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Environmental Consequences of Illegal Gold Mining in Coastal Ecosystems: A Case Study of Teluk Sumalata

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ABSTRACT

Illegal gold mining has severe environmental impacts on marine ecosystems, particularly in coastal regions like Teluk Sumalata, Indonesia. This study investigates the effects of mining on water quality and the health of mangroves, seagrass beds, and coral reefs. The research employed field sampling, water quality monitoring, and GIS-based spatial analysis to assess the levels of mercury contamination in water and sediment, alongside the health of the ecosystems. Results revealed significant mercury contamination, exceeding regulatory limits, particularly in areas close to mining operations. Mercury bioaccumulation in aquatic organisms was observed, leading to potential ecological and human health risks. Mangrove and seagrass ecosystems showed signs of degradation, with reduced biodiversity and ecosystem resilience. The study recommends implementing integrated coastal zone management, establishing marine protected areas, and engaging local communities in conservation efforts as strategies to mitigate the impacts of illegal mining. Additionally, enhancing monitoring systems using remote sensing and GIS technologies is vital for timely detection of ecological disturbances. This research contributes to understanding the environmental consequences of illegal mining and emphasizes the need for effective policy and community-based solutions to protect coastal ecosystems from further degradation.

Keywords: Illegal gold mining; Mercury contamination; Coastal ecosystems; Mangroves; Seagrass beds; Coral reefs; Marine protected areas

INTRODUCTION

The environmental impacts of illegal gold mining on marine ecosystems, particularly mangroves, seagrass beds, and coral reefs in tropical coastal areas, are profound and multifaceted. Illegal gold mining activities, often involving the use of harmful chemicals such as mercury, pose significant threats not only to biodiversity but also to the overall health of the ecosystem. Studies indicate that the indiscriminate clearing of land for mining leads to the degradation of critical habitats like mangroves and seagrasses. These habitats serve essential ecological functions, including providing coastal protection and acting as nurseries for marine species (Chakuya et al., 2023; Mamola et al., 2024; Barbier, 2017).

Mangroves, in particular, are vulnerable to the impacts of illegal gold mining. These forests face direct destruction from mining activities, which increases sedimentation and declines water quality. The physical destruction of mangrove forests diminishes their ability to serve as buffers against coastal erosion and storm surges (Mamola et al., 2024; Barbier, 2017). Similarly, seagrass beds, which rely on clear water and stable sedimentation to thrive, suffer from increased sediment runoff caused by mining. This runoff can smother seagrasses, reducing their photosynthetic capacity and negatively affecting marine ecosystems, such as coral reefs, which depend on healthy seagrass beds (Chakuya et al., 2023; Magris et al., 2019).

Mercury, used in illegal gold mining, contaminates water systems through runoff and direct discharges from mining activities (Costa et al., 2012; Mestanza-Ramón et al., 2021). Mercury bioaccumulates in aquatic food webs, posing serious risks to marine life by disrupting reproductive and neurological functions in fish and other organisms (Nirchio et al., 2025; Hilmi et al., 2023). In estuarine ecosystems—where freshwater meets saltwater—mercury concentrations can be especially high due to the dynamics of sedimentation and water exchange, ultimately harming key species that serve as indicators of ecosystem health, including various fish and invertebrates (Thushari & Senevirathna, 2020).

The ecological consequences of mercury pollution extend to significant biodiversity loss. Elevated mercury levels reduce populations of sensitive species, thereby diminishing overall species richness and destabilizing food webs in estuarine and coastal ecosystems. For example, mercury can hinder fish reproductive success and disrupt predator-prey dynamics, leading to cascading effects throughout the ecosystem (Lemos et al., 2022; Jha et al., 2024). Such biodiversity loss weakens ecosystem resilience, making these environments less capable of recovering from disturbances and compounding the impacts of other stressors, such as climate change and habitat alteration due to mining (Wu et al., 2025; Hain & Sutton, 2023).

In summary, illegal gold mining significantly impacts marine ecosystems by degrading critical habitats, releasing hazardous materials such as mercury that compromise water quality and aquatic life, and contributing to a decline in biodiversity within estuarine and coastal environments. Effective management strategies are essential to mitigate these effects and preserve these valuable ecosystems. The issue of heavy metal contamination in coastal waters—particularly regarding its sources and long-term effects—has been the focus of extensive research. Studies show that anthropogenic activities, especially mining and industrial processes, are major contributors to heavy metal pollution in marine environments, alongside agricultural runoff and urban development. These factors undermine water quality and aquatic life in coastal regions (Wu et al., 2019; Faiz et al., 2024). The bioaccumulation of these metals in marine organisms not only jeopardizes marine species' health but also poses risks to human populations that rely on seafood as a dietary staple (Venkateswarlu & Venkatrayulu, 2020; Onyena & Nwaogbe, 2024).

