# Atmospheric Microplastic Pollution in Jakarta: Environmental Impacts, Human Health Implications, and Integrated Management Strategies

Zidane Surya Pratama[1], Fahri Rozani Ardiansyah[2], Farhana Cahya Apriliya[3], Denissa Anindya Wardani Prasetyo[4], Kesya Agung Ariellintang[5], Dzaky Alhafizh Arseno[6], Faridhatun Nikmah[7], Sofyan Anif[8], Savenaca Jone Viliame[9], Noah Malek Vira[10], Phan Anh Dũng[11]

[1-7]Faculty of Sains and Technology, Universitas Islam Negeri Raden Mas Said Surakarta, Indonesia
[8]Faculty of Teacher Training and Education, Universitas Muhammadiyah Surakarta, Indonesia
[9]Department of Environmental Science, The University of Fiji, Fiji
[10]Department of Humanities and Sciences, Vanuatu Institute of Technology, Vanuatu
[11]Faculty of Science and Food Technology, Lac Hong University, Vietnam

doi: 10.23917/saintek.v3i1.18474
Received: July 13th, 2026 | Revised: July 1st, 2026 | Accepted: August 11th, 2026
Available Online: August 14th, 2026 | Published Regularly: January, 2027

**Abstract**

Microplastic pollution has become a multidimensional environmental problem because particles can be transported across atmospheric, terrestrial, freshwater, and marine ecosystems. This study examines atmospheric microplastic pollution in Jakarta, its environmental and potential human health implications, and responses to its mitigation. A descriptive qualitative approach was employed using field observations, interviews, document analysis, and secondary data from scientific publications and institutional reports. The findings indicate that atmospheric microplastics in Jakarta originate from multiple anthropogenic sources, including plastic waste fragmentation, synthetic textile fibers, vehicle tire abrasion, and plastic waste combustion. Fragments and fibers were the dominant particle types, while rainfall provides an important pathway for transferring atmospheric microplastics to soil, rivers, sediments, and coastal waters. Microplastic contamination may affect ecosystems through habitat degradation, organism exposure, and potential food-web transfer. Human exposure may occur through ingestion, inhalation, and environmental contact, although the long-term health risks require further investigation. Effective mitigation requires source reduction, improved waste management and recycling, environmental monitoring, public education, regulatory enforcement, and multi-stakeholder collaboration. These findings highlight the need for integrated and evidence-based environmental governance to reduce microplastic pollution and protect Jakarta's ecosystems and public health.

**Keywords:** microplastics deposition, atmospheric pollution, rainfall deposition, environmental impact, human health, plastic waste management, environmental governance.



✉**Corresponding Author:**
*Zidane Surya Pratama, Faculty of Sains and Technology, Universitas Islam Negeri Raden Mas Said Suraka*
*Email: syazdn3@gmail.com*

## Introduction

Microplastics are plastic particles smaller than 5 mm that are generally invisible to the naked eye. They can originate from the fragmentation and degradation of larger plastic materials through physical, chemical, and biological processes [1]. Microplastics exhibit diverse characteristics in terms of shape, color, size, and polymer type. Based on their origin, microplastics are generally classified into primary and secondary microplastics. Primary microplastics are intentionally produced at microscopic sizes, whereas secondary microplastics are generated through the degradation of larger plastic materials [2]. Environmental factors such as solar radiation, oxidation, thermal processes, wave action, and biofilm formation can accelerate plastic degradation and alter the morphology, crystallinity, color, and density of plastic particles [3]. Consequently, larger plastic debris can gradually fragment into smaller particles that are subsequently distributed across different environmental compartments.

Microplastic pollution is no longer restricted to marine ecosystems, rivers, and terrestrial environments. Recent research has demonstrated that microplastics can also be transported through the atmosphere and deposited onto land and water surfaces through precipitation [4]. Jakarta is particularly vulnerable to this emerging form of pollution because of its high population density, intensive transportation activities, industrial development, commercial activities, and substantial plastic consumption. Microplastics have been detected in several aquatic environments in Jakarta, including the Ciliwung River and Jakarta Bay. Their occurrence is associated with the accumulation and inadequate management of plastic waste, which can be transported through rainfall runoff and river systems [5]. These conditions indicate that Jakarta represents an important urban setting for examining the environmental distribution and potential consequences of microplastic pollution.

The environmental risks associated with microplastics are substantial because these particles can interact with aquatic organisms and potentially enter food webs. Their impacts may vary according to particle shape, size, concentration, and polymer composition [6]. In addition, microplastics can adsorb persistent organic pollutants and other contaminants present in the surrounding environment, potentially increasing their toxicity when ingested by organisms [7]. Exposure to microplastics has been associated with physical damage to the digestive systems of aquatic organisms, including intestinal blockage and internal bleeding [8]. Because microplastics can move through food chains, their presence may also have implications for human health and ecosystem integrity. Thus, microplastic pollution should be considered not only an issue of waste management but also an emerging environmental and public health concern.

The increasing production and consumption of plastic further intensify this problem. Global plastic production has exceeded 300 million tons annually, while the persistent characteristics of plastic materials allow them to remain in the environment for decades or even centuries [9]. The resistance of plastic to natural degradation consequently creates long-term environmental risks. Plastic particles may enter the environment directly through improperly discarded waste or indirectly through the fragmentation of larger plastic debris exposed to sunlight, waves, abrasion, and other environmental processes [10]. In densely populated urban areas such as Jakarta, these sources may interact with atmospheric processes, creating additional pathways through which microplastics are dispersed.

Atmospheric deposition has recently emerged as an important pathway for microplastic transport. Airborne microplastics can be transported by wind and subsequently deposited onto terrestrial and aquatic surfaces through rainfall. Chan et al [11] reported the presence of microplastics in atmospheric deposition in the coastal area of Jakarta, with rainfall acting as an important medium for their deposition. Their findings indicate that meteorological conditions, particularly rainfall, can influence the distribution of atmospheric microplastics. Similarly, research conducted by Yeh et al [12] detected microplastic particles in rainwater samples collected in the Jakarta area. The particles were associated with various urban activities, including the release of synthetic textile fibers, vehicle tire abrasion, and plastic waste combustion. The reported deposition rate of approximately 15 microplastic particles per square meter per day along the Jakarta coast further indicates the seriousness of atmospheric microplastic contamination.

The presence of microplastics in rainwater suggests that atmospheric transport may establish a connection between urban sources and receiving ecosystems. Microplastics released from transportation, domestic activities, industrial processes, and waste management practices can become airborne and subsequently return to the environment through precipitation [13]. This process may facilitate the transfer of microplastics among atmospheric, terrestrial, and aquatic compartments. Therefore, understanding microplastic pollution requires an integrated perspective that considers not only individual environmental media but also the interactions among different pathways of transport and deposition.

