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MORALITY BEFORE KNOWLEDGE

Analysis of river water pollution control due to activities gold mining: Causes, impacts, and effective and sustainable control efforts

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ABSTRACT

Background: This study examines river water pollution due to gold mining activities in Indonesia and its control efforts. This pollution is caused by the use of hazardous chemicals such as mercury and cyanide in the gold extraction process, as well as the disposal of mining waste without adequate treatment. The impacts of pollution include damage to aquatic ecosystems, decreased water quality, and threats to human health. **Methods:** The research methodology uses a qualitative approach with secondary data analysis from various sources such as journal articles, government reports, and case studies. Data are analyzed using triangulation techniques to ensure the validity and reliability of the information. **Findings:** The discussion shows that water pollution due to gold mining, especially illegal activities, has caused significant declines in water quality in various regions in Indonesia. The impacts of pollution include threats to human health, damage to aquatic ecosystems, decreased water quality, and disruption to the livelihoods of communities that depend on water resources. **Conclusions:** Emphasize the importance of pollution control through the application of environmentally friendly technologies, strict regulations, and public education. Recommendations for further research include further study of the long-term impacts of mercury pollution, development of more efficient waste treatment technologies, and exploration of alternative livelihoods for communities around mining areas. **Novelty/Originality of This Study:** This study lies in its comprehensive analysis of river water pollution from gold mining in Indonesia, integrating environmental, health, and socio-economic perspectives to propose sustainable pollution control strategies and alternative livelihood solutions.

KEYWORDS: aquatic ecosystems; environmentally friendly technologies; gold mining; illegal activities; mercury.

1. Introduction

Water pollution caused by gold mining activities—particularly illegal operations—has become an urgent environmental issue in Indonesia. Gold mining waste often contains hazardous substances such as mercury, arsenic, and cyanide, which contaminate water sources and have direct impacts on ecosystems and public health (Orlović-Leko et al., 2022). According to Odum (1997), pollution occurs when harmful substances enter an ecosystem, disrupting environmental balance. In Banyuwangi, gold mining waste has significantly reduced water quality, rendering it unsuitable for community use (Orlović-Leko et al., 2022).

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One of the main causes of this pollution is the use of toxic chemicals in the gold extraction process. In the Anahoni River, cyanide contamination from illegal mining activities poses serious health risks to residents who rely on the water for irrigating rice fields and fish ponds (Tubaka, 2022). Waste from these processes is often discharged directly into rivers without proper treatment, further degrading water quality. In Banyuwangi, mining waste containing heavy metals such as arsenic and mercury has also caused severe environmental damage and health problems (Orlović-Leko et al., 2022).

The impacts of water pollution on the environment and local communities are significant. In Murung Raya Regency, heavy contamination of the Barito River from small-scale gold mining activities has resulted in concentrations of heavy metals such as lead and mercury exceeding environmental quality standards (Rahmadani & Alawiyah, 2022). This situation has reduced agricultural productivity, as many communities depend on contaminated river water for irrigation (Okorogbona et al., 2018). Furthermore, exposure to heavy metals in polluted water can lead to health disorders such as skin diseases and neurological problems (Gani et al., 2017).

To mitigate water pollution from gold mining, effective control measures are needed through proper waste management and the application of environmentally friendly technologies (Tchobanoglous & Kreith, 2002). For example, in the Kahayan River, coordination between central and local governments and public education initiatives are essential to prevent further contamination (Obiri-Yeboah et al., 2021). Stricter regulations on the use of hazardous chemicals must also be enforced. This study aims to analyze the causes and impacts of water pollution resulting from gold mining activities and to formulate effective control strategies to support more sustainable mining practices.

2. Methods

2.1 Research design

This study employs a qualitative approach to understand the impacts of water pollution resulting from gold mining activities. This approach was chosen because it enables an in-depth exploration of the experiences, perceptions, and social impacts faced by communities living near mining sites. As stated by Creswell (2014), qualitative research focuses on the meanings and interpretations individuals assign to their experiences. Furthermore, Denzin (2018) emphasize that a qualitative approach provides deeper insights into social and cultural contexts. Although quantitative data can offer a clear picture of pollution levels, the qualitative approach is more suitable for uncovering contextual and nuanced aspects that cannot be measured numerically (Patton, 2015).