Research on the long-term ecological health of these environments highlights that heavy metal toxicity can lead to severe biological consequences. Contaminants such as cadmium, mercury, and lead cause oxidative stress in marine species, impairing their growth, reproduction, and survival (Faiz et al., 2024; Lu et al., 2022). Moreover, ecosystems that serve as critical habitats—such as coral reefs and mangroves—experience declines in biodiversity, which undermines the ecosystem services they provide (Faiz et al., 2024). For instance, heavy metal pollution disrupts the benthic zone, which is vital for nutrient cycling within these ecosystems (Venkateswarlu & Venkatrayulu, 2020).

Frameworks for assessing environmental quality in coastal waters, particularly in developing countries, often involve sediment sampling, water quality monitoring, and the use of bioindicator species. Several studies emphasize the need for comprehensive monitoring programs that evaluate heavy metal concentrations in both sediments and biota (Saraee et al., 2011; Fu et al., 2014). These assessments commonly use organisms like mollusks and fish as bioindicators to track metal bioaccumulation and assess ecosystem health (Onyena & Nwaogbe, 2024). However, variations in methodologies and a lack of standardized procedures can complicate data interpretation across different regions (Tanjung et al., 2019; Hasan et al., 2017).

Water quality monitoring is crucial in detecting the impacts of illegal mining on coastal regions. Routine sampling of water and sediment can help identify fluctuations in heavy metal concentrations, facilitating early detection of pollution events (Sun et al., 2020; Asih et al., 2022). Additionally, the integration of Geographic Information Systems (GIS) enables spatial analysis of pollution sources and their associated risks, which is essential for developing targeted mitigation strategies (Faiz et al., 2024; Fu et al., 2014). Implementing robust water quality monitoring systems and early warning systems will allow policymakers and stakeholders to take timely actions to preserve coastal ecosystem health (Faiz et al., 2024).

In conclusion, heavy metal contamination in coastal waters due to mining and other human activities presents a major environmental challenge. These pollutants threaten marine biodiversity and destabilize ecosystems. The establishment of comprehensive assessment frameworks and effective monitoring systems is necessary to mitigate these risks and safeguard vulnerable marine environments.

MATERIALS & METHODS

The study followed a systematic approach, combining both direct and indirect environmental measurements, and was built upon established methodologies for water quality monitoring and ecosystem assessment. The primary objective was to assess the extent of pollution caused by illegal gold mining and its impact on marine ecosystems. As pointed out by Jha et al. (2023), successful research in coastal areas affected by mining relies on a robust sampling design that accounts for both spatial and temporal variations in environmental conditions. To capture these variations, a stratified random sampling design was employed, considering the diverse habitats within Teluk Sumalata, including areas near mining operations, mangroves, seagrass beds, and coral reefs.

Spatial stratification is essential for assessing the impact of mining activities, as these activities are often concentrated in specific areas, leading to localized pollution events (Feng & Niu, 2019). The design ensured that key regions affected by mining and other anthropogenic activities were adequately represented. Temporal variations were also incorporated into the sampling process, as water quality parameters and ecosystem health can fluctuate over time due to seasonal changes, particularly rainfall patterns and variations in freshwater input from the rivers (Titah et al., 2023).

The sampling locations were chosen to include sites directly impacted by mining activities, as well as control sites located away from mining areas. This comparative approach allows for the assessment of the environmental impact of mining by contrasting areas exposed to mining-related pollution with relatively pristine locations. Figure 1 illustrates the locations of the sampling sites across the study area, highlighting the proximity to mining zones and key ecological areas.

