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A REVIEW OF POTENTIAL HUMAN HEALTH AND ECOLOGICAL RISKS ASSOCIATED WITH CONTAMINANTS AND POLLUTANTS IN RIVERS

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Abstract

Environmental pollution has become one of the most pressing challenges threatening aquatic ecosystems and public health globally. This paper focuses on reviewing the potential health and ecological risks occasioned by emerging contaminants and pollutants such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), nutrients, pharmaceuticals, and other pollutants introduced into the river system through industrial, agricultural, and domestic activities. The method used for the study is a review of related academic articles, bulletins, conference papers, textbooks, research reports and publicly available materials on potential human health and ecological risks arising from contaminants and pollutants in rivers across the globe. From the works reviewed, it was revealed that increasing urbanization, industrialization, and inadequate waste management have contributed to the continuous accumulation of both contaminants and pollutants in the river system. These contaminants and pollutants undergo processes such as bioaccumulation and biomagnification, thereby increasing exposure risks to aquatic organisms and humans. Ecologically, the contaminants and pollutants disrupt aquatic ecosystems by reducing biodiversity, promoting eutrophication, and altering food web dynamics. From a human health perspective, exposure through contaminated or polluted water and fish consumption is associated with adverse effects such as cancer, neurological disorders, organ damage, and waterborne diseases. The study concludes that emerging contaminants within the river system present significant ecological and health challenges due to their persistence and complex interactions within environmental matrices. Therefore, it is important to strengthen continuous environmental monitoring across the river system, enforce stricter environmental regulations to control pollutant discharge, and promote sustainable and low-cost remediation approaches such as phytoremediation and natural attenuation. In addition, public awareness and community engagement should be enhanced to reduce pollution inputs and limit human exposure, while further interdisciplinary research is encouraged to support effective management and long-term protection of both human health and the ecosystem.

Keywords: Contaminants and pollutants, Human health and ecological risks, Rivers

1. INTRODUCTION

Unsafe water contributes to the deaths of over 70,000 children under five each year in Nigeria alone (Adeleye, Eze and Okoro, 2021), while the World Health Organization estimates that globally over two billion people consume water contaminated with feces, resulting in approximately 485,000 deaths annually

from diarrheal diseases (WHO, 2019). Water remains an essential natural resource that supports human survival, agricultural productivity, industrial development, and ecological balance across all continents. In many developing countries, access to safe and clean water remains a major challenge due to increasing contamination of surface water bodies (Ezeh, Ezeabasili and Anike, 2021; Sorensen, Lapworth, Nkhuwa and Stuart, 2015).

Major river systems worldwide face escalating contamination from rapid industrialization, agricultural intensification, and inadequate environmental governance. The Ganges in India supports approximately 400 million people but receives an estimated 1.3 billion litres of untreated domestic wastewater and 260 million litres of industrial effluent daily (Sharma and Bhattacharya, 2017). The Yangtze River in China provides water for nearly one-third of China's population and has experienced substantial deterioration in water quality due to industrial discharge, agricultural runoff, and dam construction (Wang and Yuan, 2022). The Mississippi River in the United States contributes an estimated 1.5 million metric tons of nitrogen annually to the Gulf of Mexico, creating a seasonal hypoxic zone (Rabalais, Turner and Scaviab, 2002). In South America, the Amazon basin has experienced significant contamination from artisanal gold mining and petroleum extraction (Limbong, Togot, and Managess, 2003; Arenas-Sanches, Alberto, Rico, David, Rivas-Tabares, Aberto, Blanco, Paloma, Garcia-Doncel, 2019). In Europe, the Rhine and Danube rivers have made measurable recovery from historical pollution but continue to struggle with legacy sediment contamination and emerging contaminants (Tudor, Burton, Joyce, Johnson and Ryan, 2021). Across sub-Saharan Africa, major rivers including the Congo, Niger, and Zambezi face contamination pressures arising from rapid urbanization, industrial development and inadequate waste management infrastructure (K'oreje, Verhaeghe, Langenhove, Demestere, Dewulf, 2019; Miller, Daus, Mohapatra and Subudhi, 2022).