2.2 Data sources

The data used in this study consist of secondary data collected from various scientific publications, government reports, and case studies related to water pollution caused by gold mining activities. The sources utilized in this study include the following, journal Articles, Environmental Reports, Government Documents. Previous studies have shown that gold mining activities often result in significant water pollution (Baker, 2019). Smith & Johnson (2020) also noted that heavy metal contamination from mining operations can have long-term impacts on aquatic ecosystems. According to a report by the Environmental Protection Agency (2022), water pollution originating from mining activities can lead to extensive ecosystem degradation. The WHO (2021) further highlights that exposure to waterborne contaminants can have serious consequences for human health. Government policies on environmental protection play a crucial role. The Ministry of Environment and Forestry (2023) states that strict regulations are required to control the environmental impacts of mining activities. The BPK (2023) also notes that new regulations have been implemented to enhance monitoring of water quality in mining areas.

2.3 Data collection techniques

The data in this study were collected through several complementary methods. First, a literature review was conducted by examining various scientific publications and official documents to identify relevant information concerning water pollution caused by gold mining activities. As noted by Flick (2018), a literature review is an essential initial step in understanding the research context. Next, document analysis was employed to examine reports, articles, and other publications in order to identify patterns, themes, and key information related to environmental impacts, aligning with Prior (2008) view that documents serve as rich sources of information in qualitative research. The third method involved the use of secondary data, namely data obtained from previous studies and official documents without collecting primary data through interviews. Yin (2018) emphasizes that secondary data can provide valuable information without requiring additional time and resources, while Gerring (2017) adds that the use of secondary data enables researchers to conduct comparative analyses more effectively.

2.4 Data analysis

The data collected in this study were analyzed using several qualitative analytical techniques. First, thematic analysis was employed to identify the main themes emerging from the available data. Braun & Clarke (2006) describe this method as flexible and applicable to various types of qualitative data, while Nowell et al. (2017) emphasize the importance of organizing data into key themes to ensure a more systematic understanding. Vaismoradi et al. (2016) further note that thematic analysis plays a crucial role in formulating findings that are relevant to the research context. Next, narrative analysis was applied to understand the storylines related to the causes of pollution, its impacts, and the experiences of affected communities. Creswell & Creswell (2021) argue that narrative analysis provides insights into the meanings behind the experiences of particular groups, which are essential for formulating more effective technical solutions. Similarly, McCormack et al. (2020) demonstrate that narrative approaches can help guide the development of improved mitigation strategies. In addition, source triangulation was conducted by comparing information from multiple sources to ensure the validity and reliability of the data. Flick (2018) underscores that triangulation is a key strategy for enhancing the credibility of research findings, whereas Hammersley (2018) highlights that the use of diverse data sources can reduce bias and provide a more comprehensive understanding of the phenomenon under investigation.

3. Results and Discussion

Water pollution in rivers caused by gold mining activities in various countries, including Indonesia, demonstrates severe impacts on water quality and aquatic ecosystems. In the Batanghari River, Jambi, illegal mining activities have resulted in heavily polluted water conditions, with an average STORET score of –60, where concentrations of heavy metals such as lead (Pb) and zinc (Zn) exceed the established water quality standards (Wibowo et al., 2022). In the Pondo River, Central Sulawesi, increased turbidity has been linked to the operations of PT Citra Palu Mineral, raising concerns among local communities. The Barito River in Central Kalimantan similarly shows severe pollution, with an average score of –43.5 and elevated levels of mercury and arsenic. In the Anahoni River, Maluku, cyanide contamination from gold mining activities at Mount Botak has turned the water blue, threatening marine life and posing health risks to nearby residents (Tubaka, 2022). Additionally, reports from Central Kalimantan indicate increasing water and soil pollution due to waste from illegal gold mining, with mercury levels exceeding safe limits. In Trenggalek, East Java, although current water quality remains within safe limits, potential pollution remains a concern should mining operations commence (Asnawi, 2024).

Beyond Indonesia, gold mining pollution also constitutes a significant global concern. In Peru, particularly in the Madre de Dios region, illegal gold mining has caused severe mercury contamination in local rivers. This practice not only degrades water quality but also threatens the health of communities who rely on river resources for daily life. According to a 2018 report by the United Nations Office on Drugs and Crime (UNODC), approximately 30% of all mercury used in global gold mining originates from this region. Similarly, in Canada, there have been reports of adverse impacts from gold mining waste on water quality in the Fraser River. Studies indicate that mine waste contains heavy metals such as arsenic and cadmium, which contaminate aquatic ecosystems and affect both fish health and the well-being of local communities who depend on the river as a food source (Canadian Environmental Assessment Agency, 2019). These findings underscore the importance of sustainable management and stringent regulation to minimize adverse environmental and public health impacts.