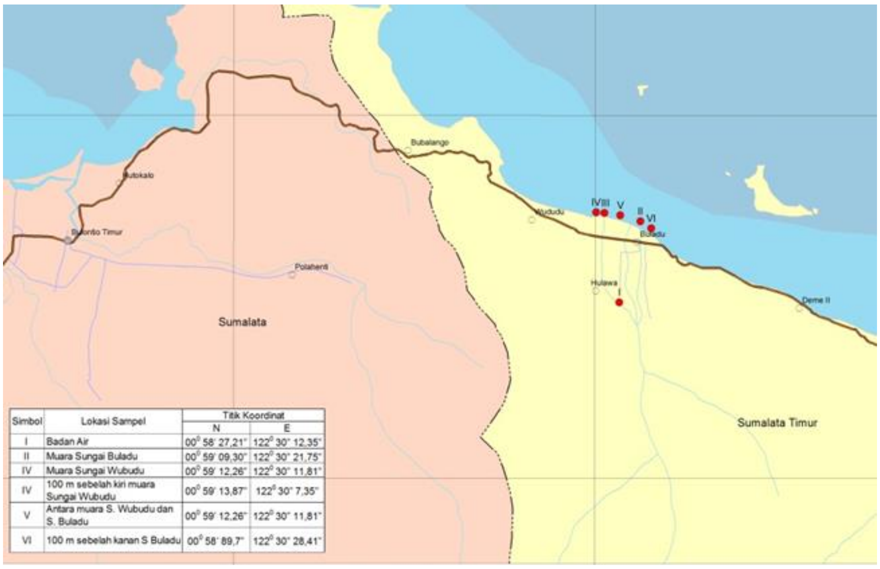

Figure 1. Illustrates the locations of the sampling

Sampling Locations and Site Selection

Field sampling was carried out in several key locations around Teluk Sumalata, with a focus on areas that represent different ecological zones: estuarine, mangrove, seagrass, and coral reef ecosystems. Sampling points were specifically chosen to encompass a range of mining activities, from areas near the river mouths where sediment runoff is significant to regions farther out into the bay where the effects of mining activities may still be detected due to ocean currents and sediment transport. Six sampling sites were selected in total, with specific coordinates provided for each (Table 1).

Table 1. Sampling Location

Sample Code	Location	North	East
A	Wubudu River	00º 58’’27,21’’	122º 30’12,35’’
B	100 m to the left of the Wubudu River estuary	00º 59’’13,35’’	122º 30’7,35’’
C	Wubudu River Estuary	00º 59’’12,26’’	122º 30’11,81’’
D	Between the Wubudu and Buladu Rivers	00º 59’’12,26’’	122º 30’11,81’’
E	Buladu River Estuary	00º 59’’09,30’’	122º 30’21,75’’
F	100 m to the right of the Buladu River Estuary	00º 59’’89,7’’	122º 30’28,41’’

The sites were divided into two categories: sites impacted directly by mining activities and sites considered less impacted, serving as a baseline for comparison. Sampling was conducted at three different zones: the river mouth, the estuarine area, and the coastal zone closer to the coral reef. The proximity of the river mouths to active mining sites makes them particularly sensitive to contamination, as runoff and sedimentation can directly affect the water quality in these regions (Sforzini et al., 2018). By including both mining-impacted and control sites, the study could evaluate the relative contribution of mining activities to the degradation of water quality and ecosystem health.

Sampling for water quality parameters was done at several depths to account for vertical gradients in contamination levels, especially for parameters like dissolved oxygen and temperature. This is crucial, as the impacts of mining activities can vary at different depths, with surface waters often being more affected by pollution from mining runoff (Sforzini et al., 2018). Sediment samples were collected from riverbeds and coastal areas, as sediments are known to serve as sinks for contaminants, including heavy metals such as mercury (Costa et al., 2012).

Environmental Parameters and Analytical Methods

A wide range of environmental parameters was measured to assess water quality and ecosystem health. The focus was on parameters that are most indicative of pollution from mining activities, particularly the presence of heavy metals like mercury (Hg), lead (Pb), and cadmium (Cd), which are commonly released during gold extraction (He et al., 2014). In addition to heavy metals, other key water quality parameters were measured, including temperature, salinity, pH, total dissolved solids (TDS), turbidity, and dissolved oxygen (DO). These parameters provide important insights into the general health of the aquatic environment and are widely used in environmental monitoring (Sforzini et al., 2018).

Heavy metal concentrations in both water and sediment were quantified using state-of-the-art laboratory techniques such as inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy (AAS). These methods are highly sensitive and capable of detecting trace amounts of metals in environmental samples, ensuring that even low concentrations of contaminants are accurately measured (Arabi et al., 2020).

Sediment samples were also analyzed for the presence of mercury and other heavy metals. Since sediments often accumulate metals from water and organic matter, analyzing sediment cores allows researchers to assess the bioavailability of metals in the benthic environment, providing insights into the potential for bioaccumulation in marine organisms (He et al., 2014).