These diverse river systems share common contamination pressures. The Pearl River Delta in China receives substantial inputs of heavy metals, PAHs, and pharmaceutical residues from manufacturing activities (Luo, Su, Craig, Du, Wu and Shi, 2021). In South Asia, rapid agricultural intensification has driven nutrient loading to critical levels in the Ganges, Indus, and Brahmaputra river systems (Sharma and Bhattacharya, 2017). In sub-Saharan Africa, urbanization and industrial expansion have outpaced the development of wastewater treatment and environmental monitoring capacity (Nnaji and Ekwe, 2017). These inputs contribute to the presence of emerging contaminants including pharmaceuticals, endocrine-disrupting compounds, heavy metals, and polycyclic aromatic hydrocarbons which interact with environmental compartments such as water, sediment, and aquatic organisms (Zhang, Liu, and Wang, 2011).

From a global perspective, emerging contaminants have been detected in river systems across all inhabited continents. Pharmaceuticals and personal care products have been found in surface waters across Europe and North America at concentrations ranging from nanograms to micrograms per litre (Hughes, Kolpin and Barnable, 2013; Kase and Paxeus, 2011), while microplastics have been identified in rivers from the Arctic to the Antarctic (Dris, 2015; Klein, Worch and Kracke, 2015). Sediments in aquatic systems often act as long-term sinks for persistent pollutants, storing contaminants that may later be released under changing environmental conditions. This sediment-mediated contaminant release has been documented in the River Thames (Vane, Harrison and Kim, 2011), the Hudson River (Nieder, Connelly and MacDonald, 2017), the Elbe River (Schwarzenbach, Escher, Fenner, Hofstetter, Johnson, von Gunten and Wehrli, 2016), the Hai River in China (Wang, Chen, Qiao, Yang, and Tian, 2015), and the Zambezi in southern Africa (Miller, Daus, Mohapatra and Subudhi, 2022).

Contaminants of emerging concerns (CECs) represent a growing environmental challenge globally. Despite limited data from developing regions, studies indicate that CEC contamination in Africa and Asia is comparable to that observed in Western regions, with certain compounds such as antimalarial and

antiretroviral drugs occurring at even higher concentrations in some locations (Sorensen, Lapworth, Nkhuwa, Stuart, Gooddy, Bell, Chirwa, Kabika, Liemisa, Chibesa and Pedley, 2015; Abafe, Martini and Sinyka 2018). In European and North American river systems, CECs such as synthetic hormones, antidepressants, antibiotics, and non-steroidal anti-inflammatory drugs have been widely detected (Hughes, Kay and Brown, 2013; Kase, Korkaric, Werner and Eggen, 2011), with documented effects on aquatic organisms including feminization of male fish and disruption of invertebrate communities (Kidd, Blanchfield, Mills and Palace, 2007; Richmond, Wood, Nunes, 2017).

Research on river pollution has largely focused on conventional indicators such as physicochemical properties, microbial contamination, and heavy metal concentrations, while far less attention has been paid to emerging contaminants such as pharmaceuticals, microplastics, and endocrine-disrupting chemicals that are now recognized as significant threats to both ecological integrity and human health (Nnaji and Ekwe, 2017). This research gap mirrors a broader pattern across much of the developing world, where environmental monitoring capacity remains limited (K'oreje, Okoth, Van Langenhove and Demeestere, 2019; Abafe, Spath, Fick, Jansson, Buckley, Stark and Martincigh, 2018). Given the critical importance of rivers as sources of water, food, and livelihood for billions of people globally, there is an urgent need to evaluate the potential human health and ecological risks associated with emerging contaminants in river systems worldwide. This review addresses that need by synthesizing available literature on emerging contaminants across diverse river systems, examining their sources, distribution within environmental matrices, and implications for ecosystem health and human well-being from a genuinely global perspective.

1.1 Statement of the Problem

Research on river water quality has historically focused on conventional parameters while emerging contaminants remain systematically under-studied, particularly in developing regions. A comprehensive review by K'oreje et al. (2019) found that emerging contaminants remain under-documented across sub-Saharan Africa, with fewer than fifty peer-reviewed publications on pharmaceutical contamination in African surface waters as of 2018, compared to thousands in Europe and North America. This disparity reflects broader structural challenges including limited analytical laboratory capacity, inadequate research funding, and weak institutional frameworks.

Globally, similar threats confront major river systems that serve as primary water sources for densely populated regions. The Ganges supports approximately 400 million people but receives largely untreated wastewater. The Yangtze provides water for nearly one-third of China's population. The Mekong supports food security for over 70 million people in Southeast Asia. The Mississippi drains 40% of the continental United States. The Amazon basin spans nine countries and supports the world's largest tropical rainforest. Each of these systems faces distinct but interconnected contamination challenges that require coordinated global responses (Sharma and Bhattacharya, 2017; Wang et al., 2022; Luo et al., 2021; Rabalais, Turner and Wiseman 2002).

