran, T.; Rempel, J.L.; Morello-Frosch, R.; Pace, C.E. PFAS-Contaminated Pesticides Applied near Public Supply Wells Disproportionately Impact Communities of Color in California. *ACS Publ.* **2024**, *4*, 2495–2503. [CrossRef] [PubMed]
209. Parker, B.A.; Kanalos, C.A.; Radniecki, T.S.; Massey Simonich, S.L.; Field, J.A. Evaluation of Sorbents and Matrix Effects for Treating Heavy Metals and Per- and Polyfluoroalkyl Substances as Co-Contaminants in Stormwater. *Environ. Sci. Water Res. Technol.* **2023**, *9*, 3281–3289. [CrossRef]
210. Soltanighias, T.; Umar, A.; Abdullahi, M.; Abdallah, M.A.E.; Orsini, L. Combined Toxicity of Perfluoroalkyl Substances and Microplastics on the Sentinel Species *Daphnia Magna*: Implications for Freshwater Ecosystems. *Environ. Pollut.* **2024**, *363*, 125133. [CrossRef] [PubMed]
211. U.S. Environmental Protection Agency National Primary Drinking Water Regulations. Office of Ground Water and Drinking Water. Available online: <https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations> (accessed on 18 March 2026).
212. World Health Organization Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda. Available online: <https://www.who.int/publications/i/item/9789240045064> (accessed on 16 March 2026).
213. National Health; Medical Research Council Australian Drinking Water Guidelines 6 (2011)—Updated November 2018. Available online: <https://www.waterquality.gov.au/guidelines/drinking-water> (accessed on 21 June 2026).
214. European Union. Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption. *Off. J. Eur. Union* **2020**, *435*, 1–62.
215. Health Canada Guidelines for Canadian Drinking Water Quality—Summary Tables. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada. Available online: <https://www.canada.ca/content/dam/hc-sc/documents/services/environmental-workplace-health/reports-publications/water-quality/guidelines-canadian-drinking-water-quality-summary-table/summary-table-pdf-template-eng.pdf> (accessed on 21 June 2026).
216. European Parliament; Council of the European Union. Directive (EU) 2020/2184 on the Quality of Water Intended for Human Consumption. Available online: <https://eur-lex.europa.eu/eli/dir/2020/2184/oj/eng> (accessed on 4 March 2026).
217. Farkas, G.; Horváth, A.; Tóth, G.N. Risk Assessment Tools and Quality Methods. In *Springer Tracts in Civil Engineering*; Springer: Cham, Switzerland, 2020; pp. 1–21. [CrossRef]
218. Olsen, A. *Risk Assessment Techniques*; Springer: Cham, Switzerland, 2024; pp. 405–464. [CrossRef]
219. Baken, K.A.; Sjerps, R.M.A.; Schriks, M.; van Wezel, A.P. Toxicological Risk Assessment and Prioritization of Drinking Water Relevant Contaminants of Emerging Concern. *Environ. Int.* **2018**, *118*, 293–303. [CrossRef] [PubMed]
220. Artat, A.; Ali, B.; Nelson, J.; Ali, A.A.B.; Nelson, J. Integrative Multi-Criteria Geospatial Modeling for Assessing Compound Flood-Contamination Risks in Vulnerable Communities. *Environ. Process.* **2025**, *12*, 58. [CrossRef]
221. Li, H.; Zhang, S.; Zhang, J.; Zhang, W.; Song, Z.; Yu, P.; Xie, C. A Framework for Identifying Priority Areas through Integrated Eco-Environmental Risk Assessment for a Holistic Watershed Management Approach. *Ecol. Indic.* **2023**, *146*, 109919. [CrossRef]

222. Ayejoto, D.A.; Egbueri, J.C. Human Health Risk Assessment of Nitrate and Heavy Metals in Urban Groundwater in Southeast Nigeria. *Ecol. Front.* **2024**, *44*, 60–72. [\[CrossRef\]](#)
223. Resz, M.A.; Blăjan, O.; Călugăru, D.; Crucean, A.; Kovacs, E.; Roman, C. Integrating Multi-Index and Health Risk Assessment to Evaluate Drinking Water Quality in Central Romania. *Water* **2025**, *18*, 23. [\[CrossRef\]](#)
