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River Water Pollution Management Strategy in Indonesia: Scientometric Analysis of Published Literature (2000-2024)

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ABSTRACT

In Indonesia, river water pollution is a major environmental issue, with contamination from industrial waste, sewage, agricultural runoff, and other sources degrading water quality and harming aquatic ecosystems. To examine the identification, detection, and mitigation technologies employed for marine pollution in Indonesia, a chronological review and analysis were conducted using a systematic search of 90,893 peer-reviewed Scopus indexed journal articles on the SCOPUS database. From 2015 to 2024, research on river water pollution management strategy encompassed a wide range of topics, including water pollution control, industrial area, pollution control strategy and policy. Result of the survey shows that effective management strategies are needed to prevent and control river water pollution. Specific management strategies must be tailored to each river based on the types and sources of pollution. An integrated approach, combining infrastructure upgrades, land use management, regulations and enforcement in addition to public outreach, is needed. With concerted efforts to control pollution and restore degraded rivers, water quality can be improved to support healthy rivers and communities.

INTRODUCTION

Rivers near industrial areas are particularly vulnerable to water pollution due to the discharge of industrial effluents containing toxic chemicals, heavy metals, and other harmful substances. Uncontrolled industrial pollution can severely degrade water quality, destroy aquatic ecosystems, and pose serious health risks to communities that rely on rivers for their water supply **(Tariq & Mushtaq, 2023)**. Effective management strategies are crucial to prevent, control, and mitigate the impacts of industrial pollution on river systems **(Kolalowe & Iyiola, 2023)**. A multi-faceted approach combining technological solutions, regulatory measures, and collaborative efforts is needed to tackle industrial river pollution.

The first line of defense is to reduce pollution at the source by promoting cleaner production processes, implementing green chemistry principles, and adopting best management practices in industrial facilities. This includes optimizing resource use, minimizing waste generation, and substituting hazardous substances with safer alternatives **(Hegab *et al.*, 2023)**. Robust wastewater treatment is essential before discharging industrial effluents into rivers. Advanced treatment technologies such as membrane filtration, activated carbon adsorption, chemical oxidation, and biological processes can effectively remove pollutants and improve effluent quality **(Thakur *et al.*, 2023)**. Zero liquid discharge systems that recycle and reuse wastewater can eliminate the need for discharge altogether. Regular monitoring of effluent quality and receiving water bodies is necessary to ensure compliance with discharge standards and to detect any adverse impacts **(Neye-Akogo *et al.*, 2023)**.

Strengthening regulatory frameworks and enforcement mechanisms is crucial for controlling industrial pollution. Governments need to establish stringent water quality standards, mandate effluent treatment, and impose penalties for non-compliance **(Saravanan, 2024)**. Market-based instruments such as pollution taxes, tradable permits, and performance bonds can create economic incentives for industries to reduce their pollution footprint **(Hassan *et al.*, 2024)**. Environmental impact assessments should be required for new industrial projects to prevent potential harm to river systems **(Bošnjaković, 2023)**.

Engaging industries, local communities, and other stakeholders is key to successful river pollution management. Collaborative platforms can facilitate dialogue, information sharing, and joint problem-solving. Industries can partner with research institutions to develop innovative pollution prevention and control technologies **(Zhou *et al.*, 2023)**. Community-based monitoring programs can help track water quality and report pollution incidents. Public awareness campaigns can educate communities about the importance of protecting rivers and promote responsible environmental behaviors.

Restoring degraded rivers is an important component of pollution management **(Chawla *et al.*, 2024)**. Ecological restoration techniques such as riverbank stabilization, riparian buffer zones, constructed wetlands, and in-stream habitat enhancements can help rehabilitate damaged ecosystems and improve water quality. Phytoremediation using aquatic plants to absorb and accumulate pollutants is a promising nature-based solution. Integrating green infrastructure and nature-based solutions into industrial landscapes can mitigate pollution impacts and enhance ecosystem services **(Štrbac *et al.*, 2023)**.

