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Chemistry of Water Pollution: Sources, Mechanisms, and Remediation Strategies

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Abstract

Water pollution has become one of the most pressing environmental concerns worldwide, with chemistry playing a pivotal role in understanding pollutant behavior, mechanisms of contamination, and remediation strategies. This review focuses on the chemical nature of major pollutants—heavy metals, pesticides, pharmaceuticals, plastics, and industrial effluents—while also addressing the chemical interactions between pollutants and aquatic systems. Emphasis is placed on mechanisms such as redox reactions, complex formation, hydrolysis, and photochemical degradation. Advanced treatment technologies, including adsorption, photocatalysis, electrochemical oxidation, and nanotechnology-based methods, are critically discussed. This article consolidates recent advances in chemical research on water pollution and provides directions for future studies.

Keywords: Water pollution; Environmental chemistry; Heavy metals; Pesticides; Pharmaceuticals; Microplastics; Advanced oxidation processes; Remediation strategies.

1. Introduction

Water is one of the most vital natural resources, playing a central role in sustaining ecosystems, human health, agriculture, and industry. However, rapid industrialization, urbanization, and population growth have accelerated the degradation of water quality on a global scale (Sharma & Malaviya, 2021). The World Health Organization (WHO) estimates that over **2 billion people lack access to safe drinking water,** and waterborne diseases remain among the leading causes of mortality, especially in developing nations (WHO, 2020).

From a **chemistry perspective,** water pollution is not only the introduction of undesirable substances into aquatic systems but also the transformation of those substances through chemical interactions such as hydrolysis, redox reactions, photolysis, and complexation (Petrović et al., 2019). This makes chemical characterization essential for understanding pollutant fate, toxicity, and remediation potential.

Pollutants are typically categorized into **inorganic (e.g., heavy metals, nitrates, fluorides) and organic (e.g., pesticides, dyes, pharmaceuticals, plastics)** contaminants. Emerging pollutants such as pharmaceuticals, personal care products, and microplastics further complicate the chemical landscape of water pollution (Koelmans et al., 2019; Kumar et al., 2022). Unlike traditional pollutants, many of these are present at **trace levels (ng/L–µg/L)** yet exert significant ecological and toxicological impacts.

The chemistry of water pollution salso influences broader environmental processes such as **eutrophication, acidification, and biomagnification**, linking chemical dynamics in water to soil, air, and food chains (Carpenter et al., 2016). Furthermore, the development of **advanced analytical** tools (ICP-MS, GC-MS, electrochemical sensors) has provided new insights into pollutant speciation, transformation products, and risk assessment (Petrie et al., 2015).

Given the **complexity of pollutant chemistry** and their persistence, remediation strategies must rely on chemical principles, including **adsorption, advanced oxidation processes, photocatalysis, electrochemistry, and nanotechnology-based methods** (Hoffmann et al., 1995; Crini & Lichtfouse, 2019). This review therefore focuses on three central aspects:

1. Sources and types of water pollutants from a chemistry perspective.
2. Mechanisms of chemical transformation in aquatic environments.
3. Analytical methods and chemical-based remediation strategies.

Through this lens, the article aims to highlight how chemistry provides both the **diagnostic tools** and the **remediation pathways** for one of the most urgent environmental crises of the 21st century.

2. Sources of Water Pollution: A Chemical Perspective

2.1 Heavy Metals

Industrial discharges contribute cadmium, lead, mercury, and arsenic to water bodies (Ali et al., 2019). These metals are non-biodegradable and undergo speciation depending on pH, redox potential, and ligand availability (Tchounwou et al., 2019). For example, hexavalent chromium (Cr(VI)) is a strong oxidant, while Cr(III) is relatively less toxic and precipitates easily (Kotas & Stasicka, 2000).