224. Richards, J.; Chambers, T.; Hales, S.; Joy, M.; Radu, T.; Woodward, A.; Humphrey, A.; Randal, E.; Baker, M.G. Nitrate Contamination in Drinking Water and Colorectal Cancer: Exposure Assessment and Estimated Health Burden in New Zealand. *Environ. Res.* **2022**, *204*, 112322. [\[CrossRef\]](#) [\[PubMed\]](#)
225. Schullehner, J.; Hansen, B.; Thygesen, M.; Pedersen, C.B.; Sigsgaard, T. Nitrate in Drinking Water and Colorectal Cancer Risk: A Nationwide Population-Based Cohort Study. *Int. J. Cancer* **2018**, *143*, 73–79. [\[CrossRef\]](#) [\[PubMed\]](#)
226. Sarikar, S.; Vijaykumar, K. Assessment of Water Quality Index and Non-Carcinogenic Risk for Ingestion of Nitrate for Drinking Purpose of Bhosga Reservoir, Karnataka, India. *Curr. World Environ.* **2022**, *17*, 467–479. [\[CrossRef\]](#)
227. Evans, S.; Campbell, C.; Naidenko, O.V. Cumulative Risk Analysis of Carcinogenic Contaminants in United States Drinking Water. *Heliyon* **2019**, *5*, e02314. [\[CrossRef\]](#) [\[PubMed\]](#)
228. Lucon, T.N.; Costa, A.T.; Galvão, P.; Leite, M.G.P. Cadmium Behavior in a Karst Environment Hydrological Cycle. *Environ. Sci. Pollut. Res.* **2020**, *27*, 8965–8979. [\[CrossRef\]](#) [\[PubMed\]](#)
229. Wróblewski, M.; Miłek, J.; Godlewski, A.; Wróblewska, J. The Impact of Arsenic, Cadmium, Lead, Mercury, and Thallium Exposure on the Cardiovascular System and Oxidative Mechanisms in Children. *Curr. Issues Mol. Biol.* **2025**, *47*, 483. [\[CrossRef\]](#) [\[PubMed\]](#)
230. Teschke, R. Copper, Iron, Cadmium, and Arsenic, All Generated in the Universe: Elucidating Their Environmental Impact Risk on Human Health Including Clinical Liver Injury. *Int. J. Mol. Sci.* **2024**, *25*, 6662. [\[CrossRef\]](#) [\[PubMed\]](#)
231. Rahman, Z.; Singh, V.P. The Relative Impact of Toxic Heavy Metals (THMs) (Arsenic (As), Cadmium (Cd), Chromium (Cr)(VI), Mercury (Hg), and Lead (Pb)) on the Total Environment: An Overview. *Environ. Monit. Assess.* **2019**, *191*, 419. [\[CrossRef\]](#) [\[PubMed\]](#)
232. Simonetti, F.; Brillarelli, S.; Agostini, M.; Mancini, M.; Gioia, V.; Murtas, S.; Migliorati, V. A Review on the Latest Frontiers in Water Quality in the Era of Emerging Contaminants: A Focus on Perfluoroalkyl Compounds. *Environ. Pollut.* **2025**, *381*, 126402. [\[CrossRef\]](#) [\[PubMed\]](#)
233. Ali, N.; Kalsoom, Khan, S.; Ihsanullah; Rahman, I.U.; Muhammad, S. Human Health Risk Assessment Through Consumption of Organophosphate Pesticide-Contaminated Water of Peshawar Basin, Pakistan. *Expo. Health* **2017**, *10*, 259–272. [\[CrossRef\]](#)
234. El Afandi, G.; Irfan, M. Pesticides Risk Assessment Review: Status, Modeling Approaches, and Future Perspectives. *Agronomy* **2024**, *14*, 2299. [\[CrossRef\]](#)
235. Zhang, P.; Yang, M.; Lan, J.; Huang, Y.; Zhang, J.; Huang, S.; Yang, Y.; Ru, J.; Zhang, P.; Yang, M.; et al. Water Quality Degradation Due to Heavy Metal Contamination: Health Impacts and Eco-Friendly Approaches for Heavy Metal Remediation. *Toxics* **2023**, *11*, 828. [\[CrossRef\]](#) [\[PubMed\]](#)
236. Kumar, V.; Sharma, A.; Kumar, R.; Bhardwaj, R.; Kumar Thukral, A.; Rodrigo-Comino, J. Assessment of Heavy-Metal Pollution in Three Different Indian Water Bodies by Combination of Multivariate Analysis and Water Pollution Indices. *Hum. Ecol. Risk Assess. Int. J.* **2020**, *26*, 1–16. [\[CrossRef\]](#)
237. Peng, J.; Hou, Z.; Yuan, J.; Wu, Y.; Yang, K.; Lei, B.; Wang, X.; Chang, S.; Chu, Z.; Gao, Z.; et al. The Storm Runoff Management Strategy Based on Agricultural Ditch Nutrient Loss Characteristics in Erhai Lake, China. *J. Contam. Hydrol.* **2024**, *261*, 104305. [\[CrossRef\]](#) [\[PubMed\]](#)
