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Microplastics in Indonesian Freshwater Ecosystems: Domestic and Industrial Sources, Ecological Impacts, and Education-Based Mitigation

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Abstract. *Microplastic pollution in freshwater ecosystems has become an environmental issue that is receiving increasing attention due to its impacts on ecosystem sustainability and human health. This study aims to examine the sources and pathways of microplastics entering Indonesian freshwater ecosystems, the mechanisms of bioaccumulation and their ecological impacts on aquatic organisms, and to formulate mitigation strategies integrated with environmental education based on Project-Based Learning. The research method employed was a systematic literature review of scientific articles published between 2021 and 2025 that are relevant to microplastics, freshwater ecosystems, and environmental education. The results indicate that microplastics are widely distributed in Indonesian freshwater bodies, with primary sources originating from domestic and industrial waste. The dominant polymer types are polyethylene, polypropylene, and polyester, predominantly in the form of small-sized fragments and fibers. Microplastics accumulate in various aquatic organisms, including freshwater fish consumed by humans, and cause physiological and ecological impacts that potentially disrupt ecosystem stability. Furthermore, the integration of microplastic issues into project-based environmental education has been shown to enhance students' scientific literacy and environmental awareness. This study emphasizes that microplastic pollution requires comprehensive management through integrated policy, technological, and sustainable educational approaches.*
Keywords: *Microplastics, Freshwater Ecosystems, Bioaccumulation, Ecological Impacts, Project-Based Learning*

1. Introduction

Environmental pollution caused by plastic waste is one of the Environmental polution caused by plastic waste is one of the increasingly complex global problems, particularly in developing countries such as Indonesia. The high production and consumption of plastics from domestic and industrial activities are not matched by effective waste management systems. This condition leads to the accumulation of plastic waste in open environments, which subsequently degrades into small-sized particles known as microplastics. This phenomenon places Indonesia as one of the regions with a high risk of microplastic pollution in Southeast Asia (Cordova et al., 2021), thereby necessitating serious attention to the subsequent impacts it generates.

Freshwater ecosystems are among the environmental compartments most affected by the presence of microplastics. Rivers, lakes, and reservoirs function as final recipients of domestic and industrial waste, as well as major pathways for the distribution of microplastics from terrestrial areas. Recent studies indicate that microplastics have been widely detected in various major rivers in Indonesia, including rivers utilized as sources of raw water and community fisheries (Syakti et al., 2022; Dewi et al., 2023). These

findings suggest that microplastic pollution is no longer localized but has spread systemically throughout freshwater ecosystems.

The emerging problem is not limited to the presence of microplastics themselves, but also involves the lack of comprehensive understanding regarding their entry pathways, environmental dynamics, and bioaccumulation mechanisms in freshwater systems. Microplastics can be ingested by aquatic organisms and accumulate within their tissues, subsequently transferring across trophic levels through the food chain. This process has the potential to cause long-term ecological impacts, including physiological disturbances, oxidative stress, and declining health of aquatic biota (Amin et al., 2021; Pangestu et al., 2021). Consequently, microplastic pollution not only threatens ecosystem sustainability but also poses implications for human health.

On the other hand, efforts to mitigate microplastic pollution in Indonesia still face various limitations. Existing policy approaches and waste treatment technologies have not yet been fully effective in reducing the rate at which microplastics enter aquatic environments. This situation is exacerbated by low levels of public awareness and environmental literacy regarding plastic waste management. Therefore, a more comprehensive and sustainable approach is required, one of which involves strengthening the role of environmental education as a means of behavior change and enhancement of ecological awareness (UNESCO, 2021). The integration of microplastic issues into learning activities, particularly through a Project-Based Learning (PjBL) approach, is considered relevant to addressing these challenges. Project-based learning enables students to examine real environmental problems through observation activities, sample collection, data analysis, and the formulation of contextual solutions. This approach has been shown to be effective in improving scientific literacy, critical thinking skills, and concern for environmental sustainability issues (Thomas, 2020). Thus, education can serve as a strategic instrument in mitigating microplastic pollution in Indonesian freshwater ecosystems.