3.1 Gold mining activities and river water pollution

The use of mercury in small-scale gold mining is one of the major sources of river water pollution. In Indonesia, unlicensed gold miners/*pertambangan tanpa izin* (PETI) frequently use mercury to extract gold from its ore. This process involves the formation of a mercury–gold amalgam, but the residual mercury is often discarded into rivers, thereby contaminating aquatic ecosystems. In the Kahayan River, Central Kalimantan, this practice has led to mercury pollution that degrades both water and soil quality in the surrounding area (Wibowo et al., 2020). Mercury contamination has also been detected in the Citarum River, West Java, and the Batanghari River, Jambi, with concentrations high enough to endanger human health and local ecosystems (Fitriyyah et al., 2024; Ratnaningsih et al., 2019). Research findings indicate that mercury pollution is present in 72% of surveyed locations, while cyanide contamination is detected in 66.7% of the sites (Astiti & Sugianti, 2014). Furthermore, mercury levels in soil have surpassed the permissible threshold (Sari, 2023).

Tailing waste is a by-product of the gold extraction process and often contains hazardous heavy metals such as arsenic, cadmium, lead, and cyanide. Improper disposal of tailings into rivers results in severe water contamination. In the Barito River, Murung Raya, small-scale gold miners discharge tailings containing arsenic and cadmium (Rahmadani & Alawiyah, 2022). Similar cases have been reported in the Musi River, South Sumatra, and the Kapuas River, West Kalimantan (Yogi et al., 2020). Uncontrolled gold mining activities can lead to contamination of surrounding water and soil (Wahyudi & Slameto, 2014). Studies also indicate that heavy-metal pollution can degrade water quality and pose threats to aquatic biota (Alwan, 2021).

Unlicensed gold mining often causes severe damage to river ecosystems, including increased erosion and water pollution. In the Batanghari River, Jambi, surveys indicate that PETI activities have led to excessive sedimentation, which destroys fish habitats and reduces water quality. In the Kapuas River, West Kalimantan, illegal mining has resulted in erosion and a decline in water quality. Unlicensed gold mining activities are frequently carried out in environmentally sensitive areas, which exacerbates ecological degradation (Hidayat et al., 2015). This illegal mining also leaves behind excavation pits that can trigger erosion and landslides (Astiti & Sugianti, 2014).

Hazardous chemicals such as cyanide and mercury are frequently used in gold mining processes, exerting substantial impacts on water quality. In the Anahoni River, Maluku, the use of cyanide by local miners has resulted in contamination that disrupts aquatic life and threatens the biodiversity surrounding the river (Samual, 2023). In the Sembakung River, North Kalimantan, the unauthorized use of hazardous chemicals has degraded water quality and destabilized the aquatic ecosystem. Hazardous substances such as mercury can significantly affect environmental health (Rissamasu et al., 2011), while residual waste from processing activities is often discharged directly into the environment without further treatment (Banunaek, 2016).

Gold mining activities that involve the excavation of soil and riverbed materials lead to drastic changes in river morphology. These activities increase erosion and sedimentation, which in turn bury fish habitats. The resulting rise in sedimentation further worsens water turbidity, blocking sunlight penetration and reducing photosynthesis in aquatic plants. Such mining operations can also damage existing vegetation and soil (Setiabudi, 2005), and may trigger landslides as well as a decline in soil fertility (Alwan, 2021).

Mining activities increase water turbidity, which reduces sunlight penetration and disrupts photosynthesis in aquatic plants. High turbidity poses significant risks to the survival of fish and other aquatic organisms. The decline in dissolved oxygen levels resulting from impaired photosynthesis induces stress in aquatic organisms. Tailing waste, which is rich in nutrients such as nitrogen and phosphorus, accelerates eutrophication by promoting excessive algal growth. This eutrophication can lead to mass mortality of aquatic organisms and long-term degradation of aquatic ecosystems (Stumm & Morgan, 1996). In addition, tailing waste can further contaminate water bodies and negatively affect aquatic ecosystems (Sari, 2023).

