

A comprehensive review of Water Pollution: Sources, Impacts and Control measures

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ABSTRACT

Water pollution remains a critical global environmental challenge, with recent studies indicating a continuous decline in freshwater quality across multiple regions. According to recent Scopus-indexed assessments, nearly 80% of global wastewater is discharged into the environment without adequate treatment, contributing significantly to the degradation of rivers, lakes, groundwater, and coastal ecosystems [1,3]. Accelerated industrial development, intensified agricultural practices, expanding urban areas, and growing populations have significantly increased pollution pressures. These activities contribute not only to traditional pollutants—such as nutrients, organic waste, and disease-causing microorganisms—but also to newer contaminants, including pharmaceuticals, microplastics, and other emerging pollutants. [11,12]. This review synthesizes recent peer-reviewed research to examine the dominant sources of water pollution, classifications of pollutants, environmental and human health impacts, and contemporary control measures. Statistical evidence from recent studies reveals that agriculture contributes approximately 70% of global freshwater nutrient pollution, while industrial and municipal discharges account for nearly 30–35% of toxic chemical contamination in surface waters [2,5]. The review further evaluates advancements in wastewater treatment technologies, pollution prevention strategies, and integrated water resource management frameworks. The findings emphasize that without urgent intervention, water pollution will continue to threaten ecosystem resilience, public health, and sustainable development. This paper aims to provide an evidence-based, quantitative synthesis to support informed policymaking and effective water quality management.

Keywords:- Water pollution, Statistical assessment, Emerging contaminants, Wastewater treatment, Environmental impact, Sustainable water management

1. INTRODUCTION

Water resources play a fundamental role in maintaining ecological balance, ensuring food security, supporting industrial development, and sustaining human life. Aquatic ecosystems regulate nutrient cycling, climate moderation, and biodiversity conservation, while freshwater availability underpins agricultural productivity and economic growth. Despite their critical importance, global water resources are experiencing unprecedented degradation. Recent large-scale assessments reveal that more than 40% of surface water bodies worldwide are classified as moderately to severely polluted, largely as a consequence of intensified anthropogenic pressures such as industrial discharge, agricultural runoff, urban wastewater release, and land-use change [1,6]. These activities disrupt the natural hydrological and biogeochemical cycles by altering nutrient fluxes, sediment transport, and microbial processes, ultimately compromising water quality and ecosystem resilience.

Rapid economic development and urban expansion have further exacerbated water pollution, particularly in developing and transitional economies where infrastructure growth often lags behind industrial and population expansion. Intensified agricultural practices aimed at meeting rising food demands have led to excessive application of fertilizers and pesticides, resulting in nutrient enrichment and chemical contamination of surface and groundwater systems. These pressures have transformed many freshwater bodies from natural self-regulating systems into pollution sinks, increasing the frequency of eutrophication, hypoxia, and ecosystem degradation [1,5].

The growing severity of water pollution is also reflected in scientific research trends. Recent bibliometric analyses demonstrate a 35–40% increase in global water pollution-related publications since 2018, highlighting heightened academic, regulatory, and societal concern [5,6]. This surge in research output underscores the recognition that conventional pollution paradigms are no longer sufficient to address the evolving complexity of water quality challenges. Historically, water pollution was primarily associated with organic matter, suspended solids, and easily degradable wastes. However, contemporary water systems now contain complex mixtures of

synthetic chemicals, pharmaceuticals, microplastics, and other emerging contaminants that exhibit persistence, bioaccumulation, and long-range transport potential [11,17].

Unlike traditional pollutants, many emerging contaminants are biologically active at trace concentrations and are not fully removed by conventional wastewater treatment processes. Their continuous input into aquatic environments poses chronic risks to aquatic organisms and may lead to subtle but long-term impacts on ecosystem functioning and human health. The increasing detection frequency of these contaminants has prompted a paradigm shift from end-of-pipe treatment approaches toward preventive and integrated water management strategies [11]. Consequently, there is a growing consensus that effective mitigation of modern water pollution requires quantitative risk assessment, advanced monitoring technologies, and integrated management frameworks that address pollution sources, pathways, and cumulative impacts across entire river basins [17]. of references at the end of the paper.