Sediments in aquatic systems act as sinks for persistent pollutants, storing contaminants that may later be released under changing environmental conditions. This sediment-mediated release has driven fish consumption advisories in the Great Lakes decades after initial emissions were curtailed (Sadraddini, Nazemi, Basirian, Jahromi and Shimizu, 2011) and remains a transboundary management challenge in the Danube basin (Tudor, Blicharska, Slobodnik, Betlej, Celic, Glinska-Lewczuk, Grecu, Gutowski, Jusik, Kokot, 2021). Understanding the global patterns of sediment contamination and their implications for long-term water quality is essential for designing effective management interventions across diverse geographic and economic contexts.

2. CONCEPTUAL FRAMEWORK

The conceptual framework of this study draws on the Source-Pathway-Receptor (SPR) model, widely applied in environmental risk assessment across diverse geographic contexts (Hughes, Kay, and Brown, 2013 and the DPSIR, Drivers-Pressures-State-Impacts-Responses Framework developed by the European Environment Agency for integrated environmental assessment (Smeets and Weterings, 1999). The combined application of these frameworks enables a structured analysis that connects pollutant sources to ecological and health outcomes through identifiable environmental pathways, while also accounting for the socio-economic drivers and policy responses that shape contamination patterns.

The framework highlights the influence of physicochemical parameters such as pH, temperature, dissolved oxygen, and organic matter on contaminant behaviour, mobility, and bioavailability. It demonstrates processes of bioaccumulation and biomagnification within the biotic matrix and their consequences for human health through water consumption and seafood intake. The framework also incorporates anthropogenic drivers including population growth, urbanization, industrial development, agricultural intensification, and climate variability as upstream factors that increase contaminant pressures on river systems.

The framework integrates a feedback loop representing policy responses and management interventions, acknowledging that human actions can modify the drivers and pressures that generate contamination. This feedback element draws on experiences from multiple jurisdictions, including the European Union's Water Framework Directive, which has driven substantial improvements in river water quality across member states (European Commission, 2021), and China's River Chief System, which has achieved notable reductions in surface water pollution through localized accountability mechanisms (Liu, Zhang, Han, Liu, Wen and Wu, 2021). Understanding these intervention pathways is essential for translating the findings of this review into actionable management recommendations applicable across diverse river systems and governance contexts.

3. METHOD

This study adopted a review-based research approach using secondary data from academic journal articles, conference papers, textbooks, institutional reports, and relevant online publications. The review methodology followed the systematic approach recommended by Khan, Kunz, Kleijnen, and Antes (2003) for scoping reviews in environmental health, incorporating explicit search strategies, selection criteria, and synthesis procedures. This approach has been widely adopted in comparable global reviews of emerging contaminants in aquatic systems, including the comprehensive reviews by K'oreje et al. (2019) for Africa, Miller et al. (2022) for Asia, and Hughes et al. (2013) for Europe.

A total of forty-two scholarly and institutional materials spanning multiple geographic regions were systematically reviewed. The reviewed literature included peer-reviewed studies from Nigeria and other African countries, studies from China, India, and Southeast Asia, research from European river systems, and investigations from North and South America. This multi-regional scope was intentionally adopted to facilitate comparative analysis and to develop a genuinely global understanding of river contamination patterns. Studies were selected based on their relevance to emerging contaminants in river systems, their methodological rigour, their publication in peer-reviewed journals or by recognized international organizations, and their availability in English.

The reviewed literature was analysed to identify major sources of contaminants, their movement within environmental matrices, and effects on aquatic ecosystems and human health. Risk assessment frameworks

applied in the reviewed studies, including the potential ecological risk index (PERI) developed by Hakanson (1980) and the hazard quotient (HQ) approach for human health risk assessment (US EPA, 2000), provided standardized metrics for comparing risk levels across different river systems and geographic regions.