3.2 Impact of river water pollution due to gold mining

River water pollution caused by gold mining waste, particularly waste containing heavy metals such as mercury, lead, arsenic, and cadmium, results in significant damage to aquatic ecosystems. Mining waste discharged into rivers leads to the accumulation of non-degradable heavy metals, thereby degrading natural habitats for various aquatic species. The accumulation of these metals in aquatic organisms, such as fish and invertebrates, disrupts their biological functions, reduces fish populations, and causes deterioration of the food chain within aquatic ecosystems. Chemical pollutants from mining activities also have the potential to alter nutrient availability around river systems, diminishing the ecosystem's capacity to support life. According to Ouma et al. (2022), heavy metals in mining waste can damage the structural integrity of aquatic habitats that are essential for fish and other aquatic organisms. Furthermore, excavation and suction dredging of riverbeds associated with gold mining activities can physically degrade river systems, causing excessive erosion and sedimentation.

In addition to its ecological impacts, river water pollution resulting from gold mining waste poses substantial risks to human health. The process of bioaccumulation, in which heavy metals such as mercury are absorbed by aquatic organisms and accumulate within their bodies, renders fish and other organisms consumed by humans hazardous. When humans ingest mercury-contaminated fish, the long-term effects can be severe, including serious neurological disorders, which are particularly dangerous for pregnant women and children (Chamoli & Karn, 2024). Moreover, direct exposure to hazardous waste from gold mining activities can cause skin disorders, nervous system diseases, and heavy metal poisoning. Respiratory problems are also commonly reported among communities directly exposed to these pollutants. Without adequate environmental management or early-warning systems, local populations that rely on rivers as a primary resource may face even greater health risks.

Pollution caused by mining waste not only threatens ecosystems but also has significant impacts on food security and human well-being, particularly regarding the availability of clean water. Mining waste containing heavy metals, hazardous chemicals, and altered pH levels from acid mine drainage severely degrades river water quality. Contaminated water becomes unfit for direct consumption as well as for agricultural and aquaculture purposes. This contamination reduces agricultural yields, damages soil quality, and decreases fish stocks available for capture. Consequently, dependence on external food supplies increases, which in turn affects local economies. WHO (2017) notes that heavy-metal contamination and hazardous chemical exposure in water can lead to various serious illnesses, including poisoning, digestive disorders, and skin diseases. Water pollution also disrupts agricultural irrigation systems, which serve as the backbone of livelihoods for many families living near mining areas.

Water pollution caused by mining waste not only threatens ecosystems but also has profound implications for food security and human well-being, particularly regarding the availability of clean water. Mining waste containing heavy metals, hazardous chemicals, and altered pH levels from acid mine drainage significantly degrades river water quality. Contaminated water becomes unfit for consumption, whether directly or for agricultural and aquaculture purposes. This deterioration reduces agricultural yields, damages soil quality, and decreases fish stocks available for harvesting. Consequently, communities become increasingly dependent on external food supplies, which in turn affects local economic stability. The WHO (2017) notes that heavy-metal and chemical contamination in water can cause severe illnesses such as poisoning, digestive disorders, and skin diseases. Water pollution also disrupts agricultural irrigation systems, which serve as the backbone of livelihoods for many families living near mining areas.

Pollution caused by gold mining waste not only affects aquatic environments but also exacerbates the degradation of terrestrial ecosystems surrounding contaminated river areas. Mining waste that infiltrates the soil alters soil quality and disrupts the balance of terrestrial ecosystems. Soil contaminated with heavy metals reduces habitat quality for terrestrial flora and fauna and diminishes the ability of plants to grow properly. When contamination becomes severe, it can lead to widespread habitat degradation and threaten species diversity. Furthermore, pollution worsens conditions in wetlands near mining areas, which serve as natural filters for pollutants and as habitats for various species (Gani et al., 2017). This contamination poses risks to bird species, fish, and other flora and fauna that depend on wetlands as essential living environments.

3.3 Pollution mitigation and control strategies

Mitigation focuses on efforts to prevent river pollution from gold mining activities before the impacts occur. These preventive measures are crucial given the substantial negative effects of gold mining—particularly the use of mercury—which can severely degrade water quality and river ecosystems. Mitigation strategies involve a comprehensive approach, ranging from community education to the implementation of environmentally friendly technologies and the adoption of policies that support sustainable environmental management. Education and outreach play a crucial role in raising community awareness about the negative environmental impacts of gold mining, particularly water pollution resulting from mercury use. These activities aim to provide the public with a deeper understanding of these impacts and to teach methods for minimizing environmental damage associated with mining practices.

