

MICROPOLLUTANTS IN WATER WITH MAJOR CONTRIBUTING HAZARDOUS WASTES

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ABSTRACT

In the twenty-first century, problems with water quality present a serious threat to humankind. The primary types of aquatic pollutants, their effects on human health, and methods for reducing freshwater pollution are all covered in this review. We mostly concentrate on chemical pollution, emphasizing a variety of synthetic organic compounds as well as inorganic and organic micropollutants, such as hazardous metals and metalloids. We also talk about the critical need for better sanitation in developing nations and waterborne illnesses. The review examines recent scientific developments intended to address the wide range of pollutants. Geogenic pollutants, mining operations, and hazardous waste sites have been major contributors of long-term regional and local water pollution, while persistent organic pollutants have impacted water systems globally for more than 50 years. On the other hand, wastewater sources and agricultural chemicals typically have shorter-term effects on regional to local scales.

Keywords: Micropollutants, Water pollution, Hazardous waste.

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INTRODUCTION

Concerns over the amount and quality of water are connected to many of the most significant problems facing humanity in the twenty-first century. It is anticipated that climate change would make these issues worse by raising water temperatures, melting glaciers, and intensifying the water cycle, which may lead to more frequent droughts and floods. Currently affecting more than one-third of the world's population, poor sanitation and a lack of access to clean drinking water have the most direct and

serious effects on human health [1-3]. Exposure to pathogens and chemical toxins through the food chain, such as when plants are irrigated with contaminated water or when toxic chemicals bioaccumulate in aquatic organisms, such as fish and seafood, as well as during recreational activities like swimming in contaminated waters, are additional serious risks [4].

The contamination of freshwater resources, such as lakes, rivers, and groundwater, is the main topic of this review. This topic focuses

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on chemical pollution, even though several recent publications thoroughly examine many aspects of waterborne diseases. Over one-third of the freshwater that is readily available on Earth is consumed for domestic, industrial, and agricultural uses. Chemical pollution of natural water has become a major global public concern, which is not surprising given that these activities frequently result in contamination with a variety of manmade and naturally occurring chemicals [5].

Chemical water pollutants can be divided into two categories: natural organic materials and a relatively small number of pollutants, which are usually found at milligram-per-liter levels and include nutrients like phosphorus and nitrogen. Although the causes and effects of these common contaminants are fairly well understood, creating sustainable treatment methods for them is still a scientific problem. For example, elevated biomass production, oxygen deprivation, and hazardous algal blooms can result from excessive nutrient loads. Long-term problems are also caused by excessive irrigation and growing salt levels in surface water from road salt. Elevated salt concentrations hinder the direct use of water for drinking and impede agricultural crop growth. This problem is further intensified in coastal areas like India and China, where marine salt intrusion into groundwater occurs due to aquifer overexploitation and rising sea levels [6].

The millions of artificial and natural trace pollutants that can be detected in natural water at quantities ranging from nanograms to micrograms per liter are examined in this article. Even at such low concentrations, several of these micropollutants can have harmful consequences, particularly when they are present in mixtures. Evaluations of these compounds' negative effects, which are usually mild and persistent rather than acute, are sometimes complicated by their large number and structural diversity. This

contrasts with the immediate health concerns associated with a small number of well-known microorganisms present in contaminated water [7]. Given the challenges in assessing the impact of micropollutants on aquatic life and human health, and the lack of effective and affordable water treatment methods in many regions, significant measures—such as restricted use, substitution, or oxidative treatment—must be taken to prevent these chemicals from contaminating natural water sources. However, as illustrated by the examples in this review, addressing this issue poses substantial challenges from technical, economic, societal, and political perspectives [8-10].

Micropollutants in natural water come from a variety of sources. Industries and municipalities use over 30% of the world's available renewable freshwater, which results in the production of enormous volumes of wastewater with a wide range of compounds at different concentrations. This wastewater is either left untreated or treated insufficiently, failing to eliminate the majority of micropollutants, in many areas, particularly developing nations like China. In developed nations, municipal wastewater is also a problem. Oil and gasoline spills, agricultural runoff, which contain millions of tons of pesticides each year, and human-caused releases of naturally occurring geogenic hazardous substances including heavy metals and metalloids are other major sources of micropollutants. Additionally, biologically produced taste and odor compounds, while not primarily toxic, raise aesthetic concerns. Numerous municipal and hazardous waste sites—particularly abandoned industrial and former military locations—also contribute to the contamination of natural water, especially groundwater. Furthermore, with over 100000 registered chemicals in daily use, there are countless potential pathways for these

substances to enter the aquatic environment [11].

