



Chemistry of environmental pollution: Sources, chemical transformation, environmental fate and remediation strategies

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Abstract

Environmental pollution is fundamentally a chemical problem involving the introduction, transformation, transport, persistence, and accumulation of substances in air, water, soil, and biological systems. Industrialization, agricultural intensification, urbanization, transportation, energy production, and increasing consumption of synthetic chemicals have introduced a diverse range of inorganic and organic pollutants into the environment. Conventional pollutants such as sulfur oxides, nitrogen oxides, carbon monoxide, particulate matter, pesticides, petroleum-derived compounds, and heavy metals continue to pose significant environmental challenges, while emerging contaminants including pharmaceuticals, personal care products, endocrine-disrupting chemicals, per- and polyfluoroalkyl substances (PFAS), microplastics, and antimicrobial-resistance-related contaminants have expanded the scope of environmental chemistry. This review examines environmental pollution from a chemistry-centered perspective, emphasizing pollutant classification, sources, chemical properties, transformation processes, transport, persistence, toxicity, and remediation. Particular attention is given to chemical reactions occurring in the atmosphere and aquatic and terrestrial environments, including oxidation, reduction, hydrolysis, photochemical transformation, adsorption, complexation, precipitation, and biodegradation. The review also considers advanced remediation approaches such as adsorption, membrane separation, advanced oxidation processes, photocatalysis, biological treatment, and integrated treatment systems. Current evidence indicates that pollution control requires not only removal of contaminants but also understanding their transformation products and environmental fate. Emerging pollutants present additional challenges because many occur at trace concentrations while remaining chemically persistent or biologically active. Future environmental chemistry research should therefore integrate molecular-level characterization, transformation pathways, toxicity assessment, life-cycle thinking, and sustainable remediation technologies.

Keywords: Environmental chemistry, environmental pollution, air pollution, water pollution, soil pollution, emerging contaminants, heavy metals, PFAS, remediation, chemical transformation

Introduction

Environmental pollution refers to the introduction of substances or forms of energy into environmental compartments at levels capable of altering their natural characteristics and producing adverse effects. From a chemical perspective, pollution involves changes in the composition and distribution of matter within the atmosphere, hydrosphere, lithosphere, and biosphere. Air, water, and soil pollution are closely interconnected. A chemical released into one environmental compartment may undergo transport and transformation and subsequently enter another compartment. For example, atmospheric pollutants can be deposited onto soil and water, agricultural chemicals can migrate through soil into groundwater, and industrial wastewater can transfer contaminants into rivers and sediments. The World Health Organization identifies particulate matter, carbon monoxide, ozone, nitrogen dioxide, and sulfur dioxide among the major air pollutants of public-health concern. (World Health Organization) The United Nations Environment Programme similarly emphasizes the significance of chemical pollution involving heavy metals, persistent chemicals, plastics, and other contaminants across environmental systems. (UNEP - UN Environment Programme)

Environmental pollution is increasingly complicated by the emergence of chemicals that were previously unrecognized or insufficiently monitored. Pharmaceuticals, personal care products, endocrine-disrupting compounds, PFAS, flame

retardants, pesticides, and other contaminants can occur at low concentrations but may remain environmentally relevant because of their persistence, biological activity, continuous release, or transformation into additional products (Khan *et al.*, 2022; Kumar *et al.*, 2023) ^[5, 6]. The chemistry of pollution is therefore not limited to identifying the original contaminant. It also involves understanding what happens to that contaminant after release.

Classification of Environmental Pollutants

Environmental pollutants can be classified in several ways.

Inorganic Pollutants

Inorganic pollutants include:

- heavy metals;
- metalloids;
- inorganic acids and bases;
- nitrogen compounds;
- sulfur compounds;
- fluoride;
- cyanide;
- inorganic salts; and
- Radioactive substances.

Heavy metals such as lead, mercury, cadmium, chromium, and arsenic-containing species are particularly important because they can persist in environmental systems and undergo changes in chemical speciation.

Unlike many organic compounds, metals cannot be chemically degraded into harmless elemental products. Their environmental behavior is instead controlled by processes such as adsorption, precipitation, dissolution, complexation, redox transformation, and biological uptake.

Organic Pollutants

Organic pollutants contain carbon-based molecular structures and include:

- Petroleum hydrocarbons;
- Pesticides;
- Phenolic compounds;
- Synthetic dyes;
- Polycyclic aromatic hydrocarbons;
- Polychlorinated compounds;
- Pharmaceuticals;
- Personal care products; and
- Industrial organic chemicals.