Previous studies have examined different aspects of microplastic pollution in Indonesia. Sun et al [14] focused on atmospheric microplastic deposition in Jakarta and identified rainfall and meteorological conditions as important factors affecting microplastic distribution. Tanjil et al [15] investigated microplastic abundance in the downstream Brantas River Basin and reported that fibers were the dominant form in both water and sediment samples. Meanwhile, Jambhulkar et al [16] reviewed the sources, distribution, and impacts of microplastics on organisms and the environment. These studies collectively demonstrate that microplastics are widely distributed across different environmental compartments and may pose significant ecological risks.

However, important research gaps remain. Existing studies tend to examine microplastics within specific environmental media, such as atmospheric deposition, water, or sediment, rather than investigating their interconnections within an integrated environmental system. Kaviyarasi et al [17], for example, primarily emphasized the identification and quantification of atmospheric microplastics, while Hartz et al [18] focused on aquatic environments. Gan et al [19] adopted a literature-based approach to discuss the broader impacts of microplastics. Consequently, limited research has specifically connected microplastic deposition through rainfall with its potential effects on ecosystems in Jakarta and examined this issue alongside governmental efforts to mitigate plastic pollution.

Another gap concerns the relationship between environmental factors, human activities, and the distribution of microplastics. Li et al [20] demonstrated the influence of meteorological factors on atmospheric deposition, the connection between atmospheric deposition, specific urban pollution sources, and ecosystem impacts requires further investigation. Moreover, research on the biological and human-health consequences of microplastic exposure remains insufficiently integrated with studies of environmental distribution. This gap is important because microplastics may carry toxic substances, including heavy metals and persistent organic pollutants, and prolonged exposure may contribute to oxidative stress, inflammation, cellular damage, allergic reactions, and other chronic health risks [21]. Nevertheless, the mechanisms of toxicity and the magnitude of risks to humans remain areas requiring further investigation.

The present study therefore addresses the need for a more integrated understanding of microplastic pollution in Jakarta, particularly the role of rainfall as a pathway for atmospheric deposition and its implications for ecosystems. The study is guided by perspectives on environmental protection, environmental pollution, environmental policy, responsive regulation, and community participation. Government intervention is particularly important because plastic waste management requires coordinated actions involving regulation, waste reduction, recycling, public education, and enforcement. Responsive Regulation theory emphasizes the importance of collaboration among government, businesses, and communities in ensuring that environmental regulations are implemented effectively [22]. Such collaboration is essential for reducing single-use plastic consumption, strengthening waste-management systems, and preventing plastic waste from entering environmental compartments.

Based on these considerations, this study investigates the impact of microplastic deposition through rainfall on ecosystems in Jakarta and examines governmental efforts to reduce the associated environmental impacts. The study is expected to contribute to a more comprehensive understanding of the relationship between atmospheric microplastic deposition, ecosystem pollution, and environmental governance. The findings may provide an empirical and conceptual basis for strengthening plastic-waste management policies, improving pollution-control strategies, and promoting more sustainable environmental practices in densely populated urban areas.

## Method

This study was conducted from April to May 2026 using a descriptive qualitative research approach supported by field observations and secondary data analysis. The study aimed to examine the environmental impacts of microplastic and plastic waste pollution in Jakarta, particularly along the coastal areas, and to analyze governmental efforts to reduce and manage these impacts. A qualitative descriptive approach was selected because the study focused on understanding environmental conditions, ecosystem impacts, community perceptions, and policy responses based on information obtained from field observations, interviews, and relevant documentary sources.

### a. Study Locations

The study was conducted at three coastal locations in DKI Jakarta that represent different characteristics of coastal activities and pollution exposure: Ancol Beach, Muara Angke Beach, and Marina Beach. Ancol Beach was selected as a representation of a tourism-oriented coastal area with intensive human activities. Muara Angke Beach represents an area that supports coastal and marine ecosystems and serves as an important habitat for marine organisms. Marina Beach was selected because its coastline is frequently exposed to the accumulation and transportation of plastic waste.

These three locations were selected purposively to provide variation in environmental characteristics, human activities, and potential sources of plastic waste. The comparison among the three locations was expected to provide a broader understanding of the distribution and potential ecological impacts of plastic pollution along the Jakarta coastline.

### b. Data Sources and Data Collection

The study used both primary and secondary data. Primary data were obtained through field observations and interviews, whereas secondary data were collected from scientific journals, research articles, books, institutional reports, news sources, and other credible online sources relevant to microplastic pollution, coastal waste management, ecosystem impacts, and governmental policies.

Field observations were conducted to identify the presence, distribution, quantity, and types of plastic waste at the three study locations. The observation process included direct examination of coastal conditions, documentation of accumulated waste, identification of dominant types of plastic waste, and assessment of its potential interaction with coastal ecosystems. Where applicable, plastic waste samples were collected and classified according to their observable characteristics and volume. Particular attention was given to areas associated with mangrove vegetation, coral reef ecosystems, and habitats used by marine organisms.

In addition to field observations, semi-structured interviews were conducted with selected fishermen, local community members, and relevant stakeholders. The interviews were intended to obtain information regarding perceived changes in coastal environmental conditions, the occurrence and sources of plastic waste, impacts on marine ecosystems and local livelihoods, and community perceptions of government interventions [23]. The respondents were selected purposively based on their knowledge, experience, or direct involvement with the coastal environment and waste-management activities.

Document analysis was also employed to strengthen the interpretation of field findings. Relevant documents were systematically reviewed to identify information concerning the sources, distribution, impacts, and management of microplastic and plastic waste. Scientific publications and institutional reports were used to provide a theoretical and empirical basis for interpreting the observations and interview findings.

### c. Data Analysis

The collected data were analyzed using an integrated descriptive approach. Quantitative information obtained from field observations, particularly the frequency, quantity, and volume of plastic waste, was summarized descriptively to illustrate the level and distribution of plastic pollution at the study sites. The quantitative results were not intended to establish statistical relationships but to provide supporting evidence for the qualitative interpretation.

Qualitative data from field observations, interviews, and documentary sources were analyzed thematically. The analysis involved several stages, including data organization, identification of relevant information, coding of recurring themes, categorization of findings, comparison across study locations, and interpretation of relationships among the identified themes [24]. Thematic analysis focused primarily on three dimensions: ecological impacts, socioeconomic impacts, and governmental responses to plastic and microplastic pollution.

The ecological impact analysis examined potential habitat degradation, particularly in mangrove and coral reef areas, physical threats to marine organisms such as fish, turtles, and birds, and potential deterioration of water quality. The socioeconomic analysis considered the perceived effects of coastal pollution on local communities and livelihoods, particularly those associated with fishing and coastal activities [25]. Meanwhile, the policy analysis examined governmental efforts to address plastic pollution through waste-management programs, restrictions on single-use plastics, public awareness initiatives, and other environmental management measures.

Data obtained from different sources were compared through source triangulation to improve the credibility of the findings. Information from field observations was compared with interview responses and relevant scientific literature and institutional reports. Differences or inconsistencies among sources were critically examined before conclusions were formulated.