Scientometric analysis provides a quantitative approach to assess research trends, key topics, influential publications, and knowledge gaps in a scientific field **(Hemaprasanth *et al.*, 2024)**. This article presents a scientometric review of the published literature on river water pollution management strategies to map the current state of research and identify future directions. The analysis reveals a steady increase in research publications on river water pollution management over the past few decades, reflecting growing attention to this critical issue. Key research themes include:

- Wastewater treatment technologies to remove pollutants before discharge into rivers,
- Pollution prevention at the source, such as cleaner industrial production, improved agricultural practices, and urban stormwater management,
- Ecological restoration of rivers and riparian zones to enhance natural purification processes,
- Policies, regulations, and economic instruments to control pollution and incentivize sustainable practices,
- Water quality monitoring and modeling to assess pollution levels and inform management decisions.

Geographically, research on river pollution management is concentrated in countries facing severe water quality challenges. International collaboration networks are also evident, highlighting the need for knowledge sharing and coordinated efforts to address transboundary river pollution issues **(Varady *et al.*, 2023)**.

River pollution in Indonesia is a serious problem that threatens environmental and public health, with around 59% of the country's rivers being polluted, mainly by industrial waste and domestic waste. The Citarum River, known as one of the most polluted rivers in the world, is a clear example of the damaging effects of this pollution. To overcome this problem, the Indonesian government has taken several important steps. First, through Presidential Regulation No. 15 of 2018, the government launched the *Citarum Harum* Program, which aims to restore the condition of the Citarum River by involving various ministries and institutions in controlling pollution. Second, the government issued a decree regarding Pollution Load Carrying Capacity (DTBP) for seven main rivers, which helps design strategies for reducing pollution loads. Third, community education and empowerment efforts are also carried out to increase awareness of the importance of keeping rivers clean and enforcing laws against environmental violations.

However, the literature indicates that gaps and challenges remain. Many developing countries lack wastewater treatment infrastructure and enforcement of pollution regulations. Non-point sources of pollution originating from agriculture and urban runoff are still difficult to control. More research is needed on the long-term effectiveness and sustainability of various management strategies, as well as social, economic, and institutional dimensions.

This scientometric analysis aims to provide an overview of the research landscape regarding river water pollution management strategies, specifically in Indonesia. A growing body of literature underscores the importance and complexity of this issue while highlighting opportunities for further research and action to protect and restore the world's rivers. An integrated approach combining technological solutions, sustainable land management, strong policies, and community participation is recommended to address this pressing environmental challenge. The aim of the study was to analyze research trends in river pollution as a first step in determining management strategies.

MATERIALS AND METHODS

Bibliometric analysis

The purpose of this systematic review was to examine chronological trends and strategies for controlling river pollution. To this end, the authors utilized the Scopus database to collect citation information and author keywords of articles that discussed marine and river pollution. Although other indexing databases such as Web of Science and Dimensions are available, the authors chose Scopus because it provides extensive coverage of journal articles and enforces a more rigorous regulatory policy compared to Dimensions. The paper analyzed focuses on research conducted in the Indonesian region.

For the search process, the authors employed a set of keywords including "river," "pollution," "industries," "environment," "water quality," and "water management pollution policy" to scan article titles, abstracts, and keywords for initial screening. The search yielded a total of 2,904 peer-reviewed Scopus-indexed journal articles published up to the year 2024, which were subsequently analyzed. To refine the results, the built-in Scopus filters were applied to exclude documents that were not journal articles or were written in languages other than English. On this basis, the authors present a comprehensive analysis of the trends and technological advancements in river pollution research, drawing from a large set of high-quality peer-reviewed articles. The bibliometric analysis method used in this study has been widely applied in previous research to conduct comprehensive analyses aimed at identifying developments, current status, and gaps in knowledge **(He *et al.*, 2023)**.

Preparation and analysis of keyword network diagrams

The study involved extracting bibliographical information and author keywords from journal articles using the Scopus database. When the number of journal articles for a given year exceeded 2,015, a relevance-based sorting method was employed due to Scopus's restriction on user access to search records beyond the first 2,015 **(Elsevier, 2024)**. To analyze research trends and technological developments from 2015 to 2024, the bibliographic dataset obtained from Scopus was used to generate keyword network diagrams with VOSviewer software. This versatile software, which incorporates bibliometric keyword analysis, has been employed in multiple studies **(He *et al.*, 2023)**. Specifically, VOSviewer was used to create diagrams based on the 100 most frequently occurring keywords in each decade.