The laboratory analysis also involved testing for several chemical parameters such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which indicate the presence of organic pollutants that could further stress marine ecosystems. Additionally, the bioavailability of mercury was assessed through its methylated form, methylmercury (MeHg), which is more toxic and prone to bioaccumulation in aquatic food webs (Nirchio et al., 2025).

Sediment and Bioindicator Sampling

Sediment sampling was an integral part of the methodology, as sediments act as both a repository and a potential source of contaminants. The process involved collecting sediment cores from different depths at each sampling site to measure metal concentrations and assess the potential for bioaccumulation in benthic organisms. According to Geneletti (2011), sediment sampling can provide valuable data on the long-term contamination levels in coastal environments, especially those affected by mining, which often leads to the accumulation of heavy metals in the sediments over time.

In addition to sediment samples, biological monitoring using bioindicators was employed to assess the effects of pollution on marine life. Bioindicators such as mollusks, fish, and plankton are useful tools for evaluating the biological effects of pollutants, particularly heavy metals, on marine organisms (Onyena & Nwaogbe, 2024). Bioaccumulation studies were conducted by analyzing the tissues of selected marine species for metal concentrations. This method provides direct evidence of the impact of pollutants on aquatic organisms and serves as a proxy for assessing the health of the entire ecosystem (Jha et al., 2023).

Laboratory Analysis and Quality Control

All samples were transported to the laboratory in sealed containers to prevent contamination, and quality control measures were employed throughout the analysis process. Water samples were filtered to remove particulate matter and then acidified to prevent the precipitation of metals during transport (Sforzini et al., 2018). In the laboratory, samples were analyzed using advanced analytical instruments, ensuring the accurate quantification of heavy metals in both water and sediment samples.

Standard operating procedures (SOPs) for sample handling, preparation, and analysis were followed to ensure the reproducibility and reliability of the results. Calibrations were performed using certified reference materials to maintain accuracy throughout the analysis, in line with the recommendations of Faiz et al. (2024). The laboratory's internal quality control measures included the use of blank samples, duplicate samples, and spiked recovery tests to assess the precision and accuracy of the measurements.

Data Analysis and Interpretation

The data collected from the field sampling and laboratory analyses were subjected to statistical analysis to identify patterns and trends in water quality and ecosystem health. Descriptive statistics were used to summarize the data, while inferential statistics were employed to determine the significance of differences between sampling sites and temporal variations in environmental parameters.

Spatial analysis using Geographic Information Systems (GIS) was performed to map the distribution of pollutants and visualize the relationship between mining activities and environmental degradation (Cruz-García et al., 2015). GIS technology allowed for the integration of various datasets, including land use patterns, sediment and water quality data, and ecological distribution maps, to provide a spatial understanding of pollution impacts and assist in identifying hotspots of contamination (Jha et al., 2023).

RESULT

This section presents the findings of the study on the environmental impacts of illegal gold mining on marine ecosystems in Teluk Sumalata. The results are organized into three main areas: water quality parameters, ecosystem health, and biological community impacts. The findings are based on data collected from various sampling sites, with a particular focus on the contamination of water and sediments, the degradation of critical ecosystems such as mangroves, seagrasses, and coral reefs, and the overall biodiversity loss due to mining-related pollution. These results are analyzed in light of the study's objectives and previous literature, providing valuable insights into the effects of illegal mining on marine ecosystems in the region.

Water Quality Parameters

The assessment of water quality at Teluk Sumalata highlighted significant variations in key parameters, particularly in areas impacted by illegal gold mining. The study measured a range of environmental variables, including temperature, salinity, pH, dissolved oxygen, turbidity, and the presence of heavy metals. These parameters were monitored at multiple depths across six sampling sites to account for vertical stratification and pollution gradients, especially near mining operations.

Temperature, Salinity, and pH Levels

Temperature, salinity, and pH levels in the sampled water bodies were found to fluctuate significantly across different zones within Teluk Sumalata. As expected, the sites closer to mining operations exhibited higher temperature variations, which are often associated with increased sedimentation and disturbances caused by mining activities. The pH levels in mining-impacted zones were notably lower, indicating increased acidity in the water, which could be linked to the runoff of acid-generating compounds such as mercury and sulfur from the mining process (Sforzini et al., 2018). This acidity may harm marine organisms that rely on stable pH levels for survival, particularly sensitive species in mangrove and coral ecosystems (Chakuya et al., 2023).