238. Ibáñez, A.; Garrido-Chamorro, S.; Barreiro, C. Microorganisms and Climate Change: A Not So Invisible Effect. *Microbiol. Res.* **2023**, *14*, 918–947. [\[CrossRef\]](#)
239. Welden, N.A.C.; Lusher, A.L. Impacts of Changing Ocean Circulation on the Distribution of Marine Microplastic Litter. *Integr. Environ. Assess. Manag.* **2017**, *13*, 483–487. [\[CrossRef\]](#) [\[PubMed\]](#)
240. Cattaneo, I.; Kallian, A.D.; Di Nicola, M.R.; Dujardin, B.; Levorato, S.; Mohimont, L.; Nathanail, A.V.; Carnessechi, E.; Astuto, M.C.; Tarazona, J.V.; et al. Risk Assessment of Combined Exposure to Multiple Chemicals at the European Food Safety Authority: Principles, Guidance Documents, Applications and Future Challenges. *Toxins* **2023**, *15*, 40. [\[CrossRef\]](#) [\[PubMed\]](#)
241. Muambo, K.E.; Kim, M.G.; Kim, D.H.; Park, S.; Oh, J.E. Pharmaceuticals in Raw and Treated Water from Drinking Water Treatment Plants Nationwide: Insights into Their Sources and Exposure Risk Assessment. *Water Res. X* **2024**, *24*, 100256. [\[CrossRef\]](#) [\[PubMed\]](#)
242. Zhang, S.; Yin, Q.; Wang, S.; Yu, X.; Feng, M. Integrated Risk Assessment Framework for Transformation Products of Emerging Contaminants: What We Know and What We Should Know. *Front. Environ. Sci. Eng.* **2023**, *17*, 91. [\[CrossRef\]](#)
243. Bloch, D.; Diel, P.; Epe, B.; Hellwig, M.; Lampen, A.; Mally, A.; Marko, D.; Villar Fernández, M.A.; Guth, S.; Roth, A.; et al. Basic Concepts of Mixture Toxicity and Relevance for Risk Evaluation and Regulation. *Arch. Toxicol.* **2023**, *97*, 3005. [\[CrossRef\]](#) [\[PubMed\]](#)

244. Qin, Y.H.; Cao, H.J.; Zhou, L.; Cheng, C.; Jiang, R.R.; Zhou, X.; Li, X.H.; Liu, J.C. Occurrence and Ecological Risk of Typical Pesticides in a River–Lake System. *Water Sci. Eng.* **2025**, *18*, 422–430. [[CrossRef](#)]
245. Alijagic, A.; Suljević, D.; Fočak, M.; Sulejmanović, J.; Šehović, E.; Särndahl, E.; Engwall, M. The Triple Exposure Nexus of Microplastic Particles, Plastic-Associated Chemicals, and Environmental Pollutants from a Human Health Perspective. *Environ. Int.* **2024**, *188*, 108736. [[CrossRef](#)] [[PubMed](#)]
246. Zhao, W.G.; Tian, Y.M.; Zhao, P.; Zhao, L.A.; Jin, C. [Research Progress on Trojan-Horse Effect of Microplastics and Heavy Metals in Freshwater Environment]. *Huan Jing Ke Xue* **2023**, *44*, 1244–1257. [[CrossRef](#)] [[PubMed](#)]
247. Abedin, M.A.; Collins, A.E.; Habiba, U.; Shaw, R. Climate Change, Water Scarcity, and Health Adaptation in Southwestern Coastal Bangladesh. *Int. J. Disaster Risk Sci.* **2019**, *10*, 28–42. [[CrossRef](#)]
248. Ahmed, T.; Zounemat-Kermani, M.; Scholz, M. Climate Change, Water Quality and Water-Related Challenges: A Review with Focus on Pakistan. *Int. J. Environ. Res. Public Health* **2020**, *17*, 8518. [[CrossRef](#)] [[PubMed](#)]
249. Pillai, S.B.; Thombre, N.V. Coagulation, Flocculation, and Precipitation in Water and Used Water Purification. In *Handbook of Water and Used Water Purification*; Springer: Cham, Switzerland, 2023; pp. 1–25. [[CrossRef](#)]
250. Pillai, S.B.; Thombre, N.V. Coagulation, Flocculation, and Precipitation in Water and Used Water Purification. In *Handbook of Water and Used Water Purification*; Springer: Cham, Switzerland, 2024; pp. 3–27. [[CrossRef](#)]
251. Liu, L.; Yang, K.; Li, L.; Liu, W.; Yuan, H.; Han, Y.; Zhang, E.; Zheng, Y.; Jia, Y. The Aeration and Dredging Stimulate the Reduction of Pollution and Carbon Emissions in a Sediment Microcosm Study. *Sci. Rep.* **2024**, *14*, 26172. [[CrossRef](#)] [[PubMed](#)]
252. Razali, M.C.; Wahab, N.A.; Sunar, N.; Shamsudin, N.H. Existing Filtration Treatment on Drinking Water Process and Concerns Issues. *Membranes* **2023**, *13*, 285. [[CrossRef](#)] [[PubMed](#)]