4. EMERGING CONTAMINANTS IN RIVER SYSTEMS

Emerging contaminants in river systems are pollutants increasingly detected due to intensified human activities and improved analytical techniques. These contaminants originate from agricultural runoff, industrial discharge, urban waste, and atmospheric deposition, and interact with environmental matrices in complex ways. The concept has evolved from initial focus on pharmaceuticals in European waters (Daughton and Ternes, 1999) to encompass microplastics, nanomaterials, and endocrine-disrupting compounds detected worldwide (Geissen, Mol, Klumpp, Umlauf, Nadal, van der Ploeg, van de Zee, and Ritsema, 2015). These contaminants are as follows:

i. Nutrient Pollutants

Nitrate and phosphate are among the most significant nutrient pollutants globally, introduced through agricultural runoff, sewage discharge, and fertilizer use. Eutrophication remains one of the most widespread water quality problems, costing billions of dollars annually (Dodds, Bouska, Eitzmann, Pilger, Pitts, Riley, Schloesser and Thornbrugh, 2009). The Mississippi River basin contributes an estimated 1.5 million metric tons of nitrogen annually to the Gulf of Mexico, creating a seasonal hypoxic zone (Rabalais, Turner and Wiseman, 2002). In the Danube basin, agricultural nutrient inputs drive eutrophication in the Black Sea coastal zone (Ludwig, Bouwman, Dumont and Lespinas, 2009). In the Mekong basin, nutrient loading from agricultural intensification alters primary productivity and fish populations (Luo et al., 2021). In the River Niger basin, farmlands contribute nitrate and phosphate through fertilizer runoff (Ekpe, Salubi and Ohwoghre-Asuma, 2023). Excessive nitrate poses direct health risks including methemoglobinemia in infants, with the WHO (2017) Guidelines of 50 mg/L exceeded in agricultural regions worldwide (Ward, Jones, Brender, de Kok, Weyer, Nolan, Villanueva and van Breda, 2018).

ii. Heavy Metals

Heavy metals including lead, cadmium, chromium, nickel, and zinc are persistent contaminants introduced through industrial effluents, mining, and atmospheric deposition (Tchounwou, Yedjou, Patlolla, and Sutton, 2012). In China's Pearl River Delta, sediment cadmium exceeds background levels by 10 to 100 times, with documented bioaccumulation in fish (Luo et al., 2021). In India's Ganges River, sediment concentrations of cadmium, chromium, and lead exceed WHO (2019) Guidelines. The global distribution of river heavy metal contamination is shifting from industrialized to industrializing regions as production activities relocate and expand near industrial centres (Sharma and Bhattacharya, 2017). In the Amazon basin of Ecuador, petroleum extraction has elevated cadmium, lead, and barium in river sediments, affecting indigenous communities (Arenas-Sanchez, Rico and Vighi, 2019). In Europe's Rhine River, heavy metal contamination has declined since the 1980s due to emission controls, though legacy sediment contamination persists (Schwarzenbach et al., 2016). In the Caspian Sea region and Persian Gulf, oil and gas development contributes to mercury and lead contamination (de Mora and Stewart, 2018).

iii. Organic Pollutants

Organic pollutants assessed using BOD and COD indicators reduce dissolved oxygen, stressing aquatic organisms and creating hypoxic conditions (Chukwuma, Eze and Uka, 2020). An estimated 80% of wastewater globally is discharged without adequate treatment, reaching 90% in some developing countries (Sato, Qadir, Yamamoto, Endo and Zahoor, 2013). In the Ganges basin, about 20% of 12,000 million litres per day receives treatment (CPCB, 2013). In the United States, 850 billion gallons of untreated sewage

discharge annually through combined sewer overflows (US EPA, 2004). In the United Kingdom, discharge of untreated sewage has become a prominent environmental policy issue (Environment Agency, 2021).

iv. Microplastics

Microplastics have emerged as contaminants of particular concern due to their persistence, ubiquity, and potential for ingestion by aquatic organisms (Dris, Imhof, Sanchez, Gasperi Galgani Tassin and Laforsch, 2015). Studies of European rivers including the Rhine, Danube, and Thames have documented concentrations of hundreds to thousands of particles per cubic metre (Mani, Hauk, Walterand Burkhardt-Holm, 2015; Klein, Worch and Knepper, 2015). In Asian rivers including the Yangtze and Ganges, microplastic pollution is widespread with documented ingestion by fish consumed by human populations (Eriksen, Lebreton, Carson, Thiel, Moore, Borerro, Galgani, Ryan and Reisser, 2013; Lebreton, van der Zwet, Damsteeg, Slat, Andrady and Reisser, 2017). The authors estimated that rivers transport 1.15 to 2.41 million tonnes of plastic to oceans annually, with the top twenty polluting rivers predominantly in Asia. While microplastic contamination of African rivers remains less documented, preliminary studies suggest significant inputs from urban runoff and inadequate waste management (Naidoo and Olaniran, 2014).