Salinity levels varied across the different sites, with estuarine and mangrove areas exhibiting lower salinity, consistent with the influence of freshwater influx from nearby rivers and mining runoff. The salinity levels near the river mouths were particularly low, likely due to the increased flow of freshwater contaminated with mining byproducts (Sforzini et al., 2018). These variations in salinity are crucial as they impact the physiological tolerance of marine organisms, particularly those inhabiting mangrove and seagrass ecosystems.

Heavy Metals: Mercury, Lead, and Cadmium

The presence of heavy metals in the water samples was a primary concern, with mercury being the most prominent contaminant. The mercury concentrations in water samples from mining-affected sites exceeded the allowable limits set by Indonesian environmental regulations (Keputusan Menteri Negara Lingkungan Hidup Nomor 51 Tahun 2004). Mercury concentrations ranged from 0.005 to 0.02 µg/L, which is significantly higher than the regulatory threshold of 0.001 µg/L for aquatic environments (Costa et al., 2012). These elevated mercury levels are consistent with previous studies on the impact of illegal gold mining, which often involves the use of mercury to extract gold, leading to its direct discharge into nearby water systems (Mestanza-Ramón et al., 2021).

Lead and cadmium concentrations were also found to be elevated in the mining zones, though not to the same extent as mercury. Lead concentrations ranged between 0.001 and 0.005 µg/L, and cadmium levels were between 0.0005 and 0.002 µg/L. These metals are toxic to marine organisms, particularly fish and invertebrates, and can accumulate in food webs, posing long-term ecological and health risks (Nirchio et al., 2025).

Dissolved Oxygen and Turbidity

Dissolved oxygen (DO) levels in the water were found to be significantly lower in the mining-impacted sites compared to the control sites. The DO levels ranged from 2.0 to 4.5 mg/L, which is below the threshold required to support most marine life (Jha et al., 2024). This decrease in oxygen levels can be attributed to increased organic pollution from mining runoff, which can lead to eutrophication and oxygen depletion in aquatic environments.

Turbidity levels were also found to be higher in the mining-impacted sites, with measurements ranging from 20 to 60 NTU (Nephelometric Turbidity Units), compared to 5 to 10 NTU at the control sites. This increase in turbidity is caused by the high sedimentation rates from mining activities, which smother benthic organisms and reduce light penetration, further exacerbating the stress on seagrass beds and coral reefs (Aliyeva et al., 2023).

Ecosystem Health: Mangroves, Seagrasses, and Coral Reefs

The health of key coastal ecosystems, including mangroves, seagrasses, and coral reefs, was assessed through direct observation and analysis of ecological parameters. The findings reveal significant degradation of these ecosystems, particularly in areas exposed to the highest levels of mining pollution.

Mangrove Ecosystems

Mangroves, which provide vital ecosystem services such as coastal protection and habitat for marine life, were found to be severely impacted by mining activities. The physical destruction of mangrove forests through illegal clearing for mining and land-use changes was evident in several sites. In areas closer to mining operations, mangrove trees showed signs of stress, including reduced growth, leaf discoloration, and dieback. The increased sedimentation and water quality decline associated with mining runoff further exacerbated the vulnerability of mangrove ecosystems (Barbier, 2017; Mamola et al., 2024).

Mercury contamination in mangrove areas was found to be significantly higher compared to the control sites. The bioaccumulation of mercury in mangrove root systems and associated fauna, such as crabs and mollusks, was evident, with mercury concentrations in plant tissues ranging from 0.02 to 0.12 µg/g (Nirchio et al., 2025). This bioaccumulation could have long-term effects on mangrove-associated food webs, further weakening the resilience of these ecosystems.

Seagrass Ecosystems

Seagrass beds, which are essential for marine biodiversity and sediment stabilization, were also negatively impacted by the mining activities. Increased turbidity and sediment runoff from mining operations smothered seagrass beds, reducing light availability and inhibiting photosynthesis. As a result, seagrass growth rates were significantly lower in mining-impacted sites. In some areas, seagrass beds were completely absent, replaced by a thin layer of sediment (Chakuya et al., 2023; Magris et al., 2019).

The loss of seagrasses has cascading effects on the ecosystem, as these plants provide important habitats and food for juvenile fish, invertebrates, and other marine organisms. The decline in seagrass cover also impacts nutrient cycling in the ecosystem, further exacerbating the degradation of water quality and ecosystem health.