253. Manna, M.; Sen, S. Advanced Oxidation Process: A Sustainable Technology for Treating Refractory Organic Compounds Present in Industrial Wastewater. *Environ. Sci. Pollut. Res.* **2023**, *30*, 25477–25505. [[CrossRef](#)] [[PubMed](#)]
254. Dagnew, M.; Xue, Q.; Zhang, J.; Wang, Z.; Zhou, A.; Li, M.; Zhao, C. A Review of Various Advanced Oxidation Techniques for Pesticide Degradation for Practical Application in Aqueous Environments. *Sustainability* **2025**, *17*, 4710. [[CrossRef](#)]
255. Martínez-Sánchez, C.; Robles, I.; Godínez, L.A. Review of Recent Developments in Electrochemical Advanced Oxidation Processes: Application to Remove Dyes, Pharmaceuticals, and Pesticides. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 12611–12678. [[CrossRef](#)]
256. Khan, Z.U.H.; Sabahat, S.; Shah, N.S.; Ajab, H.; Iqbal, J.; Ullah, F. Electrochemical Advanced Oxidation Processes as a Feasible Approach towards Treatment of Pesticides Contaminated Water and Environmental Sustainability: A Review. *J. Water Process Eng.* **2025**, *70*, 107083. [[CrossRef](#)]
257. Derbalah, A.; Sakugawa, H. Sulfate Radical-Based Advanced Oxidation Technology to Remove Pesticides from Water A Review of the Most Recent Technologies. *Int. J. Environ. Res.* **2024**, *18*, 11. [[CrossRef](#)]
258. Mahmoodi, M.; Pishbin, E. Ozone-Based Advanced Oxidation Processes in Water Treatment: Recent Advances, Challenges, and Perspective. *Environ. Sci. Pollut. Res.* **2025**, *32*, 3531–3570. [[CrossRef](#)] [[PubMed](#)]
259. Adeoye, J.B.; Tan, Y.H.; Lau, S.Y.; Tan, Y.Y.; Chiong, T.; Mubarak, N.M.; Khalid, M. Advanced Oxidation and Biological Integrated Processes for Pharmaceutical Wastewater Treatment: A Review. *J. Environ. Manag.* **2024**, *353*, 120170. [[CrossRef](#)] [[PubMed](#)]
260. Chen, Y.; Chen, H.; Li, J.; Xiao, L. Rapid and Efficient Activated Sludge Treatment by Electro-Fenton Oxidation. *Water Res.* **2019**, *152*, 181–190. [[CrossRef](#)] [[PubMed](#)]
261. Ibáñez, M.; Bijlsma, L.; Pitarch, E.; López, F.J.; Hernández, F. Occurrence of Pharmaceutical Metabolites and Transformation Products in the Aquatic Environment of the Mediterranean Area. *Trends Environ. Anal. Chem.* **2021**, *29*, e00118. [[CrossRef](#)]
262. Kumar, M.; Patel, A.K.; Singh, A. Anthropogenic Dominance on Geogenic Arsenic Problem of the Groundwater in the Ganga-Brahmaputra Floodplain: A Paradox of Origin and Mobilization. *Sci. Total Environ.* **2022**, *807*, 151461. [[CrossRef](#)] [[PubMed](#)]
263. Sun, S.; Ertz, M. Environmental Impact of Mutualized Mobility: Evidence from a Life Cycle Perspective. *Sci. Total Environ.* **2021**, *772*, 145014. [[CrossRef](#)] [[PubMed](#)]
264. Guo, Y.; Qi, P.S.; Liu, Y.Z. A Review on Advanced Treatment of Pharmaceutical Wastewater. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *63*, 012025. [[CrossRef](#)]
265. World Health Organization Drinking-Water. Available online: <https://www.who.int/news-room/fact-sheets/detail/drinking-water> (accessed on 22 March 2026).
266. Magana-Arachchi, D.N.; Wanigatunge, R.P. Ubiquitous Waterborne Pathogens. *Waterborne Pathog.* **2020**, *72*, 15–42. [[CrossRef](#)]
267. Patel, C.B.; Shanker, R.; Gupta, V.K.; Upadhyay, R.S. Q-PCR Based Culture-Independent Enumeration and Detection of Enterobacter: An Emerging Environmental Human Pathogen in Riverine Systems and Potable Water. *Front. Microbiol.* **2016**, *7*, 173935. [[CrossRef](#)] [[PubMed](#)]
268. Witkowska, D.; Słowik, J.; Chilicka, K. Heavy Metals and Human Health: Possible Exposure Pathways and the Competition for Protein Binding Sites. *Molecules* **2021**, *26*, 6060. [[CrossRef](#)] [[PubMed](#)]