**d. Policy Recommendations**

Based on the integrated analysis, the study formulated recommendations for improving coastal plastic-waste management in Jakarta. The recommendations were directed toward local government institutions, the private sector, and local communities. The proposed strategies include strengthening restrictions on single-use plastics, developing integrated coastal waste-management systems, improving waste collection and monitoring, strengthening collaboration among stakeholders, and expanding public environmental-awareness programs.

The recommendations were formulated by considering the environmental conditions identified through field observations, community perspectives obtained from interviews, and evidence reported in the scientific and institutional literature. Through this approach, the study seeks to provide practical recommendations for reducing plastic pollution and supporting the long-term sustainability of Jakarta's coastal ecosystems.

The overall methodological framework of this study, encompassing the research design, study locations, data sources, data collection procedures, data analysis, data triangulation, and formulation of policy recommendations, is illustrated in Figure 1.

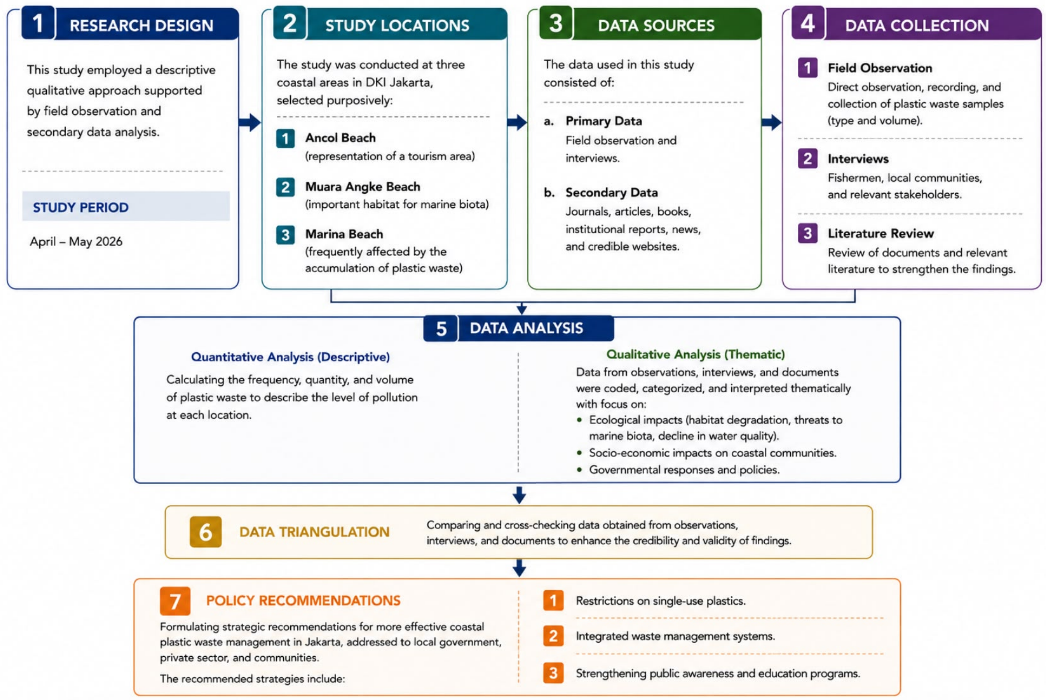


**Figure 1**. Methodological Framework

## Result and Discussion

The findings demonstrate that microplastic pollution in Jakarta is a multidimensional environmental issue that extends beyond terrestrial and aquatic ecosystems to the atmosphere and human health. Atmospheric transport and rainfall deposition provide important pathways for the redistribution of microplastics, while their persistence may generate ecological and potential health risks. These findings also highlight the need for integrated waste management, public participation, and effective governmental responses. Accordingly, the results and discussion are presented through four main aspects: atmospheric microplastic pollution and rainfall deposition, environmental impacts, human health implications, and community and government responses to microplastic pollution.

### a. Atmospheric Microplastic Pollution and Rainfall Deposition in Jakarta

Microplastic pollution has increasingly emerged as an environmental concern that extends beyond conventional terrestrial and aquatic pollution to the atmospheric environment. According Wang et al [26], plastic represents one of the most common forms of marine debris, while microplastics refer to plastic particles smaller than 5 mm. These particles may originate from the degradation of larger plastic waste as well as from synthetic fibers and other anthropogenic sources. Microplastics can be released into the atmosphere through several pathways, including vehicle tire abrasion, textile fiber emissions, plastic waste combustion, and fragmentation of plastic debris [27]. Once airborne, these particles may be transported by atmospheric circulation and subsequently deposited onto terrestrial and aquatic surfaces through precipitation, creating an important pathway of environmental redistribution.

Recent evidence indicates that atmospheric microplastic contamination is particularly concerning in densely populated urban areas. Research conducted by ECOTON and the Society of Indonesian Environmental Journalists (SIEJ) during May–July 2025 examined airborne microplastic contamination in 18 Indonesian cities and regencies. The findings identified Central Jakarta as having the highest concentration, followed by South Jakarta, Bandung, Semarang, and Kupang. Central Jakarta recorded 37 particles within a two-hour sampling period, while South Jakarta recorded 30 particles under the same sampling conditions.

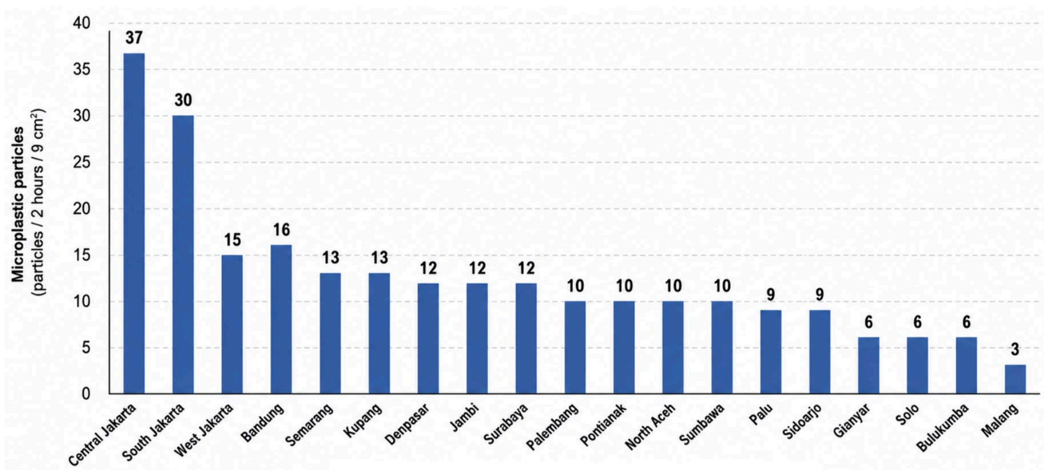


**Figure 2.** Atmospheric microplastic concentrations in selected Indonesian cities (May–July 2025)

The distribution presented in Figure 2 demonstrates a substantial concentration of atmospheric microplastics in Jakarta compared with other cities included in the study. Central Jakarta recorded 37 particles, more than twice the concentrations reported in Bandung, Semarang, and Kupang. South Jakarta also showed a relatively high concentration of 30 particles. This pattern suggests that metropolitan characteristics may contribute to elevated atmospheric microplastic contamination [28]. Jakarta combines high population density, intensive traffic, commercial activity, textile-related activities, construction, and substantial plastic consumption. ECOTON and SIEJ specifically identified activities around locations such as Tanah Abang, Sawah Besar, and Ragunan as potential contributors to airborne microplastic contamination.