In addition to education, the adoption of environmentally friendly technologies is a crucial measure for reducing pollution caused by gold mining activities. These technologies not only decrease dependence on mercury but also support improved waste management and more efficient use of natural resources. The application of appropriate technologies can provide sustainable solutions for mitigating the negative environmental impacts of mining. Appropriate regulations and policies are essential to support mitigation efforts. Policies that prohibit the use of mercury and the enforcement of stricter rules on natural resource management can reduce the risk of pollution. In addition, regulations governing mining areas and the principles of sustainability will encourage miners to act responsibly toward the environment. Based on the explanation above, this study concludes that the proposed mitigation measures to prevent pollution are summarized in Table 1.

Table 1. Mitigation of pollution

Mitigation	Activities conducted
Education and Extension	1 Implementing environmental education programs for local communities to raise awareness about the impacts of gold mining and mercury use, as well as strategies to reduce these impacts (Heriamariaty, 2020).
	2 Conducting seminars and workshops to enhance public awareness of sustainable mining practices and their adverse environmental consequences (Aziz et al., 2023).
	3 Establishing community groups to monitor illegal mining activities and providing training on how to detect and report such activities (Heriamariaty, 2020; Aziz et al., 2023).
Use of Environmentally Friendly Technology	1 Applying mercury-free gold separation technologies, such as gravity or flotation methods, to reduce water contamination (Aswadi et al., 2019).
	2 Using more efficient purification tools to minimize waste and improve the gold separation process, thereby reducing the use of hazardous substances (Heriamariaty, 2020).
	3 Adopting environmentally friendly technologies that mitigate overall environmental impacts, as well as conducting environmental audits to ensure compliance with established standards (Aswadi et al., 2019; Aziz et al., 2023).
Regulations and Policies	1 Establishing policies that prohibit the use of mercury in gold mining to prevent further mercury contamination (Aswadi et al., 2019).
	2 Developing well-planned and sustainable community mining areas that balance environmental and social considerations (Aziz et al., 2023).
	3 Implementing policies that designate no-mining zones in ecologically sensitive areas to protect habitats and biodiversity.

3.4 Control (management and rehabilitation)

Controlling river pollution resulting from gold mining is a measure undertaken to address existing contamination and prevent its impacts from worsening. This control strategy includes monitoring water quality, implementing proper waste management, and strictly enforcing regulations against miners who violate the rules. In addition, rehabilitating affected ecosystems is crucial to restoring environmental quality and preventing long-term degradation. Pollution control involves measures aimed at reducing or stopping river contamination caused by gold mining activities. These actions include regular water quality monitoring, improved waste management, and the enforcement of environmental regulations against violators. Effective monitoring and management help mitigate pollution impacts and accelerate environmental recovery.

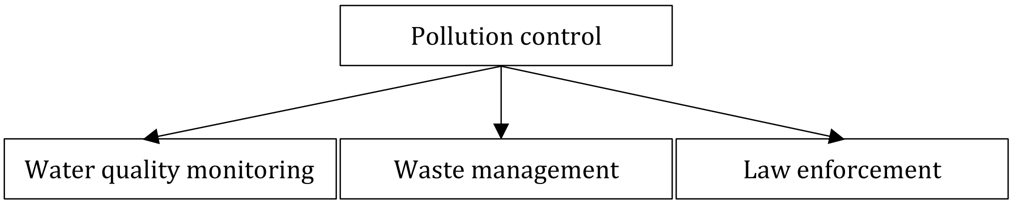

Fig. 1. Pollution control activities

Based on the Figure 1, efforts to monitor water quality are carried out through regular testing at strategic locations along the river to enable early detection of contamination and facilitate timely intervention, as noted by Aziz et al. (2023). In addition, the establishment of community-based water quality monitoring teams represents an important step toward ensuring more effective oversight. These teams are responsible for reporting real-time changes in water conditions and for educating local communities on the importance of maintaining water quality and promptly reporting any changes to the authorities. This participatory approach, as emphasized by Aswadi et al. (2019) and Heriamariaty (2020), not only enhances public awareness but also strengthens the sustainability of environmental monitoring systems.

Waste management is carried out by implementing effective treatment systems that utilize technologies capable of processing waste before it is discharged into the river, thereby minimizing the impact of pollution. The technologies employed must comply with applicable environmental standards to ensure that the treatment process is safe and adheres to regulatory requirements, as noted by Heriamariaty (2020). In addition, the use of sedimentation ponds serves as a technical measure to reduce water turbidity before wastewater is released into the river, thereby mitigating its direct impact on water quality, as highlighted by Aziz et al. (2023). Monitoring of mining activities is carried out through routine inspections to ensure that all operations comply with applicable environmental regulations. This measure includes the enforcement of strict sanctions against miners found to have violated waste management provisions or other environmental policies, as emphasized by Aswadi et al. (2022) and Heriamariaty (2020). This consistent supervisory approach aims to prevent further pollution and ensure the sustainability of environmental management within mining areas.