RESULTS AND DISCUSSION

The visualization of the research keyword network generated through bibliometric analysis using VOSviewer is shown in Fig. (1). Each node represents a keyword, with the node size indicating its frequency of occurrence in the literature. Relationships between keywords are illustrated by connecting lines, which reflect their relevance and co-citation levels. Color clusters highlight thematic groupings, where each color represents interconnected research areas with distinct focal points. This visualization provides a comprehensive overview of research trends, dominant themes, and interconnections between topics, offering a scientific summary of the field.

The red cluster illustrates several relationships, notably between climate change and phytoremediation. Climate change, driven by human activities such as greenhouse gas emissions, has increased the frequency and intensity of extreme weather events, including droughts and floods. These changes negatively impact soil health and water quality, while also increasing heavy metal contamination in the environment. Consequently, plants used in phytoremediation may experience reduced efficiency in absorbing contaminants due to abiotic stress caused by climate change.

Phytoremediation is a technique that leverages the ability of plants to remove, stabilize, or decontaminate soil and water polluted with contaminants, including heavy metals. Plants achieve this through several mechanisms: phytoextraction (absorption of metals into plant tissue), phytostabilization (reducing contaminant bioavailability), and phytodegradation (transforming pollutants into less harmful forms). However, climate change can impair plant growth and limit their ability to absorb heavy metals. For instance, more frequent droughts can reduce plant biomass, thereby decreasing phytoremediation capacity.

To address this challenge, research is exploring the development of plant varieties with greater resistance to environmental stressors such as drought and salinity. Mangroves are particularly effective in phytoremediation, especially in coastal ecosystems. Their ability to thrive in saline conditions and absorb heavy metals from sediments makes them valuable natural “green barriers.” Beyond reducing the spread of contaminants, mangroves also contribute to biodiversity conservation.

Conservation of mangroves and other ecosystems is therefore essential to preserving their ecological functions, including their role in phytoremediation. Sustainable management can strengthen ecosystem resilience to both climate change and pollution. Biodiversity further enhances ecosystem function, stability, and efficiency in managing contamination, while also providing habitats for species that support overall ecosystem health **(Samuel, 2023)**.

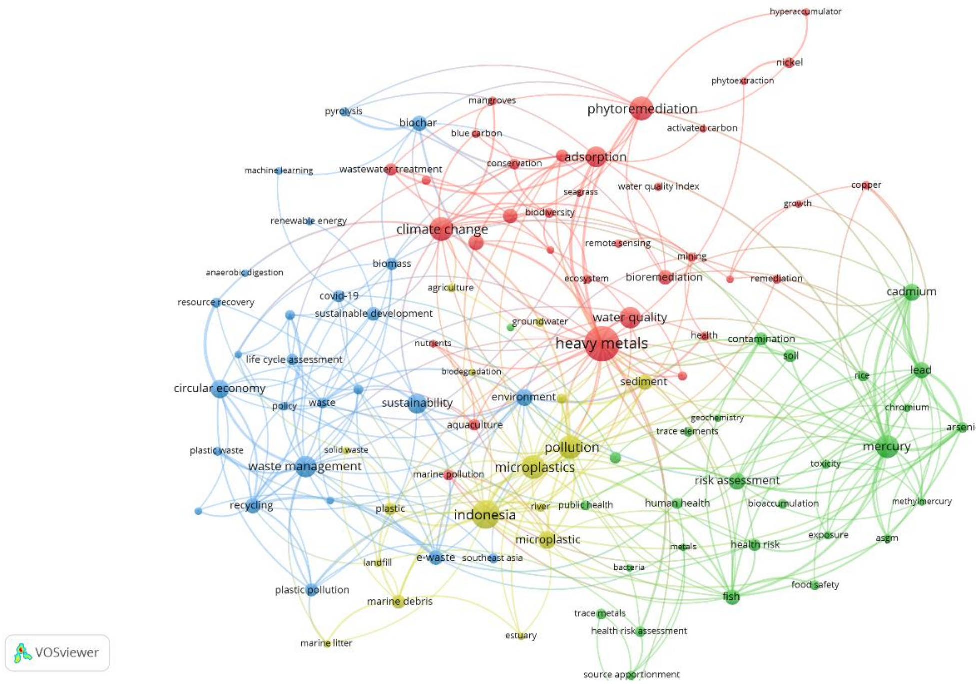

Fig. 1. Research clusters that have related topics

The blue group is dominated by topics related to the circular economy and waste management. A circular economy is an economic model that seeks to minimize waste and maximize resource efficiency through recycling and reuse. Products are designed for longer lifespans, repairability, and reduced dependence on new resources. Waste management encompasses the collection, transportation, processing, and disposal of waste. Effective systems not only reduce environmental impacts but also support circular economy goals by converting waste into reusable resources.