MICROPOLLUTANTS IN WATER

A comprehensive assessment of chemical pollution in natural water involves key elements: Understanding the type and origin of the pollutants. Availability of analytical methods to quantify the temporal and spatial variability of chemical concentrations. A thorough comprehension of the processes that influence the transport and fate of these chemicals within the system. Development of mathematical transport and fate models with appropriate complexity to design optimal sampling strategies and predict future pollution scenarios. techniques to measure these substances' harmful impact on human health and aquatic life [12-14]. Notably, the design and operation of treatment technologies and in situ remediation procedures depend heavily on the same analytical tools and process knowledge. Assessing the exposure of aquatic micropollutants presents substantial challenges and necessitates a broad interdisciplinary approach due to the wide range of structurally diverse micropollutants that can interact with various natural or anthropogenic dissolved and particulate species (such as natural organic matter, mineral surfaces, and redox-active species), as well as light and living organisms.

For inorganic pollutants, including heavy metals (e.g., Cr, Ni, Cu, Zn, Cd, Pb, Hg, U, Pu) and metalloids (e.g., Se, As), the primary challenge in evaluating environmental risks lies in their differing behaviors under various redox conditions. Unlike many organic pollutants, these elements do not degrade; instead, their transport and bioavailability are influenced by processes such as oxidation/reduction, complexation, adsorption, and precipitation/dissolution reactions. Most metallic elements exhibit varying solubility based on oxygen presence and redox conditions. Abundant redox-

sensitive metals like iron and manganese form finely dispersed oxide particles that strongly adsorb heavy metals and metalloids. When oxygen is depleted, these oxide particles can undergo reductive dissolution, releasing their adsorbed toxic loads. The precipitation and dissolution of these reactive particles in the environment are frequently controlled by microorganisms. Although it is still difficult to analyze the routes and rates of iron and manganese dissemination in environmental settings, new developments in mass spectrometry have made it possible to track microbial processes using the stable isotope signatures of metallic elements like iron [15-18].

The environmental assessment of metal pollution and its health implications is complicated by the various mineral phases and possible interactions among solutes crucial to adsorption processes. The structures of metal ions adsorbed on mineral surfaces have been clarified thanks to significant developments in X-ray spectroscopy, which have made it possible to identify particular molecular neighbors of metal ions in complex mineral environments. Understanding the variables affecting the mobility of hazardous metal ions is made easier by these molecular-level insights. Metal ions must be able to pass through cell membranes in order for biological action to take place. Uptake is usually hampered by persistent macromolecular complexes and strong connections to mineral particles. In order to evaluate the mobility and bioavailability of metal pollutants in complex media, such as soils or sediments, direct approaches have been devised. Simple or more complex reaction/transport models that incorporate physical, chemical, and (micro)biological processes can be used to scale up insights from molecular-level studies and in situ field observations to determine the fate and distribution of metals in the environment. The effects of biological

uptake are covered in the last stage of the evaluation process. The examination of possible consequences of nanoparticles serves as an example [19]. Concerns regarding the biological impacts of manufactured nanoparticles as novel anthropogenic contaminants in aquatic environments and on human health have been raised by the sharp rise in their use in commercial and industrial settings. According to preliminary data, these particles may directly cause certain negative consequences in addition to releasing dangerous metals at steady rates, which calls for more investigation. Significant progress has been made in elucidating molecular mechanisms, relevant geochemical and microbial reactions, and integrating reaction and transport pathways into biogeochemical models. However, the most critical knowledge gap remains our limited ability to predict and quantify the adverse effects of inorganic pollutants on aquatic life and human health [20].

AGRICULTURE AND WATER QUALITY

Millions of tons of chemicals are used annually in agriculture to improve crop yields by managing weeds, fungus, insects, and other pests. Tens of thousands of different commercial products with hundreds of different active ingredients are sold as pesticides and allied agrochemicals. The usage of both new and established agrochemical products is tightly controlled because of these chemicals' toxicity to humans and biota, as well as their deliberate discharge into the environment. The goal of nation-specific registration and risk assessment processes is to safeguard ecosystems, farmers, consumers, and soil and water resources [21].

Concern over the ongoing exposure of humans and biota to biologically active chemicals, as well as the poisoning of water resources in agricultural catchment areas, is

growing. Peak concentrations of pesticides and their breakdown products, like triazines and chloroacetanilides, can surpass ecotoxic levels for non-target animals in soils and aquatic systems in U.S. rivers, endangering the safety of drinking surface and groundwater. The considerable geographical and temporal variability of pesticide losses makes it difficult to quantify the percentage of employed pesticides that end up in surface and groundwater and to develop effective mitigation strategies. Pesticide runoff from hard surfaces, frequently from farmyards or storage facilities during product handling or unintentional spills, is a common point source of agricultural contamination. Pesticides can enter aquatic systems through sewage treatment plants or seep into adjacent soil depending on how they are connected to sewer systems. Point sources do not usually contribute significantly to the total mass input, although they can result in high-concentration peaks at catchment area outlets. Diffuse losses, such as spray drift, drainage/leaching into the subsoil, and field runoff, are more problematic. To reduce their impact on water resources, a variety of mitigation strategies have been assessed. Topography, weather, and soil hydraulic characteristics—such as permeability and water flow patterns—have a greater impact on the incidence of pesticide losses from runoff than do the particular characteristics of the compounds, such as sorption behavior. Targeting pesticide applications to areas prone to increased runoff would be a more effective mitigation strategy than simply replacing pesticide products or altering application timing [22-25].