3.5 Rehabilitation

Rehabilitating affected ecosystems is a crucial step in restoring environmental conditions following pollution events. This effort involves activities such as revegetating degraded land and restoring the ecological functions disrupted by mining operations. Effective rehabilitation not only restores ecosystem integrity but also improves the quality of life for surrounding communities through corporate social responsibility (CSR) programs. The rehabilitation measures that can be implemented are listed in Table 2.

Table 2. Activities for rehabilitation, CSR implementation, and monitoring in gold mining areas

Rehabilitation	Activities conducted
Rehabilitation of degraded land	1. Replanting native vegetation in former mining areas to restore ecosystems and improve the quality of degraded soils. Appropriate revegetation techniques tailored to local conditions are utilized to accelerate soil recovery and enhance soil fertility (Aziz et al., 2023; Aswadi et al., 2019). 2. Developing corporate social responsibility (CSR) programs that focus on environmental rehabilitation in areas affected by gold mining activities, as well as investing in projects that benefit surrounding communities as part of corporate social obligations (Heriamariaty, 2020; Aziz et al., 2023).
Corporate Social Responsibility (CSR) program	Developing CSR programs that not only focus on land rehabilitation but also support alternative economic activities in the post-rehabilitation phase, as well as providing new skill training for local communities to promote sustainable economic livelihoods (Aziz et al., 2023; Heriamariaty, 2020).
Monitoring and evaluation	Conducting periodic monitoring of rehabilitation outcomes to ensure the success of the program and to make necessary adjustments when required. Environmental impact evaluations are

	also carried out in the post-rehabilitation phase to assess the extent to which the implemented rehabilitation efforts have restored the environmental conditions to a more improved state (Aswadi et al., 2019; Heriamariaty, 2020).

3.6 Application of technology for mitigation and control of river pollution caused by gold mining

Several techniques can be implemented to prevent river pollution, including the adoption of stricter environmental control systems and the application of water treatment and recycling protocols in mining facilities. According to Swallow et al. (2018) in the Journal of Cleaner Production, the implementation of integrated pollution control methods in gold mining reduces negative environmental impacts through improved management practices. One applicable technique is the establishment of buffer zones around mining activities, which helps mitigate direct impacts on river ecosystems. In addition, the use of hazardous chemicals such as mercury and cyanide must be reduced to prevent further contamination. Veiga (2020), writing in Resources Policy, recommend replacing mercury-based extraction methods with more environmentally friendly techniques. Using safer chemical alternatives and implementing strict chemical-handling procedures can minimize environmental impacts. Efficient chemical management and improved tracking systems will also strengthen control over hazardous substances at mining sites.

Another important measure is the development of riparian buffer zones and ecological corridors to protect river ecosystems. Sonter et al. (2017) in Biological Conservation emphasize the importance of ecosystem protection and biodiversity conservation around mining areas to prevent broader environmental degradation. Such protection efforts may include the creation of ecological corridors that facilitate species migration and preserve natural habitat quality.