Their environmental persistence varies considerably. Some compounds undergo rapid biodegradation, whereas others resist chemical and biological transformation.

Emerging Contaminants

Emerging contaminants include substances that are newly recognized, inadequately regulated, or insufficiently monitored despite their potential environmental significance. Important groups include pharmaceuticals, antibiotics, personal care products, endocrine-disrupting chemicals, PFAS, flame retardants, microplastics, and certain industrial chemicals. Reviews have shown that research on emerging contaminants has increasingly expanded toward pharmaceuticals, PFAS, endocrine-disrupting compounds, pesticides, heavy metals, and microplastics.

Chemistry of Air Pollution

Air pollution involves gaseous, particulate, and aerosol-phase substances.

Sulfur Oxides

Sulfur dioxide is generated primarily through the combustion of sulfur-containing fuels and certain industrial processes. Atmospheric oxidation can convert sulfur dioxide into oxidized sulfur species that contribute to acidic deposition.

A simplified representation is:

$\text{SO}_2 \rightarrow \text{oxidized sulfur species} \rightarrow \text{H}_2\text{SO}_4\text{-containing atmospheric products}$

The resulting acidic species can influence atmospheric aerosols, precipitation chemistry, soil chemistry, and aquatic ecosystems.

Nitrogen Oxides

Nitrogen oxides are produced during high-temperature combustion and various industrial processes. Nitrogen dioxide participates in atmospheric photochemistry and contributes to the formation of ozone and secondary particulate matter.

Nitrogen oxide chemistry is particularly important in urban atmospheres because sunlight initiates a network of reactions involving nitrogen oxides and volatile organic compounds.

Carbon Monoxide

Carbon monoxide is produced primarily through incomplete combustion. It is chemically significant because it can participate in atmospheric oxidation processes and influence atmospheric oxidizing capacity.

Ozone

Ground-level ozone is a secondary pollutant. It is not normally emitted directly in large quantities but is formed through atmospheric photochemical reactions involving nitrogen oxides and reactive organic compounds. This distinction between primary pollutants and secondary pollutants is fundamental to environmental chemistry.

Particulate Matter

Particulate matter consists of solid particles and liquid droplets suspended in air. Its chemical composition can include sulfates, nitrates, carbonaceous materials, metals, organic compounds, and mineral components.

The chemistry and size distribution of particles influence their atmospheric lifetime, transport, deposition, and biological effects.

Chemistry of Water Pollution

Water acts as both a solvent and a transport medium for numerous pollutants. Its chemical properties strongly influence pollutant mobility and transformation.

Heavy Metals

Heavy metals can enter water through mining, metallurgy, industrial discharge, waste disposal, agricultural activities, and urban runoff.

Their behavior depends on:

- pH;
- Oxidation–reduction potential;
- Dissolved organic matter;
- Competing ions;
- Mineral surfaces; and
- Chemical speciation.

For example, metal ions may be converted into less soluble compounds through precipitation or may be retained on clay and oxide surfaces through adsorption.

Pesticides

Pesticides can reach aquatic systems through agricultural runoff, drainage, atmospheric deposition, and accidental releases. Their environmental persistence depends on molecular structure, solubility, hydrolysis, photolysis, microbial degradation, and adsorption. Some pesticide transformation products may persist longer than the original compounds or possess different biological properties.

Pharmaceuticals and Personal Care Products

Pharmaceutical compounds are increasingly recognized as environmental contaminants because their continuous use results in continuous release through wastewater pathways. A 2025 meta-analysis of global surface waters examined 101 studies comprising 714 datasets from 46 countries and found widespread occurrence of pharmaceuticals, illicit drugs, antibiotics, and PFAS. Many pharmaceutical compounds are chemically designed to remain biologically active, creating a challenge when they enter environmental systems. Conventional wastewater treatment may remove

some compounds efficiently while others may persist or undergo transformation into metabolites and transformation products.

Disinfection By-Products

Water disinfection is essential for controlling pathogens, but disinfectants can react with naturally occurring organic matter and inorganic substances to produce secondary chemicals. These disinfection by-products can become contaminants of concern in drinking-water and urban-water systems. Their formation and fate depend on disinfectant chemistry, precursor composition, pH, temperature, and treatment conditions (Xiao *et al.*, 2023)^[15].

Chemistry of Soil Pollution

Soil is chemically heterogeneous and contains minerals, organic matter, microorganisms, water, gases, and exchangeable ions.

Pollutants entering soil may undergo:

- Adsorption;
- Desorption;
- Dissolution;
- Precipitation;
- Complexation;
- Oxidation;
- Reduction;
- Hydrolysis; and
- Biodegradation.