Coral Reefs

Coral reefs in Teluk Sumalata showed signs of stress, particularly in areas near mining activities. Increased levels of mercury and sedimentation contributed to coral bleaching, with some species of corals exhibiting significant loss of their symbiotic zooxanthellae. Coral reefs are highly sensitive to pollution, and the increased nutrient levels and sedimentation from mining runoff further stressed these ecosystems, reducing their resilience to climate change and other anthropogenic impacts (Tchounwou et al., 2012; Liu et al., 2016).

The reduction in coral cover and biodiversity in mining-impacted sites was also linked to the decline in fish populations that rely on coral reefs for food and shelter. As coral reefs deteriorate, the availability of food sources for local communities that depend on fishing diminishes, leading to socio-economic challenges for these populations (Escobar-Segovia et al., 2021).

Biological Communities and Ecosystem Resilience

The impacts of mining pollution on biological communities were observed across the three key ecosystems: mangroves, seagrasses, and coral reefs. In each case, pollution from mercury and sedimentation disrupted species composition, reduced biodiversity, and weakened the ecosystem's ability to recover from disturbances.

Disruption of Species Composition

In mangrove ecosystems, mining pollution led to changes in species composition, with several sensitive species showing declines in population. The reduced abundance of key species, such as crabs and mollusks, in mining-impacted areas indicates that pollution has a direct effect on the structure of food webs in these ecosystems (Ruppen et al., 2021).

Similarly, in seagrass ecosystems, increased sedimentation and turbidity reduced the growth of seagrasses, leading to a loss of habitat for herbivorous fish and invertebrates. These changes in community structure not only affect biodiversity but also reduce the capacity of seagrass ecosystems to provide essential ecosystem services, such as nutrient cycling and carbon sequestration (Hussein & Assaf, 2020).

Declines in Ecosystem Resilience

The cumulative impact of mining pollution, including the release of heavy metals and the physical destruction of habitats, has significantly reduced the resilience of coastal ecosystems. In Teluk Sumalata, the mangrove, seagrass, and coral reef ecosystems demonstrated a decreased ability to recover from disturbances caused by mining activities. This reduced resilience makes these ecosystems more vulnerable to additional stressors, such as climate change and overfishing, further compounding the effects of mining pollution (Wu et al., 2025; Hain & Sutton, 2023).

Summary of Findings

In summary, the results of this study indicate that illegal gold mining has profound and far-reaching impacts on the marine ecosystems of Teluk Sumalata. The contamination of water and sediments with heavy metals, particularly mercury, has led to the degradation of mangrove, seagrass, and coral reef ecosystems. These ecosystems provide essential services for marine biodiversity and coastal protection, but their ability to recover from pollution is severely compromised. The findings underscore the urgent need for targeted management strategies to mitigate the impacts of mining activities and protect the biodiversity and health of these vital ecosystems. The integration of effective monitoring, enforcement, and restoration efforts will be crucial to safeguarding the marine environment of Teluk Sumalata for future generations.

DISCUSSION

The ecological impacts of illegal gold mining in coastal areas, particularly in the Teluk Sumalata region, have highlighted significant challenges concerning environmental sustainability. The results of this study underline the importance of addressing both immediate and long-term consequences of mining practices, such as mercury contamination, habitat destruction, and subsequent biodiversity loss. As shown in the previous results, the negative impacts on mangrove, seagrass, and coral ecosystems demand urgent intervention and a reevaluation of management strategies for these vulnerable habitats.

One of the most striking findings from this study is the clear degradation of vital coastal ecosystems due to the indiscriminate use of harmful substances like mercury, which is commonly used in illegal gold mining. Mercury's bioaccumulative properties in marine ecosystems exacerbate the environmental hazards already present from mining activities. Mercury contamination not only affects the health of marine species, including fish and invertebrates, but it also threatens the food security of local communities that depend on these species for sustenance. In the Teluk Sumalata region, where such activities are prevalent, local populations face risks from both ecological damage and direct exposure to toxic substances. As noted by Costa et al. (2012), mercury bioaccumulation poses a severe threat to aquatic life, disrupting reproductive and neurological functions in fish and other organisms.