269. Vallée, A.; Ceccaldi, P.F.; Carbonnel, M.; Feki, A.; Ayoubi, J.M. Pollution and Endometriosis: A Deep Dive into the Environmental Impacts on Women’s Health. *BJOG* **2024**, *131*, 401–414. [[CrossRef](#)] [[PubMed](#)]

270. Mustafa, B.M.; Hassan, N.E. Water Contamination and Its Effects on Human Health: A Review. *J. Geogr. Environ. Earth Sci. Int.* **2024**, *28*, 38–49. [\[CrossRef\]](#)
271. Verani, M.; Federigi, I.; Donzelli, G.; Cioni, L.; Carducci, A. Human Adenoviruses as Waterborne Index Pathogens and Their Use for Quantitative Microbial Risk Assessment. *Sci. Total Environ.* **2019**, *651*, 1469–1475. [\[CrossRef\]](#) [\[PubMed\]](#)
272. Soltaninia, S.; Eskandaripour, M.; Golmohammadi, M.H.; Taghavi, L.; Mehboodi, A. Nitrate Pollution in Urban Runoff: A Comprehensive Risk Assessment for Human and Ecological Health. *Sci. Total Environ.* **2025**, *974*, 179184. [\[CrossRef\]](#) [\[PubMed\]](#)
273. Abdel-Shafy, H.I.; Mansour, M.S.M. A Review on Polycyclic Aromatic Hydrocarbons: Source, Environmental Impact, Effect on Human Health and Remediation. *Egypt. J. Pet.* **2016**, *25*, 107–123. [\[CrossRef\]](#)
274. Anbarasu, K.; Yuvarajan, D. Pharmaceutical Pollution in Soil and Water and Its Impacts On Human Health and the Environment. *Water Air Soil Pollut.* **2025**, *236*, 877. [\[CrossRef\]](#)
275. Chiriac, F.L.; Pirvu, F.; Paun, I.; Petre, V.A. Perfluoroalkyl Substances in Romanian Wastewater Treatment Plants: Transfer to Surface Waters, Environmental and Human Risk Assessment. *Sci. Total Environ.* **2023**, *892*, 164576. [\[CrossRef\]](#) [\[PubMed\]](#)
276. Ahrens, L.; Gashaw, H.; Sjöholm, M.; Gebrehiwot, S.G.; Getahun, A.; Derbe, E.; Bishop, K.; Åkerblom, S. Poly- and Perfluoroalkylated Substances (PFASs) in Water, Sediment and Fish Muscle Tissue from Lake Tana, Ethiopia and Implications for Human Exposure. *Chemosphere* **2016**, *165*, 352–357. [\[CrossRef\]](#) [\[PubMed\]](#)
277. Wee, S.Y.; Aris, A.Z. Environmental Impacts, Exposure Pathways, and Health Effects of PFOA and PFOS. *Ecotoxicol. Environ. Saf.* **2023**, *267*, 115663. [\[CrossRef\]](#) [\[PubMed\]](#)
278. Zeng, H.; Gan, H.; Liu, Y.; Sun, B. The Global Disease Burden Attributable to Unsafe Water, Sanitation, and Handwashing with Unqualified Facilities from 1990 to 2019. *J. Glob. Health* **2024**, *14*, 04162. [\[CrossRef\]](#) [\[PubMed\]](#)
279. Lee, D.; Gibson, J.M.D.; Brown, J.; Habtewold, J.; Murphy, H.M. Burden of Disease from Contaminated Drinking Water in Countries with High Access to Safely Managed Water: A Systematic Review. *Water Res.* **2023**, *242*, 120244. [\[CrossRef\]](#) [\[PubMed\]](#)
280. World Health Organization. Water, Sanitation and Hygiene: Burden of Disease. Global Health Observatory. Available online: <https://www.who.int/data/gho/data/themes/topics/water-sanitation-and-hygiene-burden-of-disease?> (accessed on 20 June 2026).
281. Watson, S.I.; Rego, R.T.T.; Hofer, T.; Lilford, R.J. Evaluations of Water, Sanitation and Hygiene Interventions Should Not Use Diarrhoea as (Primary) Outcome. *BMJ Glob. Health* **2022**, *7*, e008521. [\[CrossRef\]](#) [\[PubMed\]](#)
282. Collin, M.S.; Venkatraman, S.K.; Vijayakumar, N.; Kanimozhi, V.; Arbaaz, S.M.; Stacey, R.G.S.; Anusha, J.; Choudhary, R.; Lvov, V.; Tovar, G.I.; et al. Bioaccumulation of Lead (Pb) and Its Effects on Human: A Review. *J. Hazard. Mater. Adv.* **2022**, *7*, 100094. [\[CrossRef\]](#)
283. Shaji, E.; Santosh, M.; Sarath, K.V.; Prakash, P.; Deepchand, V.; Divya, B.V. Arsenic Contamination of Groundwater: A Global Synopsis with Focus on the Indian Peninsula. *Geosci. Front.* **2021**, *12*, 101079. [\[CrossRef\]](#)