In non-agricultural and urban regions, increased runoff from pesticide-laden rainwater pours over sealed surfaces like rooftops and roadways, contaminating water in drainage and sewer systems. Reducing soil and water pollution from pesticide emissions is thought to be essential for minimizing

ecological changes and preserving biodiversity in order to address the overall environmental effects of intensive agriculture [26]. Agricultural workers are also at serious risk of acute poisoning from direct chemical exposure. An estimated 3 million incidents of

poisoning and up to 20000 unintended fatalities occur each year due to accidental exposure and intentional misuse of agrochemicals, however the magnitude of this exposure is debatable in North America and Europe.

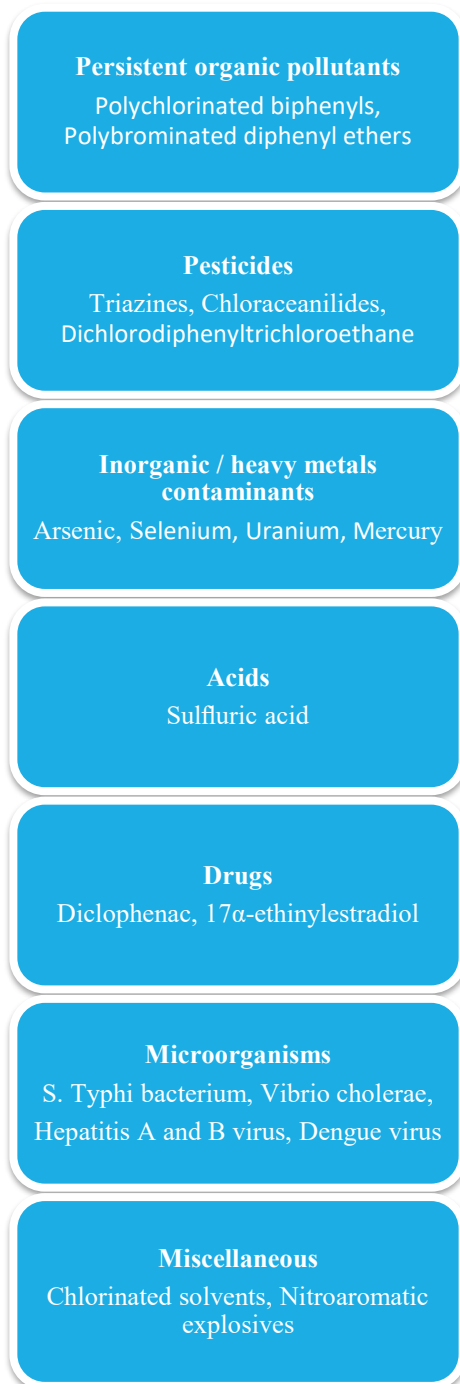


Figure 1: Prominent pollutant types and their examples.

Apart from varying climatic and ecological conditions, as well as the types of crops grown, agricultural practices in many developing countries are largely driven by the need to ensure food security for their expanding populations and the associated economic and political implications. Coupled with trends of urbanization and industrialization, these agricultural practices are contributing to water quality issues [27, 28]. Despite the increased use of pesticides per hectare of cropland—illustrated in the sidebar on Global Pesticide Consumption—the contributions to crop yields have been marginal, as seen in China. In developing nations, the resources and capabilities for monitoring pesticide concentrations in aquatic systems and assessing risks to human health and the environment are often limited, and regulatory enforcement is frequently inadequate. Monitoring programs indicate that the range of active pesticide ingredients can differ significantly from those used in developed countries. Persistent organochlorine pesticides, such as DDT and hexachlorocyclohexanes (HCHs), are still widely used for agricultural and sanitation purposes due to their relative affordability and effectiveness [29-32].