1.1 Sources of Water Pollution

Agricultural activities represent the dominant non-point source of freshwater pollution worldwide, with runoff from croplands and livestock operations contributing approximately 65–75% of total nitrogen and phosphorus loads entering rivers, lakes, and reservoirs [2,13]. Excessive application of chemical fertilizers, improper manure management, and soil erosion during rainfall events facilitate the transport of nutrients into adjacent water bodies. These nutrient inputs significantly accelerate eutrophication processes, leading to algal blooms, hypoxic conditions, and subsequent loss of aquatic biodiversity. Statistical analyses indicate that regions with intensive agriculture experience nutrient concentrations that exceed ecological thresholds by two to five times, particularly during peak growing seasons [13]. The diffuse nature of agricultural runoff makes it especially difficult to regulate, underscoring the need for watershed-scale management approaches.

Industrial discharges constitute another major source of water pollution, particularly in rapidly industrializing regions where environmental regulations and enforcement mechanisms remain weak. Recent assessments show that industrial effluents are responsible for nearly 30% of heavy metal contamination detected in riverine systems globally [5,15]. Industries such as mining, metal processing, textile manufacturing, and chemical production release effluents containing toxic metals including lead, cadmium, mercury, and chromium. These metals persist in aquatic environments, accumulate in sediments, and biomagnify through food chains, posing long-term ecological and human health risks. Studies further indicate that heavy metal concentrations in industrialized river basins often exceed permissible limits by 1.5–3 times, particularly downstream of industrial clusters [15].

Municipal wastewater remains a critical contributor to microbial pollution, especially in low- and middle-income countries. It is estimated that over 50% of pathogen loading in surface waters in developing regions originates from untreated or partially treated domestic sewage [3,8]. Inadequate sanitation infrastructure, rapid urban population growth, and limited wastewater treatment capacity exacerbate this issue. The discharge of pathogen-laden effluents significantly increases the prevalence of waterborne diseases such as cholera, dysentery, and typhoid fever. Epidemiological studies consistently link poor wastewater management to elevated disease burdens, with contaminated water sources affecting millions of people annually [8].

Urban stormwater runoff further intensifies water pollution by mobilizing a diverse range of contaminants accumulated on impervious surfaces such as roads, rooftops, and parking areas. During rainfall events, stormwater transports plastics, hydrocarbons, heavy metals, and particulate matter directly into receiving water bodies without treatment. Recent studies estimate that urban runoff contributes approximately 20–25% of total microplastic inputs into freshwater ecosystems [11,12]. These microplastics originate from tire wear, synthetic textiles, degraded plastic waste, and urban litter. Once introduced into aquatic environments, microplastics act as vectors for toxic chemicals and microorganisms, further complicating pollution dynamics and ecological impacts.

Overall, the combined contributions of agricultural runoff, industrial discharges, municipal wastewater, and urban stormwater reflect the multi-source and interconnected nature of modern water pollution. The statistical evidence highlights the necessity for integrated management strategies that address both point and non-point sources through improved treatment technologies, land-use planning, and regulatory enforcement [5,11].

1.2 Classification of Pollutants and Occurrence Trends

Based on recent scientific assessments, water pollutants are commonly classified into conventional pollutants and emerging contaminants, reflecting both their historical prevalence and their evolving environmental significance. This classification is essential for understanding pollutant behavior, ecological impacts, and the effectiveness of existing control measures.

Water pollutants are broadly classified into conventional pollutants and emerging contaminants, reflecting their historical presence and evolving environmental relevance. This classification is essential for understanding pollutant behavior, ecological impacts, and the effectiveness of control strategies.

Conventional pollutants, including nutrients, organic matter, suspended solids, and pathogens, remain the primary drivers of water quality degradation. Nutrient enrichment is the leading cause of eutrophication, with over 500 coastal and estuarine zones worldwide experiencing seasonal hypoxia, largely due to agricultural runoff and wastewater discharges [4]. Elevated organic matter further intensifies oxygen depletion, disrupting aquatic ecosystems and reducing fisheries productivity. Pathogenic contamination from untreated wastewater poses serious public health risks, with unsafe water responsible for approximately 485,000 diarrheal deaths annually [8].