The relatively high concentration in Jakarta should not, however, be interpreted solely as evidence of a single pollution source. Atmospheric microplastics are likely generated through multiple interacting sources. Synthetic textile fibers may enter the atmosphere through textile handling, laundry, and wear, while fragments may originate from the deterioration of plastic packaging and other plastic materials [29]. Vehicle movement may additionally contribute particles through tire abrasion and road-related resuspension. Open burning of plastic waste represents another potential pathway because thermal processes can release plastic-derived particles into the atmosphere [30]. Thus, the observed concentration in Jakarta can be understood as the cumulative outcome of multiple anthropogenic activities operating within a densely urbanized environment.

The composition of atmospheric microplastics provides additional information concerning their possible sources. The ECOTON–SIEJ study identified three principal morphological categories: fragments, fibers, and films. Fragments represented 53.26% of the identified particles, followed by fibers at 46.14%, while films accounted for only 0.60%.

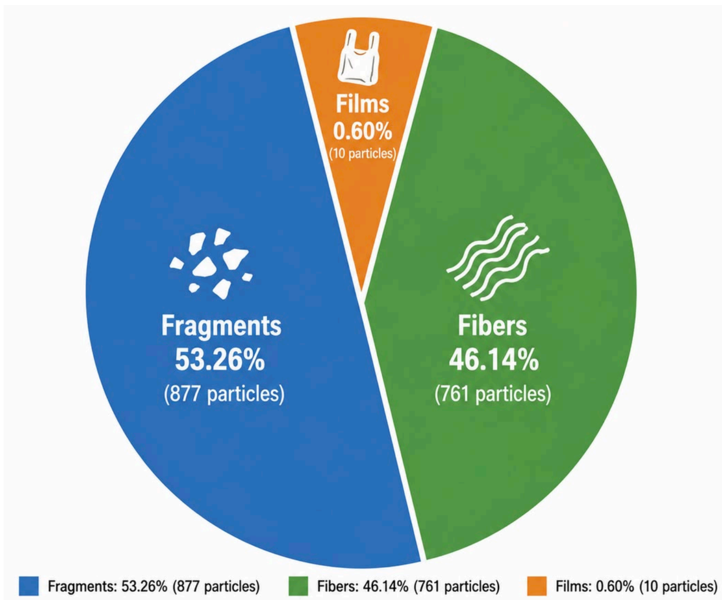


**Figure 3.** Composition of atmospheric microplastics by particle type in Indonesia

The dominance of fragments shown in Figure 3 indicates that the atmospheric microplastic problem is closely associated with the fragmentation and deterioration of larger plastic materials. Fragment-type particles may originate from plastic packaging, bottles, bags, and other consumer products that undergo mechanical abrasion, ultraviolet radiation, and environmental weathering [31]. The substantial proportion of fibers, meanwhile, highlights the importance of synthetic textiles and other fiber-releasing activities as potential contributors to atmospheric contamination. ECOTON and SIEJ identified diverse polymer types in the atmospheric samples, including PTFE, polyester, polyolefin, polyisobutylene, and other polymers, indicating that atmospheric contamination may originate from several different human activities.

The small proportion of film particles does not necessarily indicate that films are environmentally insignificant. Rather, the finding suggests that their contribution to the sampled atmospheric particle composition was relatively limited compared with fragments and fibers. Differences in particle morphology can influence atmospheric mobility, deposition, and environmental persistence [32]. Consequently, morphological composition should be considered when identifying potential sources and evaluating the environmental pathways of airborne microplastics.

The atmospheric occurrence of microplastics becomes particularly important when considered together with rainfall. Airborne particles do not remain permanently suspended in the atmosphere. Atmospheric processes can transport particles horizontally and vertically, after which precipitation can remove suspended particles through wet deposition [33]. In Jakarta, this process has been documented by Du et al [34], who investigated atmospheric microplastic deposition in the coastal urban area. Their study found that deposition rates ranged from 3 to 40 particles/m²/day, with an average of approximately 15 particles/m²/day. More importantly, deposition during the rainy season was substantially higher, reaching 23,422 particles/m²/day compared with 5,745 particles/m²/day during the dry season.