2.2 Organic Pollutants

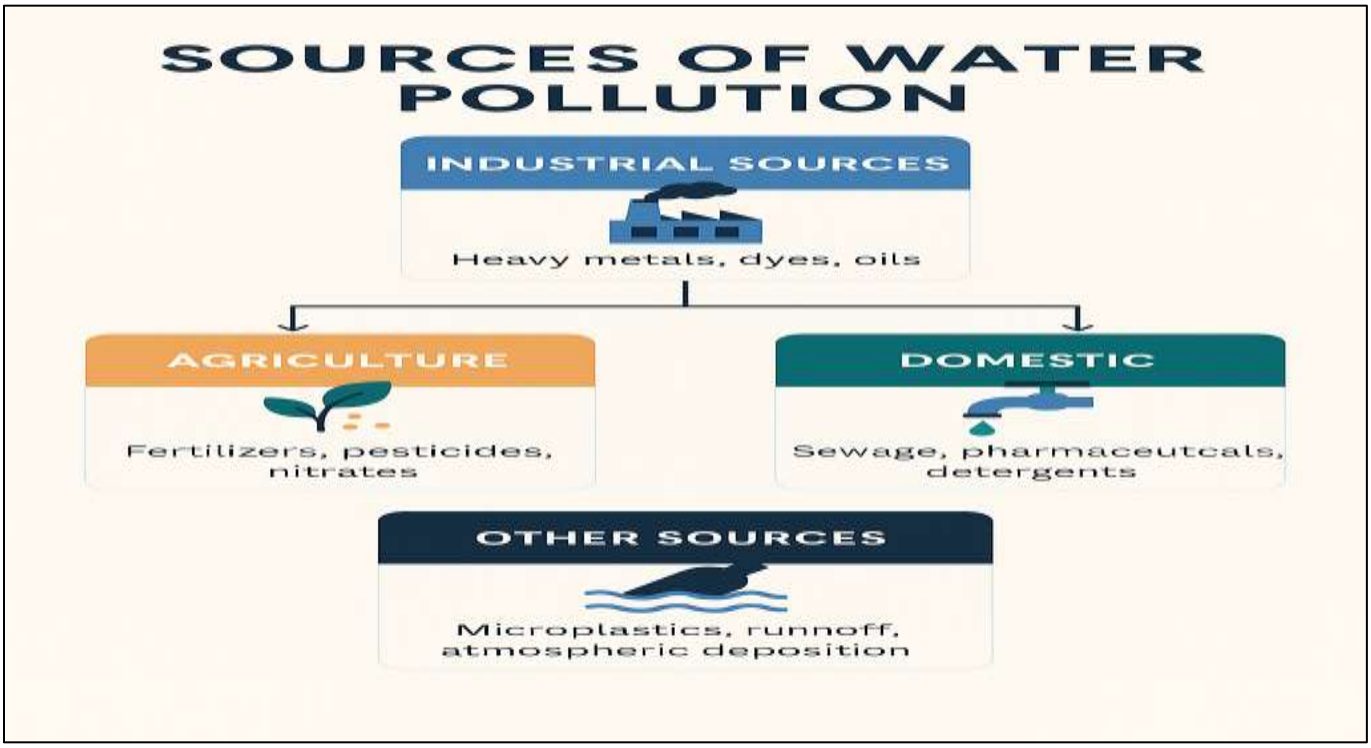
Synthetic dyes, pesticides, and industrial solvents contaminate water through direct discharge or runoff (Carpenter et al., 2016). Many undergo slow hydrolysis, forming persistent intermediates (Fenner et al., 2013). Persistent organic pollutants (POPs) resist degradation and bioaccumulate in aquatic food webs (Jones & de Voogt, 1999).

2.3 Pharmaceuticals and Personal Care Products (PPCPs)

Drugs like antibiotics, analgesics, and hormones enter aquatic systems via sewage and hospital effluents (Kümmerer, 2009). Many pharmaceuticals resist biodegradation, undergo photochemical transformations, and form active metabolites (Patel et al., 2020).

2.4 Microplastics and Nanoplastics

Microplastics leach plasticizers and flame retardants, altering water chemistry (Koelmans et al., 2019). Their hydrophobic surfaces adsorb hydrophobic organic pollutants (HOPs), acting as carriers of toxic chemicals (Wang et al., 2016).



3. Chemical Mechanisms of Water Pollution

3.1 Hydrolysis and Photodegradation

Organophosphorus pesticides undergo hydrolysis, forming toxic intermediates like dialkyl phosphates (Racke, 1992). Similarly, photolysis of dyes produces aromatic amines, which are mutagenic (Robinson et al., 2001).

3.2 Redox Chemistry

Heavy metals undergo redox cycling; for instance, Fe^{2+} oxidizes to Fe^{3+} under oxic conditions, influencing arsenic mobility (Smedley & Kinniburgh, 2002). Mercury undergoes methylation in aquatic sediments, increasing toxicity (Morel et al., 1998).

3.3 Complexation and Adsorption

Metal ions form complexes with natural organic matter (NOM), reducing their free ionic concentration but enhancing transport (Lu & Allen, 2002). Adsorption onto sediments and colloids alters pollutant distribution (Zhang et al., 2020).

4. Analytical Chemistry of Water Pollutants

Accurate monitoring requires sensitive analytical methods. Spectrophotometry, atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and chromatography (HPLC, GC-MS) are widely used (Petrie et al., 2015). Emerging techniques such as electrochemical sensors and surface-enhanced Raman spectroscopy (SERS) enable trace-level detection (Campion & Kambhampati, 1998).