Recycling plays a central role in this model. By recycling waste—especially plastic—we can reduce the demand for virgin materials, which in turn lowers greenhouse gas emissions and energy use. Plastic waste remains one of the greatest challenges in waste management: only about 14% is recycled, while the rest accumulates in landfills or pollutes the environment. The circular economy seeks to address this issue through innovations in product design and waste collection systems **(Hahladakis *et al.*, 2024)**. Wastewater treatment also contributes to circular economy objectives. Treatment plants can convert liquid waste into useful resources such as water for irrigation or industrial use. Processes like anaerobic digestion generate biogas as a renewable energy source, while nutrient recovery technologies can extract phosphorus and nitrogen for use as fertilizers—reducing reliance on non-renewable chemical fertilizers.

The yellow group highlights pollution and microplastics. Pollution refers to the introduction of harmful substances into the environment that degrade the quality of water, air, and soil. In Indonesia, pollution often stems from industrial activity, agriculture, and unmanaged domestic waste. Plastic pollution, particularly microplastics, is especially concerning. Microplastics are particles smaller than 5mm that originate from the breakdown of larger plastics or from commercial products such as cosmetics and textiles. They have been detected in Indonesian rivers, marine sediments, fish, and seafood consumed by humans. Research indicates that microplastics can carry toxic chemicals, posing risks to both ecosystems and human health.

Indonesia is a major contributor to marine plastic pollution, with estimates ranging from 0.48 to 1.29 million tons of plastic entering the ocean annually. Marine pollution not only degrades habitats but also threatens human health via the food chain **(Cahyani *et al.*, 2023)**. Studies of Indonesian beaches reveal that about 58% of macro-waste consists of plastic. Such debris entangles or is ingested by marine animals, leading to death and disruption of biodiversity-rich ecosystems. Microplastics and marine debris also damage coral reefs, reduce biodiversity, and impair ecosystem functions. In marine organisms, microplastics accumulate in tissues and may cause inflammation, hormonal disruption, and even carcinogenic effects.

Another thematic group focuses on heavy metals and their impacts. Heavy metals are high-density elements that can be toxic to living organisms, even at low concentrations. Among the most hazardous are mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As). Mercury—primarily from fossil fuel combustion, industrial waste, and mining—bioaccumulates in the food chain, especially in fish, and causes severe neurotoxic effects. Cadmium, from industry, fertilizers, and waste disposal, damages the kidneys and reproductive systems of aquatic organisms. Lead, often from motor vehicle emissions and industrial effluents, causes neurological damage and weakens immune systems. Arsenic, released from mining and pesticide use, disrupts metabolism and is linked to cancer.

Fish absorb heavy metals either directly from water through their gills or indirectly through contaminated food, a process known as bioaccumulation. Over time, concentrations increase, leading to severe health effects. Mercury and lead exposure, for example, disrupt nervous systems and reduce survival rates. Heavy metals also trigger oxidative stress, damaging cells, proteins, and DNA. Such exposure reduces reproductive success—including gonadosomatic index, fertilization, and hatching rates—ultimately threatening fish populations. Heavy metals accumulate in tissues such as the liver, kidneys, and brain, causing functional damage. Human consumption of contaminated fish poses serious health risks, including neurological disorders, kidney damage, and increased cancer risk.

The bibliometric map illustrates how these research themes interconnect. Central topics such as “heavy metals” and “pollution” are closely linked, as heavy metal pollution often arises from uncontrolled industrial and agricultural activities. Climate change and waste management intersect through greenhouse gas emissions from landfills and waste incineration. The circular economy mitigates these impacts by reducing raw material use, promoting recycling, and enhancing resource efficiency. Microplastics, as a major component of marine pollution, highlight the link between plastic degradation, ecosystem harm, and human health impacts through the food chain.