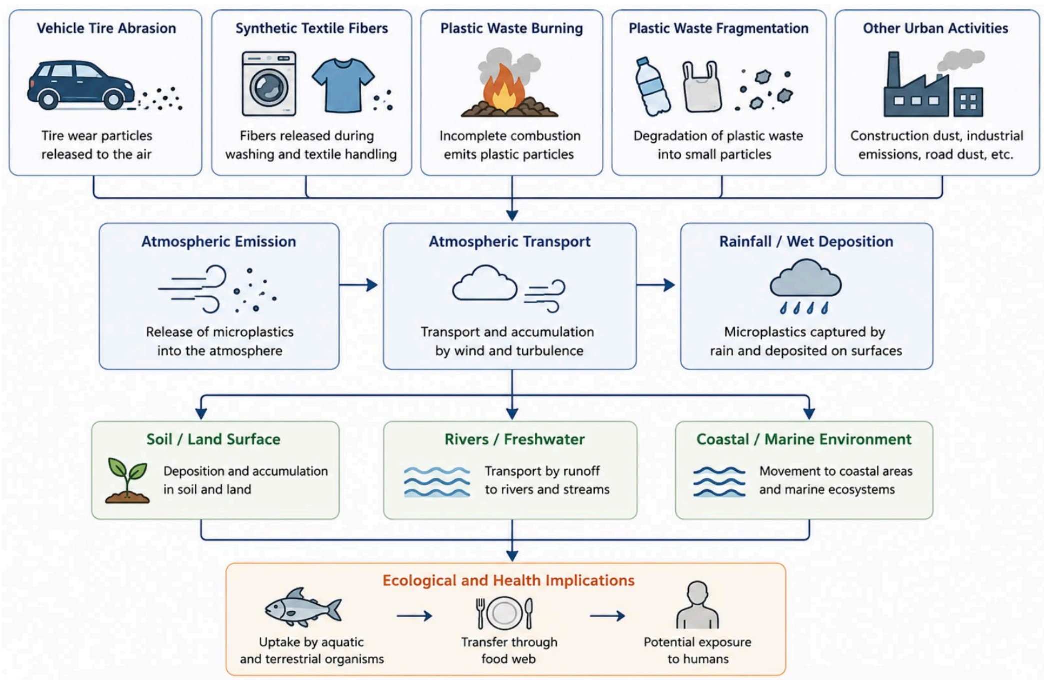


**Figure 4.** Conceptual pathway of atmospheric microplastic transport and rainfall deposition in Jakarta

Figure 4 illustrates the conceptual pathway through which microplastics may move from anthropogenic sources into atmospheric and subsequently terrestrial and aquatic environments. This pathway demonstrates that atmospheric contamination should not be treated as an isolated air-quality problem. Instead, airborne microplastics represent an intermediate environmental compartment connecting urban sources with receiving ecosystems [35]. Once particles become suspended in the atmosphere, meteorological conditions can influence their transport and eventual deposition. Rainfall is particularly important because precipitation can capture suspended particles and transfer them to soil, drainage systems, rivers, and coastal waters. The atmospheric deposition study by Sheela et al [36] supports this pathway by demonstrating substantially higher deposition during the rainy season.

The rainfall-mediated pathway is particularly relevant for Jakarta because the city has extensive interconnected drainage, river, and coastal systems. Microplastics deposited on urban surfaces may subsequently be transported through runoff into rivers and coastal waters. This creates the possibility of repeated redistribution between environmental compartments. The process therefore extends the pollution pathway from urban activities → atmosphere → rainfall → terrestrial surfaces → rivers → coastal ecosystems. Such connectivity is consistent with the broader understanding that microplastic pollution crosses environmental boundaries rather than remaining confined to the location where plastic waste is initially generated.

The environmental implications become more significant when atmospheric deposition occurs continuously. Microplastics deposited through rainfall may accumulate in soils and sediments and subsequently become available to terrestrial and aquatic organisms. Research by Costa et al [37] demonstrated that microplastics can alter soil structure and influence water-related properties and soil biological processes. Similarly, once microplastics enter aquatic systems, they may be ingested by plankton, fish, shellfish, and other organisms, creating opportunities for transfer through aquatic food webs. Therefore, atmospheric deposition represents not only a mechanism of pollutant transport but also a potential contributor to the persistence and redistribution of microplastics within ecosystems.

Overall, the findings indicate that Jakarta represents an important urban hotspot of atmospheric microplastic contamination in Indonesia. The high concentration observed in Central and South Jakarta, combined with the dominance of fragments and fibers, indicates the contribution of diverse anthropogenic activities. The substantially higher atmospheric deposition rate during the rainy season reported by Xu et al [38] further demonstrates the importance of precipitation as a pathway connecting atmospheric contamination with terrestrial and aquatic environments.

The phenomenon therefore requires a broader environmental management perspective. Controlling microplastic pollution in Jakarta cannot rely exclusively on cleaning rivers, beaches, or other receiving environments. Intervention should also address upstream sources, including excessive single-use plastic consumption, inadequate waste collection, plastic waste burning, textile-related emissions, and transportation-related particle generation [39]. The findings support the need for integrated strategies that combine source reduction, improved waste management, atmospheric monitoring, public awareness, and coordinated environmental governance. In this context, atmospheric microplastic pollution and rainfall deposition should be recognized as important components of Jakarta's wider plastic pollution problem rather than as isolated forms of air contamination.

### b. Environmental Impacts of Microplastic Exposure

The findings indicate that microplastic pollution represents a multidimensional environmental problem because these particles can be distributed across different environmental compartments, including the atmosphere, soil, freshwater systems, sediments, and marine ecosystems. Their small size, persistence, and mobility allow microplastics to move between environmental media and interact with various organisms. Recent research in Indonesia has confirmed the presence of microplastics in rivers, coastal waters, sediments, groundwater, and urban atmospheric environments, demonstrating that plastic pollution is no longer confined to a single ecosystem [40]. This interconnected distribution is particularly relevant to Jakarta because atmospheric deposition through rainfall may provide an additional pathway through which microplastics reach terrestrial and aquatic environments.

Microplastics deposited from the atmosphere may accumulate on land surfaces and subsequently be transported through rainfall runoff into drainage systems, rivers, and coastal waters. Once deposited in soil, microplastics may alter soil physical properties and interfere with biological processes. Saeed et al [41] reported that microplastics can modify soil structure, influence water-related properties, and affect microorganisms that contribute to soil functioning. Therefore, atmospheric deposition should not be viewed solely as an air-pollution issue, but rather as part of a broader environmental pathway connecting atmospheric pollution with terrestrial and aquatic ecosystems.

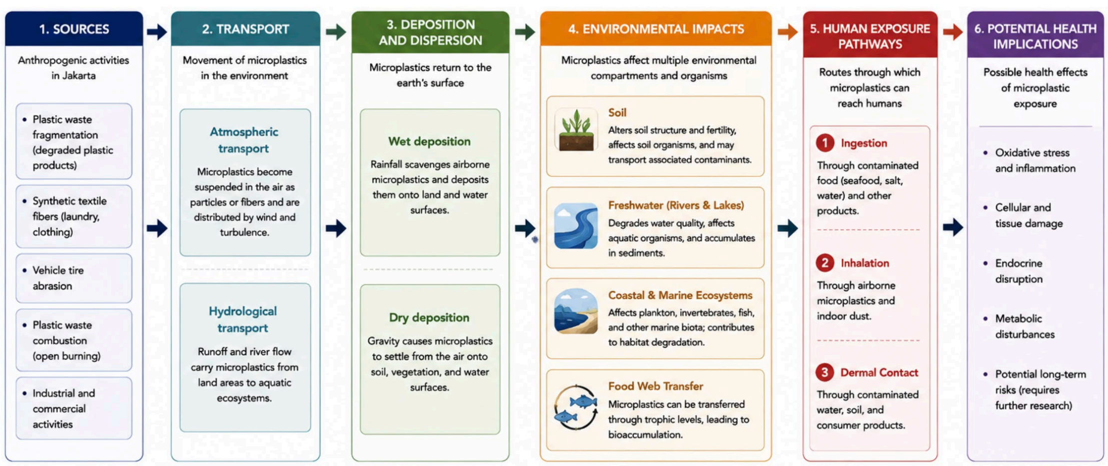

**Figure 5.** Environmental Pathways and Impacts of Microplastic Pollution

Figure 5 illustrates the interconnected movement of microplastics across environmental compartments. Microplastics released from anthropogenic activities can enter the atmosphere and subsequently be deposited through rainfall onto terrestrial surfaces. Once deposited, particles may accumulate in soil or be transported through surface runoff into rivers and coastal waters. This pathway demonstrates the potential for microplastics to move continuously between environmental media rather than remaining at their original source. The transfer is particularly important in densely urbanized areas, where drainage systems, river networks, and coastal environments are closely connected. The environmental consequences may consequently extend from changes in soil characteristics to contamination of aquatic habitats and exposure of organisms [42]. This interconnected pathway supports the argument that microplastic management requires an ecosystem-based approach rather than isolated interventions targeting only beaches, rivers, or atmospheric pollution.