These processes determine whether a contaminant remains immobilized or becomes mobile.

Heavy Metal Contamination

Heavy metals are particularly persistent in soil. Their mobility can increase or decrease according to pH, redox conditions, organic matter, mineral composition, and competing ions. For example, changes in soil pH can alter the charge of mineral surfaces and the chemical form of metal species, thereby modifying their mobility and bioavailability.

Pesticide Residues

Pesticides may bind strongly to soil organic matter or mineral surfaces. Strong adsorption can reduce immediate mobility but may also increase persistence. Conversely, weak adsorption can increase movement through soil and groundwater.

Emerging Soil Contaminants

Emerging contaminants in soil include pharmaceuticals, antibiotics, PFAS, microplastics, hormones, and other chemicals. A review of contaminants of emerging concern in soils emphasized that soil heterogeneity makes source tracking and assessment difficult and that potential health risks require greater regulatory attention (Maddela *et al.*, 2022)^[7].

Chemical Transformation of Environmental Pollutants

The environmental fate of a pollutant depends not only on its initial chemical structure but also on its transformation reactions.

Hydrolysis

Hydrolysis involves reaction with water and can be important for pesticides, pharmaceuticals, esters, amides, and other hydrolysable compounds.

Photochemical Transformation

Solar radiation can initiate photochemical reactions in surface waters and the atmosphere. Pollutants may absorb radiation directly or react with photochemically generated reactive species.

Oxidation

Oxidation may involve oxygen, ozone, hydroxyl radicals, peroxide-derived species, or other oxidizing agents. Advanced oxidation processes exploit highly reactive species to transform persistent organic compounds.

Reduction

Reduction reactions can alter the chemical form and mobility of metals and organic contaminants. Redox conditions are especially important in sediments, wetlands, groundwater, and waterlogged soils.

Biodegradation

Microorganisms can transform organic pollutants through metabolic and cometabolic pathways. Biodegradation may completely mineralize a compound or produce intermediate transformation products. Therefore, disappearance of a parent pollutant does not necessarily indicate complete detoxification.

Persistent Organic Pollutants

Persistent organic pollutants are characterized by properties such as environmental persistence, resistance to degradation, potential for long-range transport, and biological accumulation. Their chemical structures may contain stable carbon halogen bonds or other features that reduce susceptibility to environmental degradation. The environmental significance of persistent organic pollutants arises from their ability to remain in environmental systems for extended periods and potentially move through food webs.

Per- and Polyfluoroalkyl Substances

PFAS represent an important class of emerging environmental contaminants. Their carbon-fluorine chemistry contributes to high chemical stability, which can make many PFAS difficult to degrade. PFAS have been used in numerous industrial and consumer applications. Environmental reviews have documented their occurrence, transport, transformation, toxicity, monitoring, and remediation challenges (Elgarahy *et al.*, 2024)^[3]. Recent research has emphasized that PFAS contamination cannot be considered solely a water-quality issue because these substances may occur across interconnected environmental compartments. The chemical persistence of PFAS presents a major remediation challenge because conventional biological degradation may be insufficient for many compounds.

Microplastics as Chemical Pollutants

Microplastics are small plastic particles that originate from the degradation of larger plastic materials or are directly introduced into the environment. Their environmental

chemistry involves both the polymer itself and chemicals associated with the particle surface.

Microplastics can:

- Adsorb organic pollutants;
- Interact with metals;
- Provide surfaces for microbial colonization;
- Undergo weathering;
- Release additives; and
- Act as transport media for other contaminants.

Consequently, microplastics can be considered both pollutants themselves and potential carriers of other chemical contaminants.

Environmental Fate and Transport

Pollutant fate is controlled by interactions between chemical properties and environmental conditions.

Important factors include:

- Water solubility;
- Vapor pressure;
- Molecular structure;
- Partition coefficients;
- Adsorption affinity;
- Chemical stability;
- pH;
- Temperature;
- Organic matter;
- Ionic Strength; and
- Microbial activity.

Wilkinson *et al.* (2017) ^[12] emphasized that emerging contaminants can persist through wastewater treatment and enter aquatic environments as parent compounds, metabolites, or transformation products. The environmental fate of a chemical should therefore be viewed as a dynamic process rather than a simple movement from source to receptor.

Human and Ecological Implications

Chemical pollutants can affect organisms through multiple exposure pathways.

Humans may be exposed through:

- Inhalation;
- Ingestion of contaminated water;
- Consumption of contaminated food;
- Dermal contact; and
- Occupational exposure.