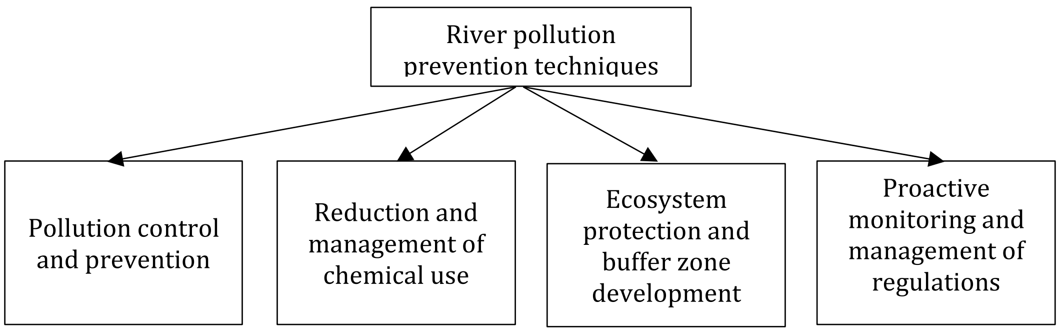

Fig. 2. River pollution prevention techniques

Finally, Hilson & McQuilken (2016) in The Extractive Industries and Society emphasize the importance of strict regulations and more intensive oversight of mining activities to prevent more severe pollution. Stronger enforcement, coupled with the implementation of financial penalties for companies that violate environmental standards, will help strengthen efforts to mitigate river pollution. The government must collaborate with local communities and organizations to develop policies that support cleaner and more sustainable mining practices. Based on the explanations above, several techniques for reducing river pollution are illustrated in Figure 2. In addition to river pollution prevention techniques, this study also highlights two other critical aspects of mitigation and control activities related to river pollution caused by gold mining. These two groups of activities are summarized and further elaborated in Table 3.

Based on Table 3, under the category of Physicochemical Treatment, techniques such as activated carbon filtration and chemical precipitation can be applied to reduce heavy metal contaminants, including mercury and cyanide, in river systems. Zhang et al. (2019) in Water Research propose an integrated watershed management approach that incorporates physicochemical techniques to remove pollutants from contaminated river water. In addition, ion-exchange technology and membrane filtration can be utilized for more effective contaminant removal.

Table 3. Mitigation technology applications and key activities for river pollution control and monitoring

Application of mitigation technology	Activities
Pollution Control and Remediation Techniques	Physicochemical Processing
	Biological Remediation
	Nanobioremediation Technology
River Water Quality Measurement and Monitoring Strategy	Water Quality Assessment
	Instrument Monitoring Technology
	Biological Indicator Methods
	Geospatial Technology and Remote Sensing

For the Biological Remediation category, one widely used method is phytoremediation, in which plants are employed to absorb heavy metals from soil and water. Ali et al. (2020) describe how certain plants, particularly aquatic species, can help filter heavy metals from polluted water. Moreover, the application of constructed wetlands and microbial bioremediation has also been proven effective in restoring rivers affected by pollutants. Nanotechnology offers a more advanced solution for treating complex forms of pollution. Ethaib et al. (2022) argue that the use of nanomaterials in filtration and remediation can enhance the efficiency of removing pollutants such as cyanide and heavy metals. This technology functions by adsorbing contaminants at the molecular level, resulting in more precise and efficient treatment outcomes.

3.7 Discussion

The findings of this study underscore the urgent need to address water pollution caused by gold mining activities, both illegal operations and licensed companies that fail to comply with environmental regulations. Water contamination by heavy metals such as mercury and arsenic—widely used in gold extraction processes—has been shown to pose long-term risks to human health, ecosystems, and overall water quality. For example, mercury used in amalgamation to extract gold from ore is one of the most hazardous pollutants for humans and animals. Scientific research indicates that mercury can accumulate in human and animal bodies through contaminated food or water, causing damage to the nervous system, kidneys, and reproductive functions. In this context, it is important to recognize that such pollution is not merely a short-term issue but a long-term environmental threat that will continue to affect future generations. A study by Gibb & O'Leary (2014) shows that communities living near gold mining sites using mercury exhibit an increased risk of neurological disorders, including permanent brain damage in children exposed to high mercury concentrations. Moreover, this study found that Illegal Gold Mining Activities contribute significantly more to water pollution than legally conducted mining operations, even when regulation of the latter is weak. PETI activities, carried out without environmental oversight, routinely disregard principles of sustainability and ecological safety. Simple mining technologies and the absence of proper waste management systems allow pollutants to be discharged directly into rivers, contaminating both water and soil.

Pollution caused by PETI is often overlooked by authorities because these activities occur in remote areas that are difficult to access and not formally recorded in regulatory systems. The study highlights that weak oversight and inconsistent law enforcement are key factors exacerbating the environmental impacts. The regulations exist to curb illegal mining, limited monitoring capacity and the lack of strict sanctions enable illegal mining activities to continue at large scale. Governments often struggle to regulate this sector due to logistical challenges and insufficient surveillance capacity in remote areas where illegal gold mining is concentrated. The wider consequences of this pollution extend to food security and the clean water crisis. Rivers contaminated by mining waste not only endanger human health but also disrupt the livelihoods of communities dependent on fisheries and agriculture. Water pollution destabilizes aquatic ecosystems, damaging fish habitats that serve as key protein sources for many communities in Indonesia. Simultaneously, contamination affects agricultural soils reliant on clean river water for irrigation, potentially reducing crop yields and increasing poverty rates in affected regions.