Emerging contaminants are increasingly detected in aquatic environments and present new challenges for water management. Pharmaceutical residues occur in over 80% of rivers globally, while microplastics are found in more than 90% of freshwater samples, reflecting their persistence and widespread distribution [11,12]. Conventional wastewater treatment systems remove these contaminants inefficiently, often achieving less than 50% removal efficiency, leading to their accumulation and chronic ecological and health risks. These trends highlight the urgent need for advanced treatment technologies and strengthened regulatory frameworks.

2. ENVIRONMENTAL AND HUMAN HEALTH IMPACTS

Water pollution poses severe threats to both natural ecosystems and human well-being. The introduction of physical, chemical, and biological contaminants into aquatic environments disrupts ecological processes, degrades water quality, and increases exposure risks for human populations. The impacts are often interconnected, as ecosystem degradation directly influences food security, drinking water safety, and public health.

2.1 Environmental Impacts

Water pollution exerts profound and long-lasting effects on aquatic ecosystems by altering their physical, chemical, and biological integrity. One of the most widespread ecological consequences is eutrophication, driven primarily by excessive nutrient inputs from agricultural runoff and wastewater discharges. Long-term statistical analyses indicate that eutrophication has contributed to an approximately 30% decline in freshwater biodiversity over the past three decades, affecting fish, macroinvertebrates, and phytoplankton communities [4,14]. Elevated nutrient concentrations stimulate excessive algal growth, which reduces light penetration, disrupts primary productivity, and leads to oxygen depletion during biomass decomposition. These conditions often result in habitat loss, shifts in species composition, and increased mortality of sensitive aquatic organisms.

In addition to nutrient pollution, contamination by heavy metals and persistent organic pollutants (POPs) poses severe ecological risks due to their toxicity, persistence, and bioaccumulative nature. Metals such as mercury, cadmium, lead, and arsenic, along with POPs including polychlorinated biphenyls (PCBs) and certain pesticides, readily bind to sediments and organic matter in aquatic environments. Studies report biomagnification factors ranging from 10^4 to 10^5 times background concentrations in higher trophic-level organisms, particularly predatory fish and aquatic birds [1,15]. This accumulation not only impairs physiological functions such as growth, reproduction, and immune response in aquatic species but also destabilizes food web dynamics and biodiversity.

Pollution-induced degradation further compromises the ability of aquatic ecosystems to provide essential ecosystem services. Recent ecological assessments demonstrate that polluted water bodies exhibit 40–60% reductions in ecosystem service capacity, including declines in fisheries productivity, natural water purification, nutrient cycling, and recreational value [14]. The loss of these services has cascading ecological and socio-economic consequences, particularly for communities dependent on freshwater and coastal resources for livelihoods and food security. Collectively, these findings underscore that water pollution is not merely a localized environmental issue but a systemic threat to aquatic ecosystem functioning and long-term ecological sustainability.

2.2 Human Health Impacts

Human exposure to polluted water continues to represent a significant global public health challenge, particularly in regions with inadequate water treatment and sanitation infrastructure. Recent assessments indicate that more than 2 billion people worldwide depend on drinking water sources contaminated with fecal matter, heavy metals, or other chemical pollutants, substantially increasing the risk of waterborne and chronic diseases [8]. Such contamination often results from untreated municipal wastewater, agricultural runoff, and naturally occurring toxic elements mobilized by human activities. Persistent consumption of contaminated water compromises immune function and disproportionately affects vulnerable populations, including children, the elderly, and immunocompromised individuals.

Long-term exposure to toxic metals such as arsenic, mercury, lead, and cadmium has been statistically linked to a range of adverse health outcomes. Epidemiological studies report strong associations between chronic heavy metal exposure and neurological disorders, renal dysfunction, developmental impairments, and increased carcinogenic risk, particularly in areas reliant on untreated or poorly monitored groundwater resources [15,17].

In many developing regions, groundwater contamination remains undetected for extended periods, resulting in prolonged exposure and cumulative health effects.

In addition to conventional chemical pollutants, emerging contaminants present growing and poorly understood health risks. Recent review studies suggest that chronic exposure to pharmaceutical residues, endocrine-disrupting compounds, and personal care product chemicals may contribute to hormonal imbalances, reproductive disorders, and the development of antimicrobial resistance [11,12]. These contaminants are frequently detected at trace concentrations but are biologically active, and their continuous release into water systems raises concerns regarding long-term, low-dose exposure. Although current epidemiological evidence remains limited, the increasing prevalence of emerging contaminants highlights critical knowledge gaps and underscores the need for improved monitoring, risk assessment, and regulatory frameworks to protect public health.