Based on these issues, this study aims to examine the sources and pathways of microplastics originating from domestic and industrial activities into Indonesian freshwater ecosystems, as well as their bioaccumulation mechanisms and ecological impacts on aquatic organisms. In addition, this study seeks to formulate microplastic pollution mitigation strategies integrated with Project-Based Learning–based environmental education as an effort to enhance environmental literacy and foster sustainable behavior.

2. Method

This study employed a systematic literature review approach aimed at compiling, analyzing, and synthesizing recent research findings related to microplastic pollution in Indonesian freshwater ecosystems and its implications for environmental education. The literature review approach was selected because it is capable of providing a comprehensive overview of general patterns, research trends, and existing gaps that still require further development, particularly in the context of developing countries such as Indonesia (Kurniawan et al., 2022). Data collection was conducted through a search for scientific articles published between 2021 and 2025 to ensure the relevance and novelty of the data. Literature sources were obtained from reputable international databases such as ScienceDirect, SpringerLink, Scopus, and PubMed, as well as national databases such as Garuda and others.

The keywords used included *microplastic pollution*, *freshwater ecosystem*, *bioaccumulation*, *ecological impact*, and *environmental education*, combined with the Indonesian context. This search strategy enabled the researchers to obtain relevant literature from both ecological and environmental education perspectives (Cordova et al., 2021). The retrieved articles were then screened based on inclusion and exclusion criteria. The inclusion criteria comprised: (1) research articles or review articles addressing microplastics in freshwater environments; (2) studies focusing on sources, pathways, bioaccumulation, or ecological impacts of microplastics; and (3) publications that addressed aspects of mitigation or environmental education. Meanwhile, articles that were not relevant to the freshwater context or did not provide sufficient data and analysis were excluded from the review.

Through this process, a number of selected articles were obtained and considered to have strong methodological quality and scientific contribution. Data analysis was conducted using thematic synthesis, namely the grouping of research findings based on major themes, including sources and pathways of microplastics, mechanisms of bioaccumulation and trophic transfer, ecological impacts on aquatic organisms, and mitigation strategies. Subsequently, a conceptual analysis was carried out to examine the relationship between microplastic pollution and the role of environmental education in mitigation efforts. This approach allowed for the integration of ecological findings and sustainability-based learning concepts (UNESCO, 2021).

As a final stage, the results of the literature synthesis were integrated with the Project-Based Learning (PjBL) approach to formulate contextual and applicable environmental education strategies. This model was developed based on the principles of Education for Sustainable Development, which emphasize the integration of scientific knowledge, critical awareness, and concrete actions in addressing environmental problems (Thomas, 2020). Thus, this research methodology not only generates theoretical understanding but also offers an applicable framework within the educational context.

3. Results and Discussions

General Characteristics of Microplastic Pollution in Indonesian Freshwater Ecosystems

The literature review indicates that microplastics have been consistently detected across various types of freshwater ecosystems in Indonesia, including rivers, lakes, reservoirs, and artificial water bodies. Microplastics are found in the water column, bottom sediments, and aquatic organisms, indicating that contamination is pervasive and not confined to a single environmental compartment. Reported concentrations are higher in rivers traversing urban and industrial areas compared to rural regions. Rivers with intensive anthropogenic activities show relatively stable microplastic accumulation throughout the year, suggesting a continuous supply from human activities. Freshwater systems function both as accumulation sites and as transport pathways for microplastics from terrestrial areas to downstream waters. This demonstrates that microplastic pollution in freshwater environments has cross-ecosystem implications and the potential to extend impacts to coastal regions.

Pathways of Microplastic Entry from Domestic and Industrial Activities

Data synthesis shows that microplastics enter freshwater ecosystems through several primary pathways: domestic wastewater, industrial effluents, surface runoff, and atmospheric deposition. Domestic wastewater is the dominant pathway, particularly from

activities such as washing synthetic clothing, the use of single-use plastics, and personal care products. Industrial wastewater—especially from textile and plastic manufacturing industries—also contributes significantly. Synthetic fibers and plastic pellets are often released into water bodies due to limitations in wastewater treatment systems.