Indonesia emerges as a key node in this network, reflecting its acute environmental challenges in waste management, biodiversity conservation, and pollution control. Overall, the visualization underscores the complexity of environmental issues and the importance of a holistic research and policy approach to achieve sustainability.

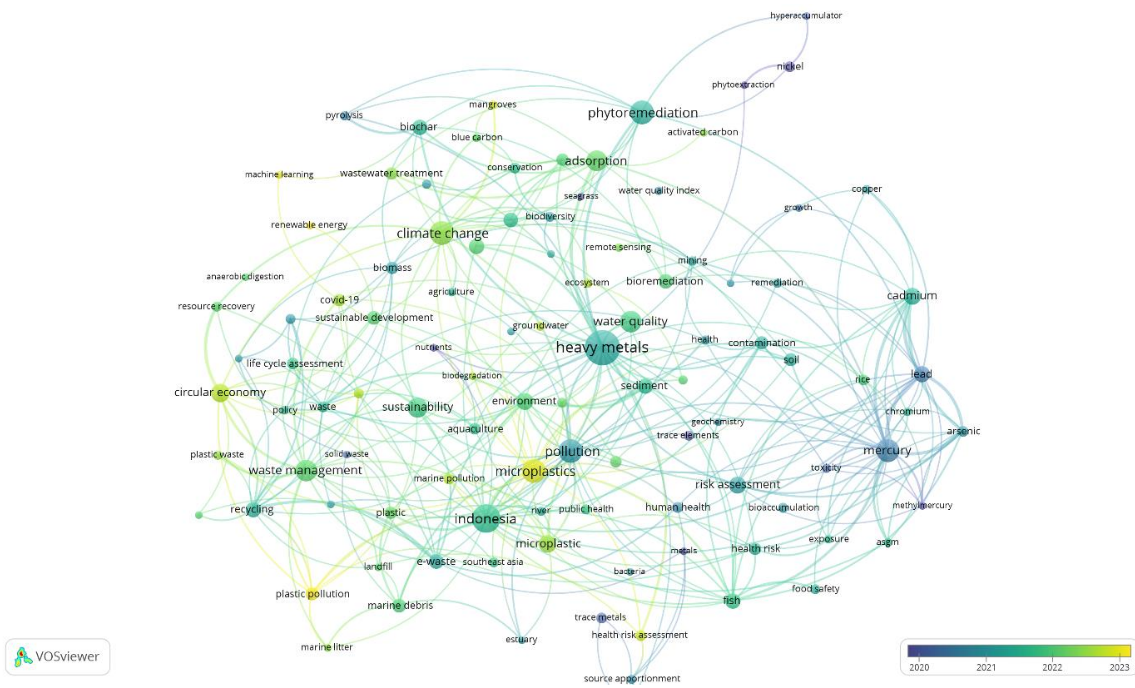

Fig. 2. Trend reseacrh about pollution in river

Microplastics have become an increasingly urgent environmental issue in Indonesia, particularly as a major contributor to river pollution. Recent studies reveal that microplastics are present in various water bodies, including large rivers that serve as sources of raw water and habitats for diverse species. A study conducted in the Opak and Progo Rivers in Bantul Regency found microplastics in all sediment samples, with the highest abundance reaching 1,799.33 ± 1,430.87 particles/kg in Opak River sediment **(Utami *et al.*, 2022)**. These findings highlight how domestic waste and surrounding industrial activities significantly contribute to microplastic accumulation.

The primary source of microplastics in Indonesian rivers is mismanaged plastic waste. Indonesia is among the largest producers of plastic waste globally, with approximately 4 million tons entering the ocean each year **(Arifin *et al.*, 2023)**. Microplastics are formed through the degradation of larger plastics caused by sunlight, friction, and other chemical processes **(Huang *et al.*, 2023; Kurniawan *et al.*, 2024)**. A report from the Nusantara River Expedition in 2022 documented microplastic pollution in the Brantas River—one of East Java’s largest rivers—with concentrations reaching 636 particles per 100 liters of water **(ESN, 2022)**. This pollution stems largely from industrial and household waste discharged into rivers without adequate treatment **(Tariq & Mushtaq, 2023)**.