v. Microbial Contaminants

Microbial contaminants enter river systems through sewage discharge, agricultural runoff, and improper waste disposal. In South Asia, an estimated 600 million people practice open defecation, contributing to heavy faecal contamination of the Ganges, Indus, and Brahmaputra (UNICEF/WHO, 2019). In sub-Saharan Africa, only 30% of the population uses safely managed sanitation services (UNICEF/WHO, 2021). In the United States, outbreaks of waterborne disease from recreational river contact have been documented across multiple states (Craun, Brunkard, Yoder, Roberts, Carpenter, Wade, Calderon, Roberts, Beach and Roy, 2010; Sadraddini, Nazemi, Basirian, Jahromi and Shimizu, 2011). In Europe, the Water Framework Directive requires member states to achieve good ecological status, although implementation varies (European Commission, 2021).

vi. Polycyclic Aromatic Hydrocarbons

PAHs are persistent, toxic, and carcinogenic organic contaminants entering river systems through oil spills, gas flaring, industrial emissions, and atmospheric deposition (WHO, 2017; Lamichhane, Bal, Krishna and Sarukkalghe, 2016). In the Yangtze River estuary, total PAH concentrations range from hundreds to thousands of nanograms per gram near industrial zones (Wang et al., 2022). In the Seine basin, benzo(a)pyrene levels exceed ecological quality standards at multiple sites (Motelay-Massei, Ollivon, Garban and Chevreuil, 2004). In the Great Lakes, historical PAH contamination continues to influence fish consumption advisories (Sadraddini et al., 2011). In the Amazon basin, oil extraction activities have contaminated rivers with documented health impacts on indigenous populations (Arenas-Sanchez, Rico and Vighi, 2019). In West Africa's Niger Delta, gas flaring and oil spills release PAHs into the atmosphere and aquatic systems (Ana, Sridhar, and Emerole, 2012). The carcinogenic potency of benzo(a)pyrene has been established through epidemiological and laboratory studies (IARC, 2010).

5. ENVIRONMENTAL MATRIX

The environmental matrix of river systems comprises the water column, sediments, and biotic components that interact to influence contaminant behaviour, fate, and effects. Understanding how contaminants move within and between these matrices is essential for assessing ecological risks and designing effective monitoring and remediation strategies. The matrices are discussed as follows:

a. Water Matrix

The water matrix serves as the primary medium for contaminant transport. In tropical river systems, seasonal hydrological variations strongly influence water matrix characteristics: during wet seasons, increased runoff mobilizes contaminants from agricultural lands and dumpsites; during dry seasons, reduced flow concentrates contaminants while elevated temperatures increase microbial activity and chemical transformation rates (Amareo, 2005; Ekpe et al., 2023). In temperate European rivers, seasonal variation is less pronounced but storm events create episodic pollutant pulses from urban runoff (Motelay-Massei et al., 2004). In monsoon-influenced Asian rivers, the seasonal pattern is extreme, with the majority of annual contaminant transport occurring during brief intense wet periods (Sharma and Bhattacharya, 2017; Miller et al., 2022).

b. Sediment Matrix

Sediments function as both sinks and secondary sources of contaminants. In the Thames estuary, sediment cores reveal industrial pollution dating to the Victorian era (Vane, Harrison, and Kim, 2007). In the Rhine, sediment contamination by mercury and cadmium remains a concern despite emission reductions (Schwarzenbach et al., 2016). In the Hai River of China, historical industrial contamination has created sediment hotspots that continue to influence water quality (Wang et al., 2015). In the Zambezi basin of southern Africa, mining-related sediment contamination affects transboundary water quality (Miller et al., 2022). In all systems, flood events mobilize sediment-bound contaminants, depositing them on floodplains where they may affect agricultural soils and groundwater quality.