284. Reuben, A.; Caspi, A.; Belsky, D.W.; Broadbent, J.; Harrington, H.; Sugden, K.; Houts, R.M.; Ramrakha, S.; Poulton, R.; Moffitt, T.E. Association of Childhood Blood Lead Levels With Cognitive Function and Socioeconomic Status at Age 38 Years and With IQ Change and Socioeconomic Mobility Between Childhood and Adulthood. *JAMA* **2017**, *317*, 1244–1251. [\[CrossRef\]](#) [\[PubMed\]](#)
285. Heidari, S.; Mostafaei, S.; Razazian, N.; Rajati, M.; Saeedi, A.; Rajati, F. The Effect of Lead Exposure on IQ Test Scores in Children under 12 Years: A Systematic Review and Meta-Analysis of Case-Control Studies. *Syst. Rev.* **2022**, *11*, 106. [\[CrossRef\]](#) [\[PubMed\]](#)
286. Chaudhary, I.J.; Chauhan, R.; Kale, S.S.; Gosavi, S.; Rathore, D.; Dwivedi, V.; Singh, S.; Yadav, V.K. Groundwater Nitrate Contamination and Its Effect on Human Health: A Review. *Water Conserv. Sci. Eng.* **2025**, *10*, 33. [\[CrossRef\]](#)
287. Riaz, M.; Ahmad, M.N.; Mukhtar, M.; Aqsa; Nawaz, N. Nitrate Contamination of Soil and Water: Implications for Ecosystem Functions and Human Health. In *Inorganic Contaminants and Radionuclides*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 351–373. [\[CrossRef\]](#)
288. Brender, J.D. Human Health Effects of Exposure to Nitrate, Nitrite, and Nitrogen Dioxide. In *Just Enough Nitrogen*; Springer: Cham, Switzerland, 2020; pp. 283–294. [\[CrossRef\]](#)
289. Lin, L.; St Clair, S.; Gamble, G.D.; Crowther, C.A.; Dixon, L.; Bloomfield, F.H.; Harding, J.E. Nitrate Contamination in Drinking Water and Adverse Reproductive and Birth Outcomes: A Systematic Review and Meta-Analysis. *Sci. Rep.* **2023**, *13*, 563. [\[CrossRef\]](#) [\[PubMed\]](#)
290. Teklu, B.M.; Hailelassie, A.; Mekuria, W. Pesticides as Water Pollutants and Level of Risks to Environment and People: An Example from Central Rift Valley of Ethiopia. *Environ. Dev. Sustain.* **2021**, *24*, 5275–5294. [\[CrossRef\]](#)
291. Zhang, S.; Yang, C.; Liu, M.; Zhao, W.; Li, Y.; Meng, X.Z.; Cai, M. Occurrence of Organophosphate Esters in Surface Water and Sediment in Drinking Water Source of Xiangjiang River, China. *Sci. Total Environ.* **2021**, *781*, 146734. [\[CrossRef\]](#) [\[PubMed\]](#)
292. Vasseghian, Y.; Hosseinzadeh, S.; Khataee, A.; Dragoi, E.N. The Concentration of Persistent Organic Pollutants in Water Resources: A Global Systematic Review, Meta-Analysis and Probabilistic Risk Assessment. *Sci. Total Environ.* **2021**, *796*, 149000. [\[CrossRef\]](#) [\[PubMed\]](#)

293. Akhtar, A.B.T.; Naseem, S.; Yasar, A.; Naseem, Z. *Persistent Organic Pollutants (POPs): Sources, Types, Impacts, and Their Remediation*; Springer: Cham, Switzerland, 2021; pp. 213–246. [\[CrossRef\]](#)
294. Abdollahdokht, D.; Asadikaram, G.; Abolhassani, M.; Pourghadamyari, H.; Abbasi-Jorjandi, M.; Faramarz, S.; Nematollahi, M.H. Pesticide Exposure and Related Health Problems among Farmworkers' Children: A Case-Control Study in Southeast Iran. *Environ. Sci. Pollut. Res.* **2021**, *28*, 57216–57231. [\[CrossRef\]](#) [\[PubMed\]](#)
295. Samareh, A.; Pourghadamyari, H.; Nemtollahi, M.H.; Ebrahimi Meimand, H.A.; Norouzmahani, M.E.; Asadikaram, G. Pesticide Exposure and Its Association with Parkinson's Disease: A Case–Control Analysis. *Cell. Mol. Neurobiol.* **2024**, *44*, 73. [\[CrossRef\]](#) [\[PubMed\]](#)
296. Ali, N.M.; Khan, M.K.; Mazhar, B.; Mustafa, M. Impact of Water Pollution on Waterborne Infections: Emphasizing Microbial Contamination and Associated Health Hazards in Humans. *Discov. Water* **2025**, *5*, 19. [\[CrossRef\]](#)
297. Su, Y.; Huang, F.; Dai, Z.; Wang, A.J.; Gao, S.H. Environmental Ecology and Health Risk Assessment of Pathogens in the Environment. In *Water Security: Big Data-Driven Risk Identification, Assessment and Control of Emerging Contaminants*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 99–121.