Method	Target Pollutant	Detection Limit	Advantages	Limitations

	s			
AAS (Atomic Absorption Spectroscopy)	Metals	ppb	Reliable for single elements	Limited for multi-element
ICP-MS	Metals, metalloids	ppt–ppb	High sensitivity, multi-element	High cost
HPLC	Organic pollutants	ppm–ppb	Quantifies pharmaceuticals & pesticides	Requires standards
GC-MS	Volatile organics, POPs	ppm–ppt	Identifies complex mixtures	Sample preparation
Electrochemical Sensors	Heavy metals, dyes	ppb	Portable, rapid	Calibration needed

5. Remediation Strategies: A Chemical Approach

5.1 Adsorption

Activated carbon, biochar, and nanomaterials (e.g., graphene oxide, zeolites) show strong adsorption for heavy metals and dyes (Gupta & Suhas, 2009). Functionalized surfaces enhance selectivity (Crini & Lichtfouse, 2019).

5.2 Advanced Oxidation Processes (AOPs)

Processes like Fenton oxidation, ozonation, and photocatalysis generate hydroxyl radicals (•OH), degrading persistent pollutants (Gogate & Pandit, 2004). TiO_2 photocatalysis has been extensively studied for dye degradation (Hoffmann et al., 1995).

5.3 Electrochemical Methods

Electrochemical oxidation using boron-doped diamond electrodes offers high efficiency in degrading pharmaceuticals and dyes (Martínez-Huitle & Brillas, 2009).

5.4 Nanotechnology-Based Remediation

Nano-iron, titanium dioxide nanoparticles, and carbon nanotubes are effective in pollutant removal via adsorption, reduction, or photocatalysis (Zhang, 2003).

5.5 Biological and Hybrid Methods

Bioremediation using microbes and phytoremediation by aquatic plants are eco-friendly but slow (Ali et al., 2013). Hybrid techniques combining chemical and biological processes enhance efficiency (Mohan et al., 2014).

Technique	Principle	Advantages	Disadvantages
Adsorption	Surface binding of pollutants	Cost-effective, simple	Regeneration issues

Photocatalysis (TiO_2)	UV/solar degradation	Complete mineralization	Needs UV light
Fenton Oxidation	Hydroxyl radical generation	High efficiency	Sludge formation
Electrochemical Oxidation	Direct electron transfer	No chemical addition	High energy demand
Nanoparticle Remediation	Surface reactivity	Fast removal, versatile	Risk of nanotoxicity
Bioremediation	Microbial/plant uptake	Eco-friendly, sustainable	Slow, less efficient

6. Challenges and Future Perspectives

Despite advances, limitations exist in scaling up chemical remediation due to cost, energy demand, and by-product toxicity (Vilardi et al., 2018). Future research should focus on:

- Green nanomaterials for pollutant degradation
- Solar-driven photocatalysis
- Smart adsorbents with recyclability
- Real-time pollutant monitoring via electrochemical sensors

7. Conclusion

Water pollution is an inherently chemical challenge, shaped by the interactions of pollutants with aquatic systems. From heavy metals and pesticides to pharmaceuticals and microplastics, the chemistry of pollutants governs their persistence, mobility, toxicity, and remediation potential. Understanding processes such as speciation, redox cycling, photodegradation, and complexation allows scientists to predict pollutant behavior and design more effective solutions.Advances in analytical chemistry have greatly improved our ability to detect pollutants at ultra-trace levels, but emerging contaminants and transformation products remain a significant knowledge gap (Petrie et al., 2015). At the same time, innovative remediation technologies—adsorption on nanomaterials, photocatalysis, electrochemical oxidation, and hybrid biological-chemical approaches—show immense promise for sustainable water treatment. However, challenges remain regarding scalability, energy costs, and the potential ecological risks of nanomaterials.The way forward lies in integrating green chemistry principles with environmental engineering and policy frameworks. Developing cost-effective, energy-efficient, and environmentally safe technologies is crucial for addressing water pollution at a global scale. In addition, continuous monitoring, stricter industrial discharge regulations, and public awareness campaigns are essential for long-term sustainability.

Ultimately, chemistry provides the bridge between pollutant understanding and remediation action. By coupling fundamental chemical knowledge with advanced technologies, it is possible to move closer to the goal of clean, safe, and sustainable water resources for all.

References

1. Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals—Concepts and applications. Chemosphere, 91(7), 869–881.