Ecological effects may occur at individual, population, community, and ecosystem levels. Heavy metals, persistent organic chemicals, pesticides, endocrine-disrupting compounds, pharmaceuticals, and PFAS may affect organisms through different biochemical mechanisms. The combined presence of multiple contaminants creates an additional challenge. Environmental exposure rarely involves a single chemical in isolation. UNEP notes that people and ecosystems can be exposed to mixtures of chemicals and materials through food, air, and water. (UNEP-UN Environment Programme)

Remediation Technologies

Environmental remediation aims to reduce pollutant concentrations, immobilize contaminants, destroy hazardous molecules, or prevent their movement.

Adsorption

Adsorption is widely used because pollutants can be transferred from water or air onto a solid surface. Common adsorbents include:

- Activated carbon;
- Biochar;
- Zeolites;
- Clay minerals;
- Metal oxides; and
- Engineered porous materials.
- Adsorption efficiency depends on surface area, pore structure, surface functional groups, pollutant chemistry, pH, and competing substances.

13.2 Advanced Oxidation Processes

- Advanced oxidation processes generate highly reactive species capable of transforming persistent organic contaminants.
- Examples include:
 - ozonation;
 - UV/peroxide systems;
 - photocatalysis;
 - Fenton-type reactions; and
 - Related radical-based oxidation systems.

These technologies are particularly relevant to pharmaceuticals, dyes, pesticides, and other organic contaminants.

Membrane Technologies

Membrane filtration can physically separate contaminants according to molecular size, charge, solubility, and interactions with membrane materials. Membrane processes include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Their application must also consider energy requirements, membrane fouling, concentrate management, and overall sustainability.

Biological Remediation

Microorganisms, plants, and biologically derived materials can contribute to pollutant removal or transformation. Biological remediation can be particularly attractive because it may operate under relatively mild conditions and can reduce chemical consumption. However, treatment efficiency depends on pollutant structure, microbial community, environmental conditions, and the availability of suitable metabolic pathways.

Combined Treatment

No single treatment technology is universally effective. Integrated treatment systems can combine:

Adsorption → oxidation → biological treatment → polishing

Such combinations may improve removal while reducing the limitations of individual processes.

Analytical Chemistry and Environmental Monitoring

Although this review does not present original analytical data, analytical chemistry remains fundamental to pollution research.

Environmental laboratories increasingly rely on highly sensitive instrumental methods for identifying and

quantifying trace contaminants. For emerging contaminants, analytical challenges include:

- Extremely low environmental concentrations;
- Complex environmental matrices;
- Large numbers of potential compounds;
- Transformation products;
- Matrix interference; and
- Difficulty obtaining appropriate reference standards.

A 2024 review of analytical methods for pharmaceuticals and personal care products highlighted the continuing development of analytical approaches for detecting these contaminants in liquid and solid environmental matrices (Alqarni, 2024) ^[2]. Analytical chemistry therefore provides the evidence base required for environmental risk assessment.

Sustainable Chemistry Approach to Pollution Control

Pollution control should increasingly move from end-of-pipe treatment toward prevention. Green and sustainable chemistry can contribute by encouraging:

1. Less hazardous chemical synthesis;
2. Safer solvents;
3. Biodegradable Products;
4. Renewable feedstocks;
5. Reduced persistence;
6. Improved chemical efficiency;
7. Recovery and recycling;
8. Reduced waste generation; and
9. Safer alternatives to persistent chemicals.

The most effective pollution-control strategy is often to prevent a hazardous substance from entering the environment rather than attempting to remove it after widespread distribution.

Conclusion

Environmental pollution is fundamentally connected to the chemistry of substances released into natural systems. The environmental behavior of a pollutant is determined by its molecular structure, chemical stability, solubility, surface interactions, reactivity, and susceptibility to biological transformation. Environmental conditions such as pH, temperature, redox potential, organic matter, sunlight, and microbial activity further modify pollutant fate. Traditional pollutants such as sulfur and nitrogen oxides, heavy metals, pesticides, and petroleum compounds remain important, while emerging contaminants have expanded the complexity of environmental pollution. Pharmaceuticals, personal care products, PFAS, endocrine-disrupting chemicals, microplastics, and other contaminants may occur at trace levels while still presenting environmental challenges. Effective pollution management therefore requires more than measuring contaminant concentrations. It requires understanding chemical transformations, environmental transport, exposure pathways, toxicity, and the formation of secondary products. Remediation technologies including adsorption, advanced oxidation, membrane separation, biological treatment, and integrated systems provide important tools, but prevention through sustainable chemistry remains the preferred long-term strategy.

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