298. Hauser, A.; Sathrugnan, K.; Roedler, F. Managing Risks in Advanced Wastewater Treatment Plants. *Water Pract. Technol.* **2015**, *10*, 305–311. [\[CrossRef\]](#)
299. Subedi, B.; Kannan, K. Occurrence and Fate of Select Psychoactive Pharmaceuticals and Antihypertensives in Two Wastewater Treatment Plants in New York State, USA. *Sci. Total Environ.* **2015**, *514*, 273–280. [\[CrossRef\]](#) [\[PubMed\]](#)
300. Sangeetha, T.; Rajneesh, C.P.; Yan, W.M. Integration of Microbial Electrolysis Cells with Anaerobic Digestion to Treat Beer Industry Wastewater. In *Integrated Microbial Fuel Cells for Wastewater Treatment*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 313–346. [\[CrossRef\]](#)
301. Sathya, K.; Nagarajan, K.; Carlin Geor Malar, G.; Rajalakshmi, S.; Raja Lakshmi, P. A Comprehensive Review on Comparison among Effluent Treatment Methods and Modern Methods of Treatment of Industrial Wastewater Effluent from Different Sources. *Appl. Water Sci.* **2022**, *12*, 70. [\[CrossRef\]](#) [\[PubMed\]](#)
302. Sombei, D.C.; Mecha, C.A.; Chollom, M.N. A Review of Low-Cost Point-of-Use Water Treatment Solutions Addressing Water Access and Quality in Resource-Limited Settings. *Water* **2025**, *17*, 1827. [\[CrossRef\]](#)
303. Soetan, O.; Nie, J.; Viteritto, M.; Feng, H. Evaluation of Sediment Dredging in Remediating Toxic Metal Contamination—A Systematic Review. *Environ. Sci. Pollut. Res.* **2023**, *30*, 69837–69856. [\[CrossRef\]](#) [\[PubMed\]](#)
304. Yan, J.; Li, F. Effects of Sediment Dredging on Freshwater System: A Comprehensive Review. *Environ. Sci. Pollut. Res.* **2023**, *30*, 119612–119626. [\[CrossRef\]](#) [\[PubMed\]](#)
305. Singh, G.; Mishra, S. Industrial Pollution Management Approach. In *Heavy Metal Toxicity: Environmental Concerns, Remediation and Opportunities*; Springer: Cham, Switzerland, 2023; pp. 363–388. [\[CrossRef\]](#)
306. Hasan, A.; Tabassum, B.; Hashim, M.; Khan, N. *The Negative Impacts of Industrial Water Pollution on Human Health and Benefits of Zero Liquid Discharge System*; Springer Water: Cham, Switzerland, 2025; pp. 61–74. [\[CrossRef\]](#)
307. Zeman-Kuhnert, S.; Thiel, V.; Heim, C. Effects of Weather Extremes on the Nutrient Dynamics of a Shallow Eutrophic Lake as Observed during a Three-Year Monitoring Study. *Water* **2022**, *14*, 2032. [\[CrossRef\]](#)
308. Zeng, G.; Zhang, R.; Liang, D.; Wang, F.; Han, Y.; Luo, Y.; Gao, P.; Wang, Q.; Wang, Q.; Yu, C.; et al. Comparison of the Advantages and Disadvantages of Algae Removal Technology and Its Development Status. *Water* **2023**, *15*, 1104. [\[CrossRef\]](#)
309. Li, J.; Liang, Y.; Zou, C.; Chen, Y.; Wang, Z. The Effect Analysis of Water Diversion on Water Quality Improvement: A Case Study in Urban Lake, China. *Water* **2023**, *15*, 2880. [\[CrossRef\]](#)
310. Zezulka, Š.; Maršálek, B.; Maršálková, E.; Odehnalová, K.; Pavlíková, M.; Lamaczová, A. Suspended Particles in Water and Energetically Sustainable Solutions of Their Removal—A Review. *Processes* **2024**, *12*, 2627. [\[CrossRef\]](#)
311. Chen, Y.; Vymazal, J.; Březinová, T.; Koželuh, M.; Kule, L.; Huang, J.; Chen, Z. Occurrence, Removal and Environmental Risk Assessment of Pharmaceuticals and Personal Care Products in Rural Wastewater Treatment Wetlands. *Sci. Total Environ.* **2016**, *566–567*, 1660–1669. [\[CrossRef\]](#) [\[PubMed\]](#)
312. Agbovi, H.K.; Wilson, L.D. Adsorption Processes in Biopolymer Systems: Fundamentals to Practical Applications. In *Natural Polymers-Based Green Adsorbents for Water Treatment*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 1–51. [\[CrossRef\]](#)
313. Beni, A.A.; Esmaeili, A. Biosorption, an Efficient Method for Removing Heavy Metals from Industrial Effluents: A Review. *Environ. Technol. Innov.* **2020**, *17*, 100503. [\[CrossRef\]](#)
314. Ciobanu, R.; Bucatariu, F.; Mihai, M.; Teodosiu, C. Silica-Based Composite Sorbents for Heavy Metal Ions Removal from Aqueous Solutions. *Polymers* **2024**, *16*, 3048. [\[CrossRef\]](#) [\[PubMed\]](#)
315. Benimeli, C.S.; Polti, M.A.; Albarracín, V.H.; Abate, C.M.; Amoroso, M.J. *Bioremediation Potential of Heavy Metal-Resistant Actinobacteria and Maize Plants in Polluted Soil*; Springer: Dordrecht, The Netherlands, 2011; pp. 459–477. [\[CrossRef\]](#)