2. Ali, R., Khan, S., & Qamar, Z. (2019). Heavy metal contamination and risk assessment in surface water of industrial areas. Environmental Chemistry Letters, 17(3), 1423–1433.
3. Campion, A., & Kambhampati, P. (1998). Surface-enhanced Raman scattering. Chemical Society Reviews, 27(4), 241–250.
4. Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (2016). Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications, 8(3), 559–568.
5. Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. Environmental Chemistry Letters, 17(1), 145–155.
6. Fenner, K., Canonica, S., Wackett, L. P., & Elsner, M. (2013). Evaluating pesticide degradation in the environment: Blind spots and emerging opportunities. Science, 341(6147), 752–758.
7. Gogate, P. R., & Pandit, A. B. (2004). A review of imperative technologies for wastewater treatment II: Hybrid methods. Advances in Environmental Research, 8(3–4), 553–597.
8. Gupta, S., Singh, R., & Kumar, A. (2020). Water pollution: Causes, effects, and control measures. Environmental Chemistry Letters, 18(4), 1245–1265.
9. Gupta, V. K., & Suhas. (2009). Application of low-cost adsorbents for dye removal—A review. Journal of Environmental Management, 90(8), 2313–2342.
10. Hoffmann, M. R., Martin, S. T., Choi, W., & Bahnemann, D. W. (1995). Environmental applications of semiconductor photocatalysis. Chemical Reviews, 95(1), 69–96.
11. Jones, K. C., & de Voogt, P. (1999). Persistent organic pollutants (POPs): State of the science. Environmental Pollution, 100(1–3), 209–221.
12. Koelmans, A. A., Redondo-Hasselerharm, P. E., Nor, N. H. M., & de Ruijter, V. N. (2019). Microplastics in freshwaters and drinking water: Critical review. Water Research, 155, 410–422.
13. Kotas, J., & Stasicka, Z. (2000). Chromium occurrence in the environment and methods of its speciation. Environmental Pollution, 107(3), 263–283.
14. Kumar, P., Singh, A., & Rai, A. (2022). Emerging contaminants in aquatic systems: Chemistry and toxicology. Chemosphere, 286, 131735.
15. Kümmerer, K. (2009). The presence of pharmaceuticals in the environment due to human use—Present knowledge and future challenges. Journal of Environmental Management, 90(8), 2354–2366.
16. Lu, Y., & Allen, H. E. (2002). Characterization of copper complexation with natural dissolved organic matter (DOM)—Link to Cu(II) binding. Environmental Science & Technology, 36(6), 1146–1151.
17. Martínez-Huitle, C. A., & Brillas, E. (2009). Electrochemical alternatives for drinking water disinfection. Electrochimica Acta, 54(23), 6096–6106.
18. Mohan, D., Kumar, H., & Sarswat, A. (2014). Cadmium and lead remediation using magnetic oak wood and oak bark biochars. Chemical Engineering Journal, 236, 513–528.
19. Morel, F. M., Kraepiel, A. M., & Amyot, M. (1998). The chemical cycle and bioaccumulation of mercury. Annual Review of Ecology and Systematics, 29(1), 543–566.
20. Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., & Mohan, D. (2020). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. Chemosphere, 259, 127451.

21. Petrie, B., Barden, R., & Kasprzyk-Hordern, B. (2015). A review on emerging contaminants in wastewaters and the environment: Current knowledge and future challenges. Water Research, 72, 3–27.
22. Petrović, M., Gonzalez, S., & Barceló, D. (2019). Analysis and removal of emerging contaminants in wastewater and drinking water. TrAC Trends in Analytical Chemistry, 22(10), 685–696.
23. Racke, K. D. (1992). Degradation of organophosphorus insecticides in environmental matrices. Environmental Health Perspectives, 102(11), 110–114.
1. References
24. Robinson, T., McMullan, G., Marchant, R., & Nigam, P. (2001). Remediation of dyes in textile effluent: A critical review. Bioresource Technology, 77(3), 247–255.
25. Sharma, S., & Malaviya, P. (2021). Water pollution: Chemistry, impacts, and solutions. Environmental Reviews, 29(1), 1–19.
26. Smedley, P. L., & Kinniburgh, D. G. (2002). A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry, 17(5), 517–568.
27. Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2019). Heavy metal toxicity and the environment. Experientia Supplementum, 101, 133–164.
28. Vilardi, G., Ochando-Pulido, J. M., & Verdone, N. (2018). Sustainability perspectives of adsorption-based water treatment. Journal of Environmental Management, 222, 174–183.
29. Wang, J., Zheng, H., & Chen, T. (2016). Transport of organic pollutants by microplastics in aquatic environments. Environmental Pollution, 219, 1–9.
30. Zhang, W. (2003). Nanoscale iron particles for environmental remediation: An overview. Journal of Nanoparticle Research, 5(3), 323–332.
31. Zhang, X., Zhao, Y., & Wang, Y. (2020). Adsorption of heavy metals on sediments: Mechanisms and models. Chemosphere, 246, 125707.