The impacts of microplastic pollution extend beyond aquatic ecosystems and pose risks to human health. Microplastics can accumulate in aquatic organisms and enter the human food chain through the consumption of fish and seafood **(Unuofin & Iqwaran, 2023; Anggayasti *et al.*, 2025)**. Research indicates that microplastics may lead to hormonal imbalances and elevate cancer risks **(Goswami *et al.*, 2024)**. Furthermore, they can disrupt biological and physical processes within aquatic systems, degrading ecosystem health.

Addressing this issue requires effective waste management. Both regional and national governments must take concrete steps to improve waste handling systems and enforce stricter regulations on waste disposal into rivers. Industries operating along riverbanks also require strict monitoring to ensure hazardous waste is not released without proper treatment.

Overall, current research demonstrates that microplastics pose a serious threat to water quality and public health in Indonesia. Collaborative efforts between government, society, and the private sector are essential to reduce microplastic pollution and safeguard both ecosystems and human well-being.

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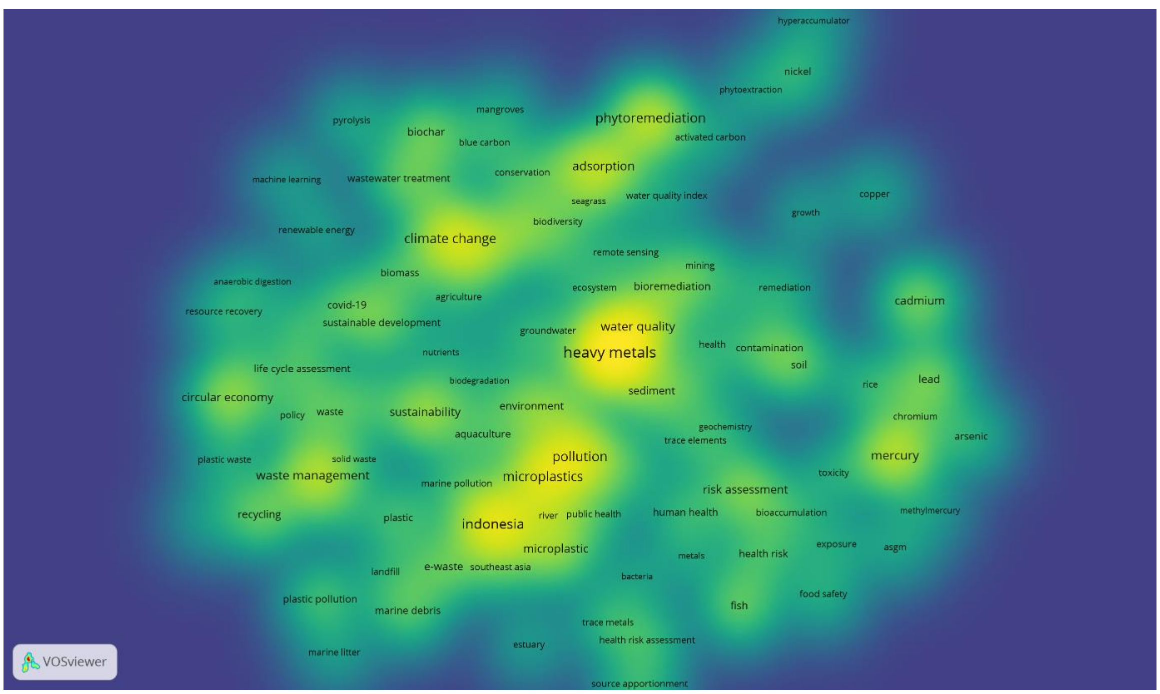

Fig. 3. The intensity of research that has related topics

The heat map in Fig. (3) depicts various topics and concepts related to the environment and sustainability. A color gradient ranging from dark blue to light yellow indicates the intensity or frequency of keyword occurrence. Prominent topics at the center of the map, highlighted in bright yellow, include “heavy metals,” “water quality,” “climate change,” and “pollution,” reflecting their central role in environmental and sustainability research. Surrounding these core topics are related concepts that illustrate thematic interconnections. For example, “phytoremediation” and “adsorption” are positioned near “heavy metals,” indicating their role as treatment techniques for heavy metal contamination. Similarly, “microplastics” and “waste management” cluster near “pollution,” representing specific challenges and mitigation approaches. Policy and economic dimensions such as “circular economy” and “sustainable development” demonstrate the integration of holistic approaches in addressing environmental issues. The presence of geographic keywords such as “Indonesia” and “Southeast Asia” highlights a regional focus in the literature.