The effects of microplastics vary according to the environmental compartment in which they accumulate. In terrestrial environments, particles may interact with soil aggregates, alter water infiltration, and influence microbial activity. In aquatic systems, microplastics can remain suspended in the water column, settle into sediments, or be transported downstream toward coastal environments. Sediment therefore functions as both a sink and a potential secondary source because deposited microplastics may subsequently be resuspended under changing hydrodynamic conditions. Research conducted in the Musi River sediment, for example, identified microplastics in the form of fragments, fibers, and films, demonstrating that plastic contamination can reach the bottom of aquatic systems [43]. The persistence of these particles in sediments may prolong their environmental residence time and increase opportunities for interaction with benthic organisms.

The environmental effects identified in the literature are summarized in Table 1.

**Table 1.** Environmental Impacts of Microplastics Across Ecosystem Compartments

| Environmental compartment | Major microplastic pathway | Potential ecological effects | Organisms or components affected | Supporting evidence |
|---|---|---|---|---|
| Atmosphere | Airborne transport and rainfall deposition | Redistribution of plastic particles to terrestrial and aquatic environments | Air, soil, vegetation, aquatic systems | Costa et al [21] |
| Soil | Deposition and accumulation on land surfaces | Changes in soil structure, water-related properties, and microbial activity | Soil microorganisms, plants, terrestrial ecosystem | Nematollahi et al [2] |
| Rivers and freshwater | Runoff, direct disposal, and downstream transport | Reduced environmental quality and exposure of aquatic organisms | Plankton, fish, benthic organisms | Phu et al [3] |
| Sediments | Settling from the water column and accumulation | Habitat contamination and potential remobilization into the water column | Benthic organisms and sediment communities | Hosseinpour et al [44] |
| Coastal and marine waters | River discharge, rainfall runoff, and direct plastic pollution | Ingestion, physical stress, and potential food-web transfer | Fish, shellfish, plankton, marine biota | Du et al [34] |

Table 1 demonstrates that the environmental effects of microplastics occur across multiple interconnected compartments. The presence of microplastics in the atmosphere provides a mechanism for transferring particles toward terrestrial and aquatic systems, while rainfall and surface runoff can further facilitate their redistribution. In terrestrial environments, changes in soil properties and microbial activity may influence ecosystem functioning over time. In aquatic environments, the effects become more complex because microplastics can remain suspended, settle in sediments, or be ingested by organisms. The identification of fragments, fibers, and films in river sediments reported by Hosseinpour [44] demonstrates the persistence of different particle morphologies within aquatic environments. Furthermore, the potential ingestion of microplastics by aquatic organisms creates an additional pathway for biological transfer. Thus, the environmental significance of microplastic pollution is determined not only by particle concentration but also by their persistence, mobility, and interactions with ecological processes.

One of the most important ecological consequences of microplastic contamination is the exposure of aquatic organisms. Microplastics can be ingested by plankton, fish, shellfish, and other aquatic organisms because their size and appearance may cause them to be mistaken for food or unintentionally consumed during feeding. Once ingested, microplastics may interfere with feeding behavior and digestive processes and may contribute to physiological stress [45]. In addition, microplastics can act as carriers for other contaminants because their surfaces can adsorb chemicals and persistent pollutants from the surrounding environment. This characteristic potentially increases the ecological significance of microplastic exposure because organisms may be exposed not only to plastic particles themselves but also to associated chemical contaminants.

Thanigaivel et al [46] reported that microplastic contamination in coastal environments and marine organisms may be associated with physiological and metabolic disturbances, including potential effects on liver and kidney functions. Thakur et al [10] further emphasized the potential for bioaccumulation and biomagnification, whereby contaminants associated with microplastics may move through different trophic levels. These processes demonstrate that the ecological implications of microplastics extend beyond individual organisms and may influence food-web structure and ecosystem functioning.

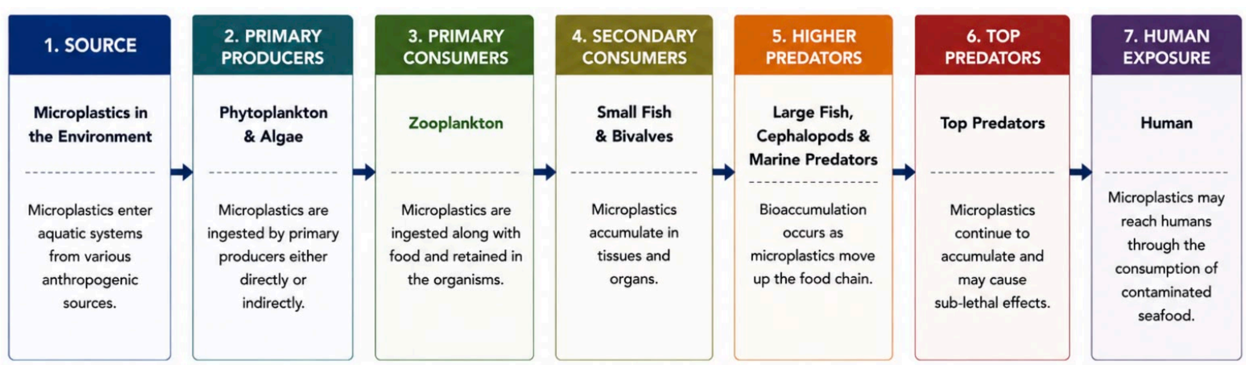

**Figure 6.** Potential Transfer of Microplastics Through the Aquatic Food Web

Figure 6 presents a conceptual representation of how microplastics may enter aquatic food webs. Particles present in water and sediments may become available to plankton and benthic organisms, which can subsequently be consumed by small fish and other organisms at higher trophic levels. Larger fish, shellfish, and other aquatic organisms may then represent additional exposure pathways for organisms at subsequent trophic levels, including humans through seafood consumption. This process does not imply that biomagnification necessarily occurs for all microplastic particles or associated contaminants; rather, it illustrates a potential pathway for exposure and trophic transfer that requires further empirical investigation. The ecological significance of this pathway lies in the persistence and widespread distribution of microplastics, which increase the probability of repeated interactions between particles and organisms [47]. Consequently, understanding microplastic pollution requires consideration of both environmental contamination and biological exposure across trophic levels.

The presence of microplastics in sediments further reinforces their potential ecological persistence. Sediments can accumulate particles transported from upstream areas and may therefore function as long-term reservoirs of plastic contamination. When environmental conditions change, such as during strong rainfall, flooding, tidal movement, or other hydrodynamic events, particles accumulated in sediments may be resuspended and re-enter the water column [48]. This creates a potentially recurring contamination cycle in which microplastics move between water and sediment rather than being permanently removed from the aquatic environment. The identification of fragments, fibers, and films in Musi River sediments supports the occurrence of this type of contamination in Indonesian aquatic environments [49].