Table 1. Pathways of Microplastic Entry into Freshwater Ecosystems

Entry Pathway	Main Sources	Relative Contribution
Domestic wastewater	Households, laundry	High
Industrial wastewater	Textile, plastics	Moderate–high
Surface runoff	Open landfills	Moderate
Atmospheric deposition	Airborne particles	Low–moderate

Based on Table 1, domestic wastewater—particularly household activities and laundry—contributes the most to microplastic inputs into freshwater ecosystems. These findings indicate that everyday activities, such as the use of single-use plastics and washing synthetic clothing, play a major role in releasing microplastics into aquatic environments. Domestic wastewater typically enters water bodies through drainage systems and wastewater treatment plants that are not designed to filter micro-sized particles, allowing microplastics to pass through and accumulate in freshwater systems.

The moderate to high contribution from industrial wastewater, particularly from textile and plastic manufacturing sectors, indicates that production activities are also important sources of microplastics. Synthetic fibers and plastic fragments released during industrial processes can enter water bodies when liquid waste management is suboptimal. This suggests that microplastic pollution is influenced not only by individual behavior but also by production systems and industrial waste management technologies that still have limitations in micro-particle filtration. Additionally, surface runoff from open landfills and atmospheric deposition contribute to microplastic pollution, albeit at lower intensities. Surface runoff acts as a secondary pathway transporting plastic fragments from land to water during rainfall, while atmospheric deposition indicates that microplastics can be transported through the air before settling into water bodies. These findings underscore the complexity of microplastic transport pathways involving multiple environmental compartments.

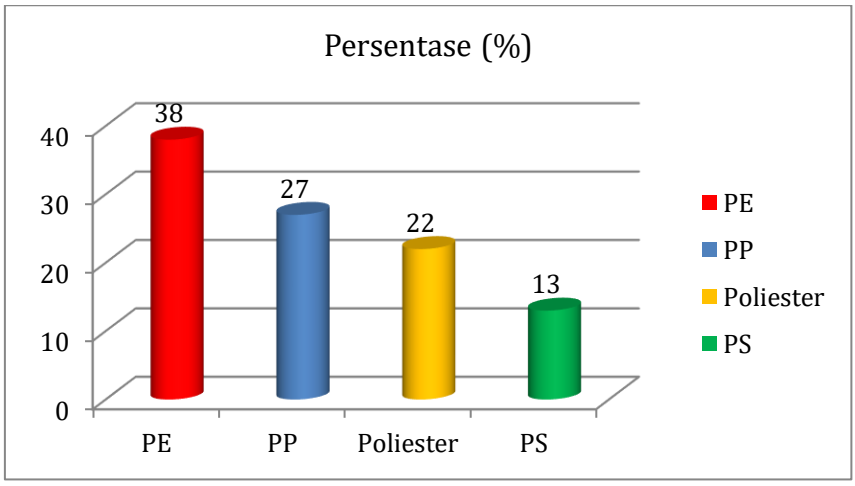
Overall, the entry pathway patterns shown in Table 1 indicate that microplastic pollution control efforts should focus on upstream source reduction, particularly from domestic and industrial activities. Mitigation approaches emphasizing behavioral change, improvements in waste treatment technologies, and strengthened industrial regulations are strategic steps to sustainably reduce microplastic inputs into freshwater ecosystems.

Polymer Types and Microplastic Composition

The dominant microplastic polymer types identified are polyethylene (PE), polypropylene (PP), and polyester. These polymers are commonly used in food packaging, plastic bags, beverage bottles, and synthetic clothing. The dominance of lightweight polymers causes microplastics to float easily and disperse widely following water currents, while higher-density polymers tend to accumulate in sediments.