c. Biotic Matrix

The biotic matrix includes fish, plankton, and other aquatic organisms that interact with contaminants through bioaccumulation and biomagnification. In the Great Lakes, biomagnification of PCBs and mercury through the food web has driven decades of fish consumption advisories (Craun et al., 2011). In the Mekong River, bioaccumulation of pesticides and heavy metals in fish has been linked to kidney dysfunction and neurological effects in consuming populations (Luo et al. 2021). In the Ganges basin, heavy metals bioaccumulate in commercially important fish species, creating exposure risks for the 400 million people who depend on the river (Sharma and Bhattacharya, 2017). In the Amazon, mercury bioaccumulation from artisanal gold mining has been linked to neurological effects in indigenous communities (Limbong et al., 2003). The biotic matrix also plays an active role in contaminant transformation, providing a basis for phytoremediation approaches applied in constructed wetland systems worldwide (K'oreje et al., 2019).

d. Physicochemical Control Matrix

The physicochemical matrix regulates contaminant behaviour through parameters such as temperature, pH, turbidity, conductivity, and dissolved oxygen. In Scandinavia and eastern North America, lowered pH from acid rain increased aluminium toxicity and mobilized heavy metals (Driscoll, Lawrence, Bulger, Butler, Cronan, Eagar, Lambert, Likens, Stoddard, and Weathers, 2001). In South Asia's turbid rivers, high suspended sediment loads adsorb organic pollutants, influencing transport and bioavailability (Sharma and Bhattacharya, 2017). In tropical Africa and Southeast Asia, elevated temperatures accelerate microbial degradation while increasing chemical transformation rates (Nnaji and Ekwe, 2017). Effective monitoring and risk assessment must account for these controlling parameters.

6. GLOBAL COMPARATIVE PERSPECTIVES

A comparative analysis of river contamination across continents reveals both common patterns and significant regional variations. In Europe, the Water Framework Directive has driven measurable improvements in river water quality, although diffuse agricultural pollution and legacy sediment contamination persist (European Commission, 2021). In North America, the Clean Water Act achieved

substantial point source reductions, though non-point sources and emerging contaminants remain challenges (Kolpin, Furlong, Meyer, Thurman, Zaugg, Barber and Buxton, 2002). In Asia, rapid industrial and agricultural growth has placed enormous pressure on rivers, but China's River Chief System has achieved notable reductions in surface water pollution through localized accountability mechanisms (Liu, Zhang, Han, Liu, and Wu, 2021). In Latin America, the Amazon basin has experienced contamination from artisanal gold mining and petroleum extraction, affecting both wildlife and indigenous communities (Limbong et al., 2003; Arenas-Sanchez et al., 2019). In Africa, research capacity remains limited but available evidence suggests significant contamination comparable to other developing regions (K'oreje et al., 2019).

The reviewed literature indicates an urgent need for systematic monitoring and pollution control across all regions examined. Physicochemical parameters such as pH generally ranged within 6.3 to 8.4, often within WHO limits. However, dissolved oxygen frequently fell below healthy levels near organic pollutant sources. Conductivity and turbidity indicated elevated dissolved solids and suspended particles across diverse river et al., systems. Heavy metals were frequently detected exceeding permissible limits, with cadmium and lead identified as priority risk drivers across Nigeria (Ekpe et al., 2023), China (Wang et al., 2015; Luo 2021), India (Sharma and Bhattacharya, 2017), and Europe (Schwarzenbach et al., 2016). PAHs and organic pollutants were found to accumulate more in sediments than in water, posing long-term ecological risks.

Surface water pollution is driven by anthropogenic activities converging across studies from different continents. Industrialized regions have made progress in controlling point source pollution while continuing to struggle with diffuse agricultural pollution and emerging contaminants. Developing regions face challenges from all pollution sources simultaneously, often without adequate institutional and financial capacity. These experiences demonstrate that river pollution is a planetary challenge requiring coordinated responses at multiple scales.

7. ECOLOGICAL AND HUMAN HEALTH RISK ASSESSMENT

Pharmaceuticals have been detected across all continents. In Europe, concentrations of ibuprofen, diclofenac, and carbamazepine reach levels sufficient to cause sub-lethal effects on aquatic organisms (Hughes et al., 2013). In North America, hormones from contraceptive use have feminized male fish at environmentally relevant concentrations (Kidd et al., 2007). In Africa, Sorensen et al. (2015) detected multiple pharmaceuticals in surface water across sub-Saharan Africa at concentrations comparable to European rivers. Abafe et al. (2018) documented particular concern regarding antiretroviral drugs. Microplastic contamination is similarly global: Mani et al. (2015) and Klein et al. (2015) documented concentrations of hundreds to thousands of particles per cubic metre in European rivers, while Lebreton et al. (2017) identified Asian rivers as dominant sources of ocean plastic pollution.