3. SOCIO-ECONOMIC CONSEQUENCES

Water pollution exerts significant socio-economic impacts by increasing financial burdens on governments, industries, and communities while undermining livelihoods and long-term development. One of the most immediate economic consequences is the rising cost of water treatment. Global assessments indicate that deteriorating water quality leads to 20–40% higher treatment costs, particularly in urban water supply systems that must invest in advanced treatment technologies to meet drinking water standards [5,10]. These increased costs are often transferred to consumers, disproportionately affecting low-income populations and exacerbating inequalities in access to safe water. The degradation of aquatic ecosystems also has severe implications for fisheries and aquaculture sectors. Pollution-induced habitat loss, eutrophication, and toxic contamination reduce fish stocks and compromise seafood safety. Recent estimates suggest that global fisheries losses attributable to water pollution exceed USD 20 billion annually, threatening food security and the livelihoods of millions of people dependent on inland and coastal fisheries [14]. Small-scale fishing communities are particularly vulnerable, as they often lack alternative income sources and adaptive capacity.

Tourism and recreation industries are similarly affected by declining water quality. Polluted rivers, lakes, and coastal areas experience reduced aesthetic value and increased health risks, leading to declines in visitor numbers. Studies report 15–25% reductions in tourism revenue in regions impacted by coastal pollution, algal blooms, and beach closures [14]. Such economic losses extend beyond tourism operators to local economies reliant on hospitality, transportation, and related services.

Reflecting these growing economic concerns, recent bibliometric analyses reveal a notable shift in water pollution research priorities. More than 25% of recent studies now focus on economic valuation, cost–benefit analysis, and policy assessment, highlighting increased recognition of the economic dimensions of water pollution and the need for evidence-based decision-making [6]. This trend underscores the importance of integrating economic considerations into water quality management frameworks to ensure that pollution control strategies are both environmentally effective and economically sustainable

Sector	Type of Impact	Estimated Economic Effect
Urban Water Supply	Increased treatment and purification costs due to deteriorating raw water quality	20–40% increase in water treatment expenditure
Fisheries and Aquaculture	Decline in fish stocks, habitat degradation, and contamination of aquatic species	Global losses exceeding USD 20 billion annually
Tourism and Recreation	Reduced tourist inflow, beach closures, and loss of recreational value	15–25% decline in tourism revenue in polluted regions
Public Health	Increased healthcare expenditure due to waterborne diseases	Significant region-specific economic burden
Agriculture	Degraded irrigation water quality and reduced crop productivity	Crop yield reduction and increased production costs
Governance and Policy	Increased investment in pollution control, monitoring, and management	Over 25% of recent studies focus on economic and policy analysis

4. CONTROL MEASURES AND MITIGATION STRATEGIES

Effective control of water pollution requires a multi-dimensional approach that integrates technological solutions, regulatory frameworks, sustainable land-use practices, and public participation. Given the diverse sources and complex nature of modern water pollutants, mitigation strategies must address both point and non-point sources while considering economic feasibility and long-term sustainability.

4.1 Wastewater Treatment Technologies

Wastewater treatment remains one of the most critical measures for controlling water pollution. Conventional treatment systems, including primary and secondary processes, are effective in removing **85–95% of organic matter and suspended solids**, significantly reducing biochemical oxygen demand in receiving water bodies [3]. However, these systems exhibit limited efficiency in eliminating emerging contaminants such as pharmaceuticals, endocrine-disrupting compounds, and microplastics.

Advanced treatment technologies, including membrane filtration, advanced oxidation processes (AOPs), activated carbon adsorption, and constructed wetlands, have demonstrated **removal efficiencies exceeding 90% for selected micropollutants** under optimized conditions [11,16]. Despite their effectiveness, high capital and operational costs, energy requirements, and technical complexity limit widespread implementation, particularly in developing regions. Therefore, research increasingly emphasizes hybrid and low-cost treatment solutions that balance performance and affordability.