Table 2. Polymer Composition of Microplastics

Polymer	Percentage (%)	Dominant Source
PE	38	Bags and packaging
PP	27	Food packaging
Polyester	22	Textile fibers
PS	13	Styrofoam



Based on the table and accompanying data, the polymer composition of microplastics in Indonesian freshwater ecosystems is dominated by polyethylene (PE) at 38%. This dominance indicates that single-use plastics, such as plastic bags and various packaging materials, are the primary sources of microplastic pollution. These plastics are widely used due to their light weight, low cost, and practicality, yet they are highly resistant to natural degradation, making them prone to fragmentation and accumulation in aquatic environments. Polypropylene (PP) ranks second at 27%, typically originating from food packaging and household items. The high contribution of PP reflects consumption patterns that remain heavily dependent on plastic-based products. Its relatively low density also allows PP microplastics to float and disperse widely in the water column, increasing interactions with aquatic organisms.

Polyester, accounting for 22% of microplastics, primarily originates from synthetic textile fibers released during laundry activities. This finding highlights that microplastic sources are not limited to solid waste but also include domestic liquid waste routinely discharged into the environment. Polyester fibers are very small and difficult to filter using conventional wastewater treatment systems, allowing them to persist long-term in freshwater environments. Polystyrene (PS) from Styrofoam contributes a smaller percentage but remains ecologically significant. PS readily fragments into micro- and nanoplastics with potentially higher toxic effects on aquatic organisms. Therefore, despite its lower quantitative contribution, PS warrants attention in microplastic pollution control efforts.

Overall, the dominance of PE, PP, and polyester indicates that microplastic pollution is closely linked to consumption patterns and the widespread use of plastic products and synthetic textiles. These findings reinforce the importance of mitigation strategies focused on reducing single-use plastics, managing textile waste, and

developing environmentally friendly alternative materials to reduce microplastic burdens in freshwater ecosystems.

Morphology and Size of Microplastics

The dominance of fragment- and fiber-shaped microplastics in freshwater ecosystems indicates that microplastic pollution in Indonesia is largely secondary in nature, originating from the degradation of larger plastic items and routine human activities. Fragment-shaped microplastics reflect continuous macroplastic weathering due to ultraviolet radiation, mechanical abrasion, and physicochemical processes in aquatic environments. This condition reflects the long-term accumulation of plastic waste that has not been optimally managed. The presence of fiber-shaped microplastics underscores the significant contribution of domestic activities, particularly washing synthetic clothing. These fibers are very small and flexible, making them easily released into wastewater and difficult to capture using conventional treatment systems. This indicates that microplastic pollution arises not only from visible solid waste but also from liquid waste routinely discharged without public awareness.

From a size perspective, the dominance of small-sized microplastics has important ecological implications. Smaller particles are more easily ingested by low-trophic-level organisms, such as zooplankton and benthic invertebrates. Their small size also increases relative surface area, enhancing the adsorption of hazardous chemicals from the aquatic environment and potentially increasing toxic risks upon ingestion.

Overall, the morphological and size characteristics dominated by small fragments and fibers indicate that microplastic pollution in Indonesian freshwater ecosystems results from long-term accumulation of human activities. These findings emphasize that mitigation efforts should not only focus on reducing macroplastic waste but also on controlling less visible microplastic sources, particularly from domestic activities and synthetic textile use. Thus, morphology and size are key indicators for assessing ecological risk and the effectiveness of environmental management strategies.

Bioaccumulation of Microplastics in Freshwater Organisms

The review shows that microplastics have accumulated in a wide range of freshwater organisms, from zooplankton and benthic invertebrates to fish. Organisms with non-selective feeding habits exhibit higher accumulation levels. Commonly consumed freshwater fish, such as tilapia, common carp, and Mozambique tilapia, have consistently been reported to contain microplastics in their digestive tracts.