Ecological risk assessments using PERI have identified cadmium and lead as priority risk drivers across Nigeria (Ekpe et al., 2023), China (Wang et al., 2015; Luo et al., 2021), and India (Sharma and Bhattacharya, 2017). In Europe, legacy sediment contamination poses risks in historically industrialized reaches (Schwarzenbach et al., 2016). Human health risk assessments have identified non-carcinogenic risks exceeding acceptable levels for children and subsistence fishing communities. In the Ganges, hazard quotients for heavy metal exposure through fish consumption frequently exceeded unity (Sharma and Bhattacharya, 2017). In the Amazon, mercury exposure has been linked to neurological effects in indigenous communities (Limbong et al., 2003). In the Pearl River Delta, cancer risk estimates associated with PAH and heavy metal exposure exceeded acceptable levels (Luo et al., 2021). These findings

demonstrate that health risks disproportionately affect vulnerable populations globally, including the poor, women, children, and subsistence-dependent communities.

8. RECOMMENDATIONS

Based on the reviewed literature, the following recommendations are proposed, drawing on successful interventions across multiple continents.

Strengthening waste management and pollution control infrastructure by countries across the globe is very important as being done in China and Europe. Nigeria and other developing countries should prioritize similar investments, supported by international development assistance.

Implementation of continuous environmental monitoring programmes by all nations is highly needed. To this end, the Regional cooperation models, such as the Danube monitoring programme coordinating assessment across fourteen countries should be replicated in other regions, including West Africa through ECOWAS and in Southeast Asia through the Mekong River Commission.

Enforcement of national environmental laws and regulations plus international conventions on water quality management stands out clearly as a panacea for abating the high rate of pollution of rivers worldwide. Countries should fully implement commitments under the Basel Convention, Stockholm Convention, and Convention on Biological Diversity. Regional frameworks should develop shared water quality standards for transboundary river basins. Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA) Act provides a legislative foundation, but enforcement remains weak due to limited capacity and requires strengthening.

Promotion of research on emerging contaminants and innovative remediation is another strategy for managing the river water system. South-south research collaboration between institutions in Africa, Asia, and Latin America could accelerate capacity development in this direction. Investment in analytical instrumentation and researcher training is essential to close the monitoring gap between developed and developing regions.

Enhancement of public awareness, community engagement, and access to safe water should be explored. Access to safe water is a fundamental human right, and progress toward Sustainable Development Goal 6 requires substantial expansion of safe water supply infrastructure. Where centralized treatment is not feasible, point-of-use technologies including ceramic filters, chlorination, and solar disinfection can provide interim protection against microbial and some chemical contaminants. Community engagement in river protection has proven effective across diverse contexts, from citizen science programmes in the United Kingdom to community-based watershed management in the Philippines. This ought to be replicated in all countries of the world.

9. CONCLUSION

The reviewed studies demonstrate that surface water pollution is a major environmental problem affecting river systems across the globe. Industrial discharge, urbanization, agriculture, mining, and oil exploration introduce heavy metals, PAHs, pharmaceutical residues, microplastics, and other contaminants into rivers, leading to water quality degradation, biodiversity loss, and increased health risks. In developing countries across Africa, Asia, and Latin America, rapid economic growth has outpaced the development of environmental governance capacity, producing escalating contamination in major river systems. In industrialized countries, progress in controlling point source pollution has been substantial, but challenges from diffuse agricultural pollution, legacy sediment contamination, and emerging contaminants persist.

The persistence of contaminants in river sediments, their bioaccumulation in aquatic organisms, and biomagnification through food webs create exposure pathways linking environmental contamination to cancer, neurological disorders, organ damage, and waterborne diseases. Children, pregnant women, subsistence fishing communities, and the poor face disproportionate risks globally. The comparative evidence reviewed demonstrates that meaningful improvements in river water quality are achievable when political will, institutional capacity, and financial resources are aligned, as evidenced by the European Water Framework Directive, the US Clean Water Act, and China's River Chief System.

Addressing this global challenge requires a multifaceted approach: strengthening monitoring, improving regulation and enforcement, investing in waste management infrastructure, promoting innovative remediation technologies, enhancing public awareness, and fostering international cooperation in research and technology transfer. Countries facing acute river pollution challenges should draw on the global experience documented in this review to accelerate progress toward clean and healthy river ecosystems that sustain both ecological integrity and human well-being for present and future generations.

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