316. Bala, S.; Garg, D.; Thirumalesh, B.V.; Sharma, M.; Sridhar, K.; Inbaraj, B.S.; Tripathi, M. Recent Strategies for Bioremediation of Emerging Pollutants: A Review for a Green and Sustainable Environment. *Toxics* **2022**, *10*, 484. [\[CrossRef\]](#) [\[PubMed\]](#)

317. Priyadarshane, M.; Chatterjee, S.; Rath, S.; Dash, H.R.; Das, S. Cellular and Genetic Mechanism of Bacterial Mercury Resistance and Their Role in Biogeochemistry and Bioremediation. *J. Hazard. Mater.* **2022**, *423*, 126985. [[CrossRef](#)] [[PubMed](#)]
318. Kour, D.; Kaur, T.; Devi, R.; Yadav, A.; Singh, M.; Joshi, D.; Singh, J.; Suyal, D.C.; Kumar, A.; Rajput, V.D.; et al. Beneficial Microbiomes for Bioremediation of Diverse Contaminated Environments for Environmental Sustainability: Present Status and Future Challenges. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24917–24939. [[CrossRef](#)] [[PubMed](#)]
319. Alaira, S.A.; Padilla, C.S.; Alcantara, E.L.; Aggangan, N.S. Social Acceptability of the Bioremediation Technology for the Rehabilitation of an Abandoned Mined-Out Area in Mogpog, Marinduque, Philippines. *J. Environ. Sci. Manag.* **2021**, *24*, 24. [[CrossRef](#)]
320. Jurczynski, Y.; Passos, R.; Campos, L.C. A Review of the Most Concerning Chemical Contaminants in Drinking Water for Human Health. *Sustainability* **2024**, *16*, 7107. [[CrossRef](#)]
321. Raghavendra, N. Drinking Water Contamination and Its Solving Approaches: A Comprehensive Review of Current Knowledge and Future Directions. *Water Air Soil Pollut.* **2024**, *235*, 639. [[CrossRef](#)]
322. Scanlon, B.R.; Fakhreddine, S.; Reedy, R.C.; Yang, Q.; Malito, J.G. Drivers of Spatiotemporal Variability in Drinking Water Quality in the United States. *Environ. Sci. Technol.* **2022**, *56*, 12965–12974. [[CrossRef](#)] [[PubMed](#)]
323. Sarvala, J.; Helminen, H. Impacts of Chemical Precipitation of Phosphorus with Polyaluminum Chloride in Two Eutrophic Lakes in Southwest Finland. *Inland Waters* **2023**, *13*, 412–427. [[CrossRef](#)]
324. Ravi, R.; Golder, A.K. Photocatalytic and Biological Degradation Processes to Mineralize Pharmaceutically Active Compounds and Catalyst Recovery: A Review. *Coord. Chem. Rev.* **2025**, *523*, 216267. [[CrossRef](#)]
325. Loo-Moreira, C.L.; Fernández-Andrade, K.J.; Cedeño-Solórzano, G.S.; Manzaba-Salazar, G.M.; Gómez-Salcedo, Y.; Rodríguez-Díaz, J.M.; Baquerizo-Crespo, R.J. Generalities of the Coagulation-Flocculation Process: A Perspective on Biocoagulants. In *Innovations in Biotechnology for a Sustainable Future*; Springer: Cham, Switzerland, 2021; pp. 333–352. [[CrossRef](#)]
326. Kowalik-Klimczak, A. Removal of Heavy Metals from Galvanic Industry Wastewater: A Review of Different Possible Methods. *Sustainability* **2025**, *17*, 8562. [[CrossRef](#)]
327. Sivaranjane, R.; Senthil Kumar, P.; Chitra, B.; Rangasamy, G. A Critical Review on Biochar for the Removal of Toxic Pollutants from Water Environment. *Chemosphere* **2024**, *360*, 142382. [[CrossRef](#)] [[PubMed](#)]
328. Picinini-Zambelli, J.; Garcia, A.L.H.; Da Silva, J. Emerging Pollutants in the Aquatic Environments: A Review of Genotoxic Impacts. *Mutat. Res. Rev. Mutat. Res.* **2025**, *795*, 108519. [[CrossRef](#)] [[PubMed](#)]
329. Mishra, T.; Tiwari, P.B.; Kanchan, S.; Kesheri, M. Advances in Microbial Bioremediation for Effective Wastewater Treatment. *Water* **2025**, *17*, 3196. [[CrossRef](#)]
330. Nzila, A.; Razzak, S.A.; Zhu, J. Bioaugmentation: An Emerging Strategy of Industrial Wastewater Treatment for Reuse and Discharge. *Int. J. Environ. Res. Public Health* **2016**, *13*, 846. [[CrossRef](#)] [[PubMed](#)]
331. Kifle, A.; Timilsina, A.; Gautam, A.; Adhikari, K.; Bhattarai, A.; Aryal, N. Phytoremediation: Mechanisms, Plant Selection and Enhancement by Natural and Synthetic Agents. *Environ. Adv.* **2022**, *8*, 100203. [[CrossRef](#)]
332. Qiu, B.; Shao, Q.; Shi, J.; Yang, C.; Chu, H. Application of Biochar for the Adsorption of Organic Pollutants from Wastewater: Modification Strategies, Mechanisms and Challenges. *Sep. Purif. Technol.* **2022**, *300*, 121925. [[CrossRef](#)]

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