In the context of climate change, water pollution from gold mining further weakens environmental resilience. Polluted rivers lose their capacity to store water during the rainy season, increasing the risk of flooding following heavy rainfall. This diminished water absorption capacity exacerbates the impacts of climate variability, contributing to unpredictable rainfall patterns. Such conditions create broader ecosystem instability, including the inability of rivers to regulate optimal water flow, thereby degrading freshwater ecosystems as a whole. Therefore, this study calls for more aggressive pollution control actions through a comprehensive approach involving stricter monitoring, the adoption of environmentally friendly mining technologies, and community education on environmental stewardship. Collaboration among governments, local communities, and the private sector is essential to ensure that natural resource exploitation does not compromise human well-being and ecosystem sustainability in the future.

The study also highlights the need for more accurate and detailed data-driven policies to better understand how mining activities affect water quality. A study by Lioumbas et al. (2023) indicates that satellite-based water quality mapping and monitoring technologies can improve oversight in remote and inaccessible areas. This approach enables more effective monitoring and allows authorities to respond more rapidly to pollution incidents in geographically isolated regions.

Monitoring the quality of polluted river water involves chemical analyses to measure the concentrations of heavy metals, cyanide, pH, dissolved oxygen, and total suspended solids. These measurements provide a comprehensive overview of water quality status and potential threats to the ecosystem. Regular assessments of these parameters help detect early changes in water quality (Esterby, 1996). Continuous water-quality monitoring using multi-parameter sondes or online monitoring systems enables real-time assessment of river conditions. This method provides faster information on pollution events, allowing for more timely interventions (Kelly et al., 2012).

Biomonitoring approaches—such as the use of aquatic macroinvertebrates, observations of fish populations, and changes in algal communities—can offer early indications of ecological impacts. Bioaccumulation studies in aquatic organisms are also effective for determining the levels of pollutants accumulated within biological tissues (Amrillah et al., 2023). The use of GIS mapping, satellite imagery, and drone technology is highly beneficial for monitoring water quality across large areas. These tools allow for the detection of isolated pollution hotspots and facilitate tracking the progression of contamination over time.

4. Conclusions

Gold mining activities, particularly illegal mining, cause severe water pollution in rivers across Indonesia. The use of hazardous chemicals such as mercury and cyanide in gold extraction contaminates water sources with heavy metals, posing serious risks to aquatic ecosystems and human health. This pollution leads to a decline in water quality, rendering it unsuitable for community use and threatening food security by damaging agricultural land and fisheries. Long-term exposure to pollutants such as mercury can result in neurological disorders, especially in children.

Effective pollution control requires a multifaceted approach involving technology, policy, and community participation. This includes the adoption of environmentally friendly mining technologies, stricter regulations on the use of hazardous chemicals, and improved waste management practices. Enhanced monitoring systems utilizing advanced technologies, such as automated sensors and satellite-based water quality mapping, can improve early detection and response to pollution incidents. In addition, strengthening law enforcement and raising public awareness through educational programs are crucial for preventing further environmental degradation.

Further research is needed to develop more efficient and environmentally friendly waste treatment technologies, such as bioremediation and activated carbon, to reduce heavy metals in water. Exploring alternative livelihoods to replace illegal mining activities, while considering the social and economic sustainability of local communities, is also essential. Future studies should focus on strengthening sustainable natural resource management policies and educating communities about environmentally responsible mining practices. International collaboration for funding and the transfer of green technologies, as outlined in the Paris Agreement, is crucial to address pollution and the impacts of climate change.

The development of more efficient and environmentally friendly waste treatment technologies, such as bioremediation and activated carbon to reduce heavy metals in water, is of critical importance. Further research should also focus on water remediation technologies, including the use of microbial or plant-based biofilters to absorb pollutants, as well as the rehabilitation of river ecosystems contaminated by heavy metals, in order to improve water quality and restore degraded aquatic ecosystems. The implementation of advanced water quality monitoring technologies, such as drones, automated sensors, and blockchain-based platforms, can provide real-time data and enhance transparency in monitoring. This enables authorities to respond promptly to pollution incidents and improves accountability. In addition, evaluating more effective community-based oversight policies and employing economic incentives to reduce illegal mining should be prioritized. Strengthening sustainable natural resource management policies and educating communities about environmentally friendly mining practices can help mitigate pollution impacts. Training programs on mercury-free mining and safe waste handling should be introduced, while outreach on more environmentally sustainable alternative livelihoods can reduce dependence on illegal mining activities.

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