PHARMACEUTICALS WASTE IN DRINKING WATER

Municipal wastewater is a major contributor to the micropollutant load in aquatic environments, with pharmaceutical compounds and personal care products being the primary concerns. Painkillers, antibiotics, beta blockers, contraceptives, cholesterol regulators, and antidepressants are among the over 3000 medications being used in Europe and the US. About 30 new drugs are introduced to the market annually in Germany alone, making about 8% of all research and development spending worldwide. It is anticipated that around 300 new pharmaceutical compounds are

introduced every year, based on a global R&D investment of approximately US\$83 billion in 2007. With 100,000 tons produced annually, the global pharmaceutical business was estimated to be worth US\$773 billion. In most European countries, per capita sales range from around 200 – 400 US\$ [33].

Pharmaceutical compounds are highly bioactive, and their discharge into the aquatic environment can lead to unintended effects on organisms, especially given their mobility due to polarity. While the presence of pharmaceuticals in wastewater and natural waters is expected due to their large-scale production and widespread use, it was only advances in analytical chemistry—specifically LC-MS/MS—that enabled the detection of these compounds in the nanogram to microgram per liter range typical of wastewater and aquatic systems. Observed concentrations of human pharmaceuticals in raw sewage can reach several micrograms per liter, confirming that municipal wastewater is a primary pathway for their release into receiving water bodies [34-37].

Currently, pharmaceuticals are unintentionally removed in wastewater systems through sorption to sludge and biodegradation. However, biodegradation often does not result in full mineralization; instead, it leads to the formation of metabolites. For example, 12 metabolites of iopromide, an iodinated X-ray contrast medium, have been identified. Therefore, when evaluating the toxicological effects of discharged wastewater, it is crucial to consider both the parent compounds and their metabolites. Fortunately, more hydrophilic metabolites are generally expected to pose a lower toxicological risk than their hydrophobic parent compounds, unless a specific mode of action becomes relevant [38]. Even though different pharmaceuticals and their metabolites were found in the

wastewater effluent, recent mode-of-action tests using five in vitro bioassays showed that both nonspecific effects (like bioluminescence and growth rate inhibition) and specific effects (like acetylcholine esterase activity, estrogenicity, and genotoxicity) significantly decreased from primary wastewater to the effluent [39].

Although the ecotoxicological effects of pharmaceuticals in wastewater effluents are the main cause for concern, their presence in drinking water from direct or indirect potable reuse is raising concerns about their potential effects on human health. Pharmaceuticals and their metabolites can enter aquifers through riverbanks in indirect reuse systems. Luckily, riverbanks frequently provide strong barriers against a variety of harmful substances. Only sulfamethoxazole was detected in the bank filtrate of research that found 19 antibiotics in surface water at values ranging from 5 to 150 ng/L. However, recent reviews on pharmaceutical residues in aquatic environments indicate that complete removal of all potential pharmaceutical residues via riverbank filtration cannot be guaranteed [40]. Comparisons of drinking water concentrations of pharmaceuticals, such as sulfamethoxazole, reveal a difference of over six orders of magnitude compared to the therapeutic dose of this compound. For other pharmaceuticals, the safety margin may range from four to six orders of magnitude—significantly higher than the safety factor of 1000 applied to potentially carcinogenic compounds like the herbicide atrazine. Pharmaceuticals are also among the synthetic organic compounds that have undergone the most extensive testing when it comes to human toxicology. Clinical trials and thorough information on pharmacology, pharmacokinetics, and toxicology are necessary for the authorization of new pharmaceutical substances. According to our evaluation, there seems to be little chance of being exposed to certain medications in

drinking water. Nevertheless, further investigation is required to comprehend the consequences of prolonged exposure to pharmacological combinations and low dosages [41-44].

Ozonation and activated carbon are two polishing treatment techniques that are being examined as mitigation strategies because wastewater is a major source of pharmaceuticals. Ozonation is feasible with reasonable operating costs, according to recent large-scale investigations. Polishing wastewater discharge shields water resources and the aquatic environment from endocrine disruptors and human medications. Alternatively, a few treatment methods, including oxidation, nanofiltration/reverse osmosis, and granular or powdered activated carbon, can successfully eliminate these substances if the main issue is their presence in drinking water.

CONCLUSION

Addressing global water pollution necessitates a comprehensive approach involving effective policies, technologies, and scientific advancements across various scales. The enduring presence of persistent priority pollutants, like PCBs, underscores the need for a global phase-out and regulatory efforts. Volatile chemicals, such as halogenated compounds and mercury, which do not biodegrade and accumulate in the food chain, should be restricted to tightly controlled applications. Human food production systems must be rigorously protected against compounds with bioaccumulation potential; therefore, water requires equal attention. Additionally, the precautionary principle should guide the design of potential substitutes for priority pollutants to ensure that today's solutions do not create tomorrow's problems. Increasing agricultural yields while preserving the environment and preventing contamination of the food chain is a major problem facing global agriculture. More integrated farming

practices are necessary to improve water quality in agricultural areas.

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