Overall, this heat map provides a comprehensive visual representation of the interconnections among environmental issues, ranging from causes (e.g., “agriculture” and “mining”) to impacts (e.g., “health risk” and “food safety”) and potential solutions (e.g., “renewable energy” and “bioremediation”). Such visualization underscores the complexity of environmental challenges and the multifaceted strategies required for sustainability.

The high research intensity on heavy metal pollution, water quality, climate change, and pollution in Indonesia reflects increasing recognition of their serious impacts on public health and ecosystems. Studies on heavy metals—such as lead (Pb), cadmium (Cd), and mercury (Hg)—show that many Indonesian water bodies experience significant contamination due to industrial and domestic waste. For example, research in the Martapura River reported concentrations of Fe and Pb exceeding government quality standards, with values of 2.096 mg/L and 0.5843 mg/L, respectively **(Sudarningsih *et al.*, 2023)**. This highlights how human activities, including direct waste disposal into rivers, are major contributors to pollution. Similarly, research in Biringkassi waters found that waste from a steam power plant (PLTU) increased heavy metal concentrations in sediments, specifically Pb and Cd, although such pollutants were not detected in the water column **(Nata & Muslim, 2024)**. This finding demonstrates that heavy metals not only degrade water quality but also accumulate in sediments, posing long-term risks to aquatic ecosystems.

Water quality is another dominant focus. Research in Central Java revealed correlations between heavy metal levels in river sediments and pollution sources such as industrial discharge and agricultural runoff **(Handayani *et al.*, 2023; Al Zamzami *et al.*, 2025)**. Poor water quality disrupts aquatic ecosystems and increases risks to human health through the food chain. Climate change further exacerbates these issues by altering temperature and rainfall patterns, which in turn affect pollutant concentrations. For instance, higher temperatures can accelerate chemical reactions that produce hazardous compounds from heavy metals **(Aziz & Kareem, 2023)**. More frequent flooding events also transport pollutants into rivers and other water bodies.

The growing body of research on these interconnected issues is essential for developing effective mitigation strategies. Detailed analysis of the interactions between heavy metal pollution, water quality, and climate change can inform stronger policies for water resource management. Collaborative efforts among governments, researchers, and local communities are therefore vital for addressing environmental pollution comprehensively. Overall, the strong research focus on heavy metal pollution and water quality in Indonesia highlights the urgent need to understand their impacts and develop sustainable solutions to safeguard public health and ecosystems.

Fig. (4) provides an additional visualization of research topic networks, illustrating relationships among keywords related to environmental issues. Each node represents a topic such as “heavy metals,” “water quality,” “sustainability,” or “pollution,” with node size reflecting the frequency of discussion. The node and line colors represent temporal relevance, ranging from blue (earlier research) to yellow (more recent research), covering trends from 2020 to 2023. Line thickness indicates the strength of associations between topics. Notably, “Indonesia” and “microplastics” appear as prominent nodes, underlining their particular significance in the local research context. This visualization demonstrates how environmental research topics are interconnected and how scholarly focus has evolved over time.