Microplastic contamination is also relevant to freshwater resources that are directly or indirectly connected to human activities. Li et al [50] reported potential microplastic contamination in groundwater in Karawang Regency and highlighted concerns related to the persistence and difficulty of degrading these particles. Although groundwater represents a different environmental compartment from Jakarta's coastal ecosystems, the finding demonstrates the broader capacity of microplastics to reach water resources that are closely associated with human activities. This observation strengthens the argument that microplastic pollution should be addressed through integrated environmental management rather than through isolated coastal clean-up activities.

From an ecosystem perspective, the environmental effects of microplastics can therefore be understood through three interconnected mechanisms: physical alteration of environmental media, biological exposure, and transfer across ecological pathways. Physical effects include changes in soil and sediment characteristics, while biological effects include ingestion and physiological stress in organisms [51]. Ecological transfer occurs when microplastics move through water, sediments, organisms, and food webs. These mechanisms can interact with one another, potentially increasing the persistence and ecological significance of plastic contamination.

The findings also demonstrate that rainfall-mediated atmospheric deposition can strengthen the connectivity between urban sources and aquatic ecosystems. Microplastics generated by transportation, textile activities, plastic degradation, and other urban processes may become airborne before being removed from the atmosphere through precipitation [52]. Once deposited, particles may enter soil, drainage networks, rivers, and coastal waters. This pathway is particularly important in Jakarta because of the close spatial relationship between densely populated urban areas, river systems, drainage infrastructure, and coastal ecosystems.

Overall, microplastic exposure should be considered an environmental challenge that transcends individual ecosystem boundaries. The particles can move from the atmosphere to land and water, accumulate in sediments, interact with organisms, and potentially enter food webs. The evidence from Indonesia demonstrates that microplastics are already present across several environmental compartments, while their ecological effects may persist because of their resistance to degradation and capacity for environmental redistribution [53]. Therefore, effective management requires simultaneous attention to source reduction, waste-management improvement, environmental monitoring, ecosystem protection, and public awareness. Preventing plastic waste from entering the environment remains more effective than relying solely on downstream removal because microplastics can become increasingly difficult to recover once they have fragmented and dispersed across environmental compartments.

**c. Human Health Implications of Microplastic Exposure**

The increasing detection of microplastics in atmospheric, terrestrial, freshwater, and marine environments raises important concerns regarding potential human health implications. The phenomenon of rainfall-associated microplastic deposition indicates that plastic particles can move from the atmosphere to land and water surfaces and subsequently enter environmental media that are closely connected with human activities. Microplastics may therefore reach humans through several exposure pathways, particularly ingestion of contaminated food and water, inhalation of airborne particles, and, to a lesser extent, direct dermal contact [54]. Their small size and persistence enable them to remain in the environment for extended periods and potentially facilitate repeated human exposure.

Microplastics are particularly concerning because they may function not only as physical particles but also as carriers of chemical contaminants. According to Mahendra et al [55], the presence of microplastics in the human body may potentially cause adverse biological effects because plastic particles can contain or carry chemical substances with toxic properties. Microplastics can also adsorb pollutants from their surrounding environment, potentially facilitating the transport of contaminants into biological systems. Consequently, exposure should be understood as involving both the physical presence of plastic particles and the possible biological effects associated with chemicals carried by these particles.

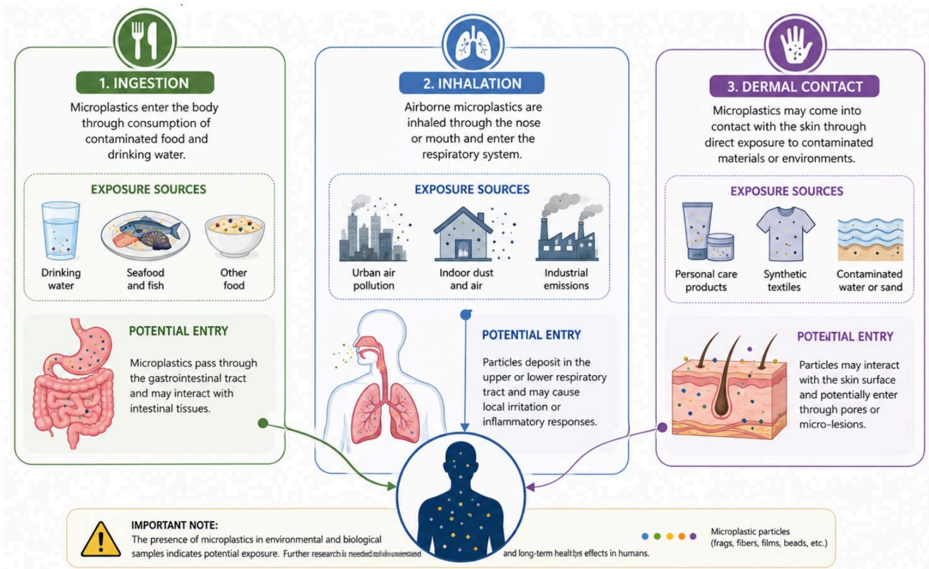


**Figure 7.** Potential Pathways of Human Exposure to Microplastics

Figure 7 illustrates the three principal pathways through which humans may potentially be exposed to microplastics: ingestion, inhalation, and dermal contact. Among these pathways, ingestion is particularly relevant because microplastics can occur in drinking water and food, including seafood obtained from contaminated aquatic environments. Inhalation is also important in urban environments because airborne microplastics can remain suspended in the atmosphere and subsequently enter the respiratory system. Dermal contact may occur through direct interaction with contaminated environmental media, although its contribution to systemic exposure remains less clearly established [56]. These pathways demonstrate that microplastic contamination is not restricted to environmental compartments but can establish direct interfaces with human exposure. However, the presence of microplastics in an exposure pathway should not automatically be interpreted as evidence of a specific disease outcome. The magnitude of risk depends on factors such as particle size, polymer characteristics, concentration, exposure frequency, duration, and the biological properties of associated contaminants.

Among the different exposure pathways, ingestion is considered particularly important because microplastics may enter the digestive system through contaminated food and drinking water. Azizi et al [57] identified ingestion, inhalation, and dermal contact as the three major routes through which microplastics may enter the human body. Once ingested, particles encounter the gastrointestinal tract and may interact with the intestinal epithelium. The extent of uptake depends on particle characteristics, including size, shape, surface properties, and other physicochemical characteristics.

Previous research has suggested that larger microplastic particles may interact with the intestinal epithelial barrier, while smaller particles may have greater potential for cellular uptake and translocation. Margenat et al [53] described the possibility that particles may cross intestinal barriers and subsequently enter lymphatic or systemic circulation. Particularly small particles may interact with Peyer's patches, where specialized M cells can facilitate the transport of particulate material from the intestinal lumen toward underlying lymphoid tissues. This mechanism is important because it provides a potential pathway through which particles may move beyond the gastrointestinal tract.