The Impact of Illegal Mining on Marine Ecosystems

The direct physical destruction of mangroves, seagrasses, and coral reefs is compounded by the pollution of nearby waters through mining runoff. In mangrove ecosystems, mining activities lead to sedimentation and a reduction in water quality, which diminishes the ability of these ecosystems to provide essential services like coastal protection and habitat for marine species. As Barbier (2017) and Mamola et al. (2024) observed, mangroves are particularly vulnerable to sedimentation, as they serve as crucial buffers against coastal erosion and storm surges. The degradation of these ecosystems directly impacts the coastal communities that rely on them for protection against natural disasters.

Seagrass beds, as essential components of coastal ecosystems, are similarly impacted by the increased sediment runoff from mining activities. Seagrasses depend on clear water for photosynthesis, and the increased turbidity and sedimentation from mining disrupt their growth, leading to reduced biodiversity in these areas. This disruption has far-reaching effects on marine food webs, as seagrasses provide critical habitats for various species of fish and invertebrates, which in turn support the broader marine ecosystem (Chakuya et al., 2023). In many cases, the decline in seagrass health and coverage directly correlates with the decline in fish populations that depend on these habitats.

Similarly, coral reefs in the region are under stress, as mining activities not only release toxic chemicals like mercury into the surrounding waters but also contribute to sedimentation, which can smother corals. As noted by Tchounwou et al. (2012), coral reefs are highly sensitive to environmental stressors, particularly pollutants such as mercury and sediment. These pollutants hinder the ability of coral species to survive and thrive, contributing to the overall decline in coral health and resilience. Furthermore, coral reefs are vital for maintaining biodiversity and providing ecosystem services such as habitat for marine species and shoreline protection.

The Role of Mercury in Ecosystem Degradation

The effects of mercury contamination in Teluk Sumalata are profound and long-lasting, with the potential to disrupt entire marine ecosystems. Mercury from illegal gold mining enters the ecosystem through runoff and direct discharges, where it accumulates in sediments and aquatic organisms. The findings from this study align with previous research (Driscoll et al., 2013) that shows mercury's ability to bioaccumulate and biomagnify through the food chain, ultimately affecting top predators, including humans, who consume contaminated seafood.

As the mercury accumulates in the tissues of aquatic organisms, it poses significant risks to marine life. In fish and other species, mercury affects reproductive success, growth, and survival rates, which can lead to population declines (Nirchio et al., 2025). In the Teluk Sumalata region, this has severe implications not only for the health of marine species but also for the livelihoods of local fishing communities that depend on these species for food and income.

The bioaccumulation of mercury in the food chain is a critical concern, as it can have both immediate and long-term impacts on ecosystem health. The loss of biodiversity, particularly among sensitive species such as fish and invertebrates, undermines the stability of marine food webs. This, in turn, compromises the resilience of coastal ecosystems, making them less able to recover from disturbances and more vulnerable to additional stressors such as climate change and habitat alteration (Wu et al., 2025; Hain & Sutton, 2023). The findings of this study underscore the need for targeted efforts to mitigate mercury contamination and protect vulnerable marine species.

Importance of Monitoring and Management in Mitigating Ecological Impacts

To mitigate the ecological impacts of illegal mining, effective monitoring and management strategies are essential. The use of remote sensing and Geographic Information Systems (GIS) technologies can significantly enhance the detection and monitoring of pollution sources and their impacts on coastal ecosystems (Barbier et al., 2011). By mapping the spatial distribution of pollutants and ecological hotspots, these tools can help guide the development of targeted mitigation strategies, such as the establishment of Marine Protected Areas (MPAs) around critical habitats like mangroves and coral reefs.

Marine protected areas have been shown to be effective in safeguarding coastal ecosystems from further degradation by restricting harmful human activities, including mining (Fakhrurrozi et al., 2023). In addition to MPAs, community-based conservation programs can provide an important complement to government-led efforts. By involving local communities in monitoring and protecting coastal resources, these programs can foster stewardship and increase local awareness of the importance of sustainable practices (Murtasidin et al., 2023). Furthermore, strengthening local governance structures and ensuring that communities have a voice in decision-making processes can improve the enforcement of environmental regulations and contribute to the sustainability of coastal ecosystems.

Community Engagement and Sustainable Livelihoods

Community engagement plays a crucial role in the success of conservation efforts aimed at mitigating the impacts of illegal mining. In Teluk Sumalata, community members who rely on mining for their livelihoods may be reluctant to adopt sustainable practices without alternative income sources. Therefore, integrating sustainable livelihoods into conservation programs is essential for addressing the socio-economic pressures that drive illegal mining. Bayraktarov et al. (2020) and Harries et al. (2023) emphasize the importance of developing alternative livelihoods, such as sustainable agriculture, fishing, or ecotourism, which can provide long-term economic benefits without the environmental costs associated with mining.