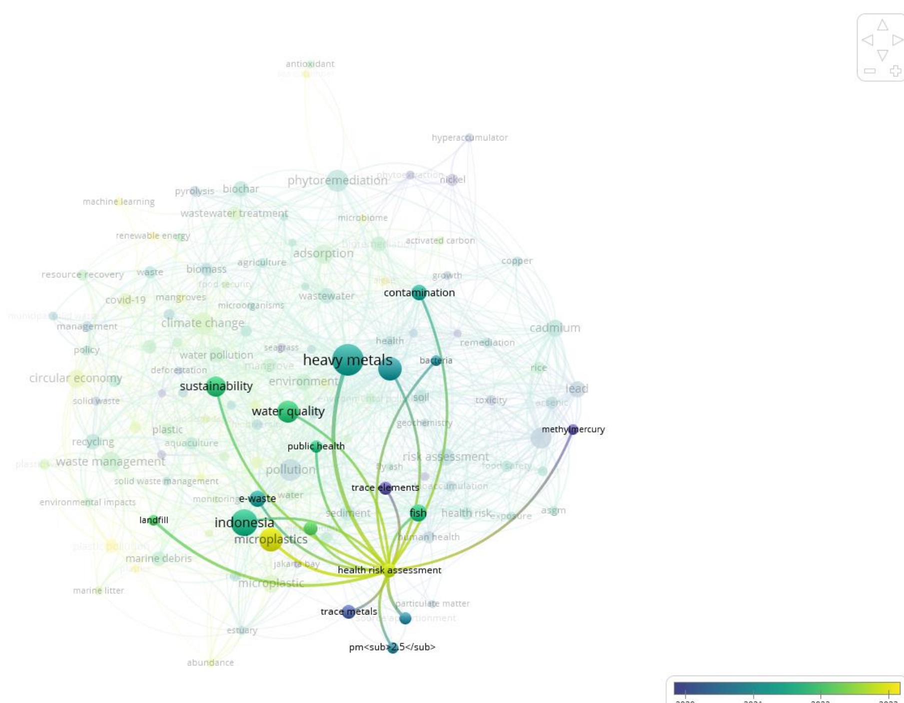

Fig. 4. New trend research for pollutants’ management

Health risk assessment (HRA) has become a critical issue in river pollution management in Indonesia, particularly given the high levels of contamination in many major rivers. Water pollution—especially from heavy metals and microplastics—poses significant risks to public health. Research indicates that more than 80% of waste generated from human activities is discharged into rivers without adequate treatment, creating serious health hazards for communities that rely on these water sources **(Sharma *et al.*, 2024)**. For example, the Brantas River, one of the largest rivers in East Java, was found to contain 636 microplastic particles per 100 liters of water, alongside untreated industrial waste **(Sin *et al.*, 2023; Kurniawan *et al.*, 2025)**. These findings demonstrate the very poor water quality in such rivers and the potential for diseases ranging from digestive tract infections to chronic illnesses such as cancer.

In this context, HRA serves as an important tool for assessing and understanding the health risks posed by polluted rivers. It enables the government to identify pollution sources and evaluate their impacts on public health. Research on the Citarum River, for example, found that concentrations of heavy metals such as lead and chromium exceeded safe limits, with hazard index values indicating significant potential health risks for local residents **(Fahimah *et al.*, 2023)**. By providing measurable data, HRA supports the formulation of effective mitigation policies to reduce exposure to hazardous contaminants.

Moving forward, the government must take concrete steps to integrate HRA into river pollution management. First, regulations on industrial and domestic waste management should be strengthened, with stricter enforcement against violations in waste disposal to prevent further pollution. Additionally, investment in waste processing infrastructure is needed to ensure more effective treatment before waste enters rivers.

Second, the government should implement regular and comprehensive water quality monitoring programs. Access to accurate and up-to-date water quality data would enable faster responses to pollution events and facilitate preventive action before health impacts emerge. Technologies such as the Internet of Things (IoT) for real-time monitoring offer innovative solutions for improving water resource management.

Third, public education on the importance of clean rivers and the health risks of pollution must be reinforced. Raising awareness about proper waste disposal and the consequences of pollution can mobilize community support for government initiatives to protect water quality.

Implementing HRA in river pollution management is therefore essential for safeguarding public health and the environment in Indonesia. With strong regulations, technological innovation, and active community involvement, water quality can be improved and pollution-related health risks minimized.

CONCLUSION

This study highlights the interconnected challenges of river water pollution driven by climate change, microplastics, and heavy metals, while emphasizing phytoremediation and circular economy approaches as potential solutions. Yet, the effectiveness of phytoremediation can be limited by abiotic stress, and recycling innovations remain insufficient to tackle the growing burden of plastic and industrial waste. A holistic and integrated strategy is therefore required to ensure environmental sustainability. Future research should prioritize (1) comparative assessments in under-studied regions, particularly in the Global South, (2) synergistic approaches combining phytoremediation with microbial-assisted systems to enhance resilience under climate stress, and (3) circular economy models that integrate advanced wastewater treatment with resource recovery, focusing on emerging pollutants such as pharmaceuticals and endocrine disruptors.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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