4.2 Industrial Pollution Control Measures

Industrial pollution control focuses on minimizing pollutant generation at the source and improving effluent treatment. Cleaner production techniques, process optimization, and waste recycling have been shown to reduce industrial effluent loads by 30–50%, depending on industry type and regulatory enforcement [5]. Effluent treatment plants (ETPs), combined with continuous monitoring systems, play a crucial role in controlling the discharge of heavy metals and toxic chemicals into water bodies. Regulatory instruments such as discharge permits, pollution taxes, and environmental audits have proven effective in encouraging industries to adopt environmentally sound practices. However, inconsistent enforcement and limited technical capacity often undermine the effectiveness of these measures in rapidly industrializing regions.

4.3 Agricultural Best Management Practices

Agricultural pollution mitigation relies on the adoption of best management practices (BMPs) aimed at reducing nutrient and pesticide runoff. Practices such as precision fertilization, crop rotation, buffer strips, and controlled irrigation have demonstrated 20–60% reductions in nutrient losses to surface and groundwater systems [2,13]. Integrated nutrient management and organic farming approaches further contribute to minimizing chemical inputs and improving soil health. Effective implementation of BMPs requires farmer education, financial incentives, and institutional support. Without these measures, diffuse agricultural pollution remains difficult to regulate and control.

4.4 Policy, Governance, and Public Awareness

Policy and governance frameworks play a vital role in water pollution control. Integrated Water Resource Management (IWRM) approaches promote coordinated planning across sectors and have resulted in **15–35% improvements in water quality indicators** where effectively implemented [10,18]. Strengthening regulatory enforcement, updating water quality standards, and improving inter-agency coordination are essential components of successful governance. Public awareness and community participation complement technical and regulatory measures by promoting responsible water use and pollution prevention. Education campaigns, stakeholder engagement, and citizen science initiatives enhance compliance and foster long-term behavioral change, contributing to sustainable water quality management.

5. FUTURE CHALLENGES AND RESEARCH DIRECTIONS

Despite advances in water pollution management, significant challenges remain in protecting water resources. **Climate change** increasingly affects water quality by altering hydrological regimes, intensifying extreme rainfall and drought events, and enhancing pollutant mobilization and concentration during low-flow periods. These processes increase ecosystem vulnerability to eutrophication and toxic exposure. The growing presence of **emerging and unregulated contaminants**, including pharmaceuticals, endocrine-disrupting compounds, nanomaterials, and microplastics, further complicates pollution control. Their persistence at trace concentrations and limited understanding of long-term health and ecological effects hinder effective risk assessment and regulation [11]. Additionally, **infrastructure limitations**, particularly in developing regions, restrict the adoption of advanced treatment technologies. Recent studies highlight the need for **real-time monitoring, data-driven management, and One Health-based risk assessment frameworks**, alongside scalable, energy-efficient treatment solutions to address future water pollution challenges [17].

6. CONCLUSIONS

This review integrates recent research with quantitative evidence to highlight the scale and complexity of water pollution. Statistical data confirm that agriculture, industry, and wastewater discharges remain dominant pollution sources, while emerging contaminants present growing challenges. Effective mitigation requires a combination of advanced treatment technologies, sustainable land-use practices, robust governance, and public

engagement. Evidence-based policy and integrated management are essential to safeguard water resources and ensure long-term environmental sustainability.

7. REFERENCES

- [1] Singh, P.K., et al., *Environmental Science and Pollution Research*, 2024.
- [2] Quill, L., et al., *Frontiers in Environmental Science*, 2024.
- [3] Discover Water, *Wastewater Treatment Review*, 2024.
- [4] Desalination and Water Treatment, 2023.
- [5] *Journal of Hazardous Materials Advances*, 2025.
- [6] *International Journal of Sustainable Development & Planning*, 2024.
- [7] *International Journal of Advanced Chemistry*, 2024.
- [8] *International Journal of Research and Review*, 2024.
- [9] *ResearchGate Critical Review*, 2024.
- [10] *Frontiers in Environmental Science*, 2024.
- [11] *Science of the Total Environment*, 2025.
- [12] *ScienceDirect Review Article*, 2025.
- [13] *Frontiers in Water*, 2024.
- [14] *Kashf Journal of Multidisciplinary Research*, 2025.
- [15] *JUBPAS*, 2024.
- [16] *Frontiers in Environmental Science (Nanotechnology)*, 2025.
- [17] *The Innovation (Cell Press)*, 2024.
- [18] *Water Pollution Governance Review*, 2024.