Table 3. Average Microplastics in Freshwater Fish

Species	Habitat	Particles/Individual
Tilapia	Urban rivers	6–12
Common carp	Agricultural rivers	5–10
Mozambique tilapia	Reservoirs	4–8

As shown in Table 3, microplastics have accumulated in freshwater fish commonly consumed by the public. The highest range (6–12 particles per individual) was found in tilapia from urban rivers, indicating higher exposure levels in urban waters. Common carp from agricultural rivers contained 5–10 particles per individual, demonstrating that agricultural activities and surface runoff also contribute to microplastic inputs.

Mozambique tilapia from reservoirs showed lower accumulation (4–8 particles per individual), suggesting that water body characteristics influence exposure levels, with reservoirs generally having calmer flows and fewer direct pollution sources than rivers.

Physiological and Ecological Impacts on Biota

The review indicates that microplastic exposure in freshwater organisms is associated with various physiological disturbances, particularly in the digestive system. Ingested microplastics can cause irritation of gastrointestinal walls and inhibit nutrient absorption. These effects are observed across multiple organism groups, from benthic invertebrates to fish, indicating biological responses to foreign particles.

In addition to digestive disturbances, several studies report increased oxidative stress indicators in organisms exposed to microplastics, reflected by altered antioxidant enzyme activity and cellular responses. The severity of these effects varies depending on microplastic size, type, and quantity accumulated. At the ecosystem level, microplastics in the water column can reduce light penetration, decreasing phytoplankton photosynthetic efficiency and primary productivity. This reduction may affect energy availability at higher trophic levels and disrupt freshwater food web stability.

Findings Related to Education-Based Mitigation Strategies

The review shows that integrating microplastic issues into environmental education through a Project-Based Learning (PjBL) approach positively affects students' understanding of plastic pollution and its implications for aquatic ecosystems. Students engaged in project-based learning can identify sources, pathways, and impacts of microplastics more contextually through direct interaction with local environmental problems. Participation in field projects—such as water sampling, microplastic observation, and simple analyses—demonstrates increased scientific literacy, including data interpretation, conclusion drawing, and linking field findings to ecological concepts. Project-based activities also promote more active and reflective learning compared to lecture-based instruction.

The review further indicates increased environmental awareness and concern among students following PjBL-based learning. Students exhibit more critical attitudes toward single-use plastics and propose alternative solutions to reduce plastic pollution in their surroundings, including environmental campaigns and educational initiatives focused on waste reduction.

Overall, these findings demonstrate that project-based environmental education functions not only as a knowledge enhancement tool but also as a long-term mitigation strategy for microplastic pollution. Education plays a strategic role in shaping awareness, attitudes, and sustainable behaviors with the potential to produce tangible impacts in controlling microplastic pollution in Indonesian freshwater ecosystems.

4. Conclusions

Based on the results and discussion, it can be concluded that microplastic pollution in Indonesian freshwater ecosystems is a widespread, complex, and persistent environmental problem. Microplastics are present in multiple aquatic compartments, including the water column, sediments, and aquatic organisms. The main pathways of microplastic entry originate from domestic and industrial activities, with household waste and synthetic textile fibers as dominant contributors. This condition highlights the

significant role of everyday human activities in increasing microplastic loads in freshwater environments.

The identified microplastics are dominated by polyethylene, polypropylene, and polyester polymers, with fragment and fiber morphologies of small sizes. These characteristics increase the likelihood of ingestion by freshwater organisms and accumulation within food chains. The review reveals bioaccumulation of microplastics in various organisms, including freshwater fish consumed by humans, as well as physiological impacts such as digestive disturbances and increased oxidative stress. At the ecosystem level, the presence of microplastics has the potential to reduce primary productivity and disrupt the stability of freshwater food webs.

The findings further emphasize that Project-Based Learning–based environmental education holds strategic potential as part of long-term microplastic pollution mitigation efforts. Integrating microplastic issues into learning processes enhances scientific literacy, environmental awareness, and students' concern for environmental problems. Therefore, controlling microplastic pollution requires an integrated approach that combines source reduction, improved waste management technologies, and the strengthening of environmental education as a foundation for sustainable behavioral change.

The conclusions section should answer your research questions and explain what your results mean. In other words, the majority of the conclusions section should be an interpretation of your results.

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