Education and capacity-building programs are also essential for fostering awareness of the environmental impacts of mining and the importance of conservation. These programs can help local communities understand the value of coastal ecosystems and the services they provide, such as water purification, shoreline protection, and habitat for marine life. By educating community members about the long-term benefits of ecosystem conservation, it becomes more likely that they will actively participate in protecting their local environment (Dao et al., 2019; Mercado-Garcia et al., 2018). Moreover, community-based initiatives can increase local engagement in monitoring and reporting illegal mining activities, thereby strengthening enforcement efforts.

Policy and Regulatory Frameworks for Sustainable Mining Practices

The regulation of illegal mining in coastal areas requires a robust policy and regulatory framework that incorporates both environmental protection and sustainable development. Effective policies should include the establishment of clear environmental standards for mining activities, such as environmental impact assessments (EIA), and the promotion of sustainable mining practices (Dao et al., 2019). Additionally, policies should encourage the use of clean technologies in mining operations, which can significantly reduce the release of harmful pollutants like mercury into the environment (Ackerman et al., 2015).

Strengthening the legal framework surrounding coastal resource management is critical for ensuring the enforcement of mining regulations. As shown by the successful case studies from other regions (Fakhrurrozi et al., 2023; Utami et al., 2024), collaboration across local, regional, and national governments can enhance the enforcement of policies and ensure the long-term sustainability of coastal ecosystems. In the case of Teluk Sumalata, such collaboration is essential for addressing the complex challenges posed by illegal mining and for promoting sustainable management practices that protect both the environment and the livelihoods of local communities.

Scaling Up Restoration and Conservation Efforts

Scaling up ecosystem restoration efforts is crucial for rehabilitating areas impacted by illegal mining. The rehabilitation of mangrove ecosystems, in particular, requires the integration of ecological, social, and economic factors to ensure the success of restoration initiatives. As Rosa et al. (2020) and Ellison et al. (2020) suggest, restoration projects must take into account local hydrology and species-specific needs, as well as the socio-economic context of the region.

Furthermore, successful restoration requires the active involvement of local communities, who can contribute valuable knowledge and labor to restoration efforts. By empowering local populations and incorporating traditional ecological knowledge into restoration projects, the chances of success are significantly increased (DeAngelis et al., 2020). In addition, promoting policies that recognize the value of ecosystem services provided by restored habitats, such as carbon sequestration and coastal protection, can help secure long-term support for restoration initiatives (Blair et al., 2015; Birnbaum & Trevathan-Tackett, 2022).

In conclusion, the discussion highlights the urgent need for integrated strategies that address the ecological, social, and economic impacts of illegal mining in Teluk Sumalata. These strategies should include effective monitoring, community engagement, sustainable livelihood development, and robust regulatory frameworks to protect vulnerable coastal ecosystems. By implementing these strategies, the region can mitigate the detrimental effects of illegal mining and enhance the resilience of its coastal ecosystems for future generations.

CONCLUSION

This study aimed to assess the environmental impacts of illegal gold mining on marine ecosystems, specifically focusing on Teluk Sumalata. The findings revealed significant degradation in key coastal habitats, including mangroves, seagrass beds, and coral reefs, primarily due to the contamination of water and sediments with heavy metals like mercury. These pollutants, especially mercury, were found to bioaccumulate in marine organisms, causing detrimental effects on biodiversity and ecosystem health. The study also highlighted the importance of understanding the intricate relationships between mining activities, water quality, and marine life to develop effective conservation strategies.

The discussion emphasized that strategies such as integrated coastal zone management, community-based conservation initiatives, and enhanced monitoring using GIS and remote sensing technologies are essential for mitigating the impacts of illegal mining. Moreover, the involvement of local communities in monitoring and protection efforts plays a critical role in fostering environmental stewardship and ensuring the sustainability of coastal resources.

This research contributes to the existing body of knowledge by providing a detailed assessment of the environmental consequences of illegal mining on coastal ecosystems, particularly in a region that has been under-researched. It calls for further investigation into the long-term ecological impacts of mercury contamination and the effectiveness of community-based governance models in mitigating such impacts. Future research could focus on evaluating the success of restoration initiatives and their socio-economic benefits, as well as exploring alternative livelihoods that do not rely on harmful mining practices.

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