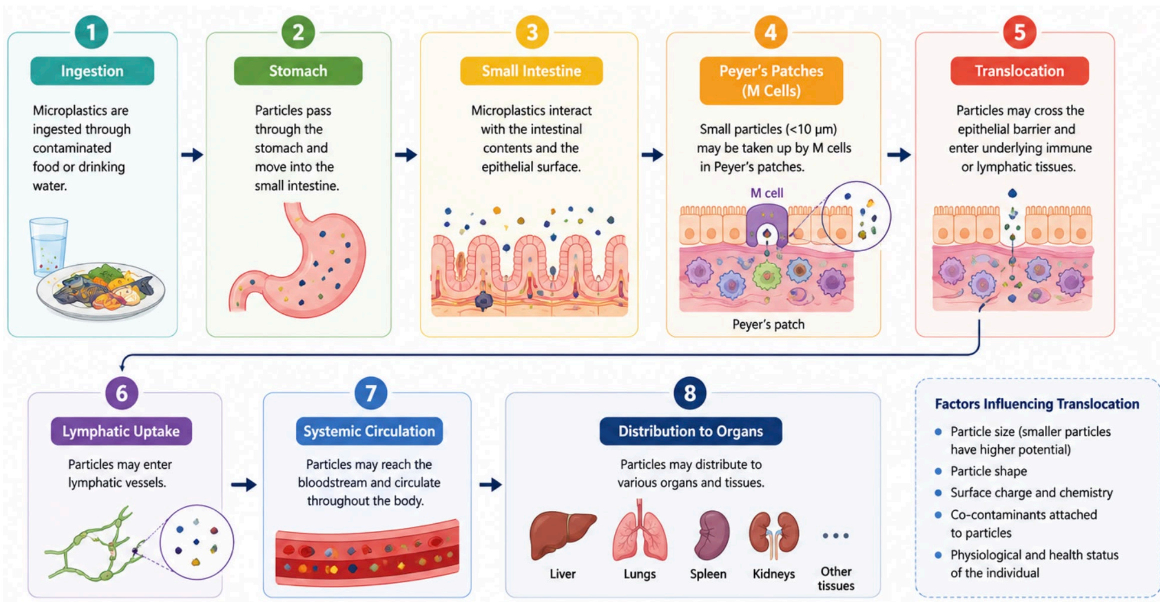


**Figure 8.** Potential Gastrointestinal Uptake and Translocation of Microplastics

Figure 8 presents the potential sequence of events following the ingestion of microplastics, beginning with exposure through contaminated food or water and continuing through the gastrointestinal tract. After reaching the small intestine, particles may interact with the intestinal epithelium. Smaller particles may potentially be taken up through specialized structures such as M cells associated with Peyer's patches. Following uptake, particles may potentially enter lymphatic or systemic circulation and become distributed to other tissues. This conceptual pathway is important for understanding why gastrointestinal exposure has attracted substantial scientific attention [58]. Nevertheless, the figure represents a potential biological pathway rather than direct evidence that all ingested microplastics undergo systemic translocation. Particle size, morphology, polymer type, surface characteristics, exposure concentration, and biological conditions may influence whether and to what extent translocation occurs. Therefore, further experimental and epidemiological studies are necessary to establish the magnitude and clinical relevance of these processes in humans.

The potential biological consequences of microplastic exposure have been associated with several mechanisms, including physical irritation, oxidative stress, inflammation, cellular damage, and disruption of metabolic processes. Repeated exposure may be particularly relevant because persistent particles can potentially interact with biological tissues over extended periods. The inflammatory response is of concern because chronic inflammation may affect tissue function and contribute to broader physiological disturbances [59]. Similarly, oxidative stress can occur when the generation of reactive oxygen species exceeds the body's antioxidant capacity, potentially resulting in cellular damage.

The potential health implications identified in previous studies are summarized in Table 2.

**Table 2.** Potential Human Health Implications Associated with Microplastic Exposure

| Exposure pathway | Potential entry source | Biological process | Potential health implication | Supporting citation |
|---|---|---|---|---|
| Ingestion | Contaminated food and drinking water | Interaction with gastrointestinal tissues and potential particle uptake | Gastrointestinal irritation, inflammation, and potential systemic exposure | Prata (2018); Wright (2017) |
| Inhalation | Airborne microplastics | Deposition and interaction with respiratory tissues | Potential respiratory irritation and inflammatory responses | Prata (2018) |
| Dermal contact | Contaminated environmental surfaces and materials | Interaction with skin barrier | Potential localized exposure; systemic significance remains uncertain | Prata (2018) |
| Gastrointestinal translocation | Small particles reaching intestinal epithelium | Uptake through intestinal structures and potential lymphatic transport | Potential distribution beyond the gastrointestinal tract | Prata (2018) |
| Chemical-associated exposure | Pollutants adsorbed to microplastic surfaces | Co-exposure to plastic-associated or environmental contaminants | Potential oxidative stress, inflammation, and cellular effects | Wright (2017) |

Table 2 indicates that human exposure to microplastics involves several possible pathways, although the strength of evidence varies among them. Ingestion represents an important pathway because food and drinking water can become contaminated through environmental exposure. Inhalation is particularly relevant to the present study because the atmospheric deposition of microplastics in Jakarta demonstrates that plastic particles can become part of the urban atmospheric environment [60]. The possibility of gastrointestinal translocation further increases scientific interest in particle size and physicochemical properties. However, the potential health outcomes listed in the table should be interpreted cautiously. Current evidence does not justify assuming that exposure to environmental microplastics inevitably causes specific diseases. Rather, the available literature indicates plausible biological mechanisms that require further experimental, toxicological, and epidemiological validation.

The potential interaction between microplastics and chemical contaminants is another important consideration. Microplastics can adsorb substances from surrounding environmental media, including persistent organic pollutants and other chemical compounds. When contaminated particles are ingested, these substances may potentially be introduced into biological systems together with the plastic particles. Azizi et al [58] emphasized the concern that microplastics may act as carriers of chemical substances, thereby complicating the assessment of their biological effects. The potential combination of physical particle effects and chemical exposure means that health-risk assessment should consider not only the concentration of microplastics but also their polymer characteristics, surface properties, associated contaminants, and environmental history.

In the context of Jakarta, the atmospheric pathway deserves particular attention because the city is characterized by dense population, intensive transportation, commercial activities, and substantial plastic consumption. The presence of microplastics in atmospheric deposition means that humans may be exposed to particles that circulate within the urban environment before being deposited by rainfall [36]. Rainfall may transfer atmospheric particles to soil, water bodies, food-production environments, and coastal ecosystems. These pathways create opportunities for microplastics to enter food and water resources that are eventually consumed by humans.

The potential health implications are also connected with aquatic food webs. Microplastics can be ingested by plankton, fish, shellfish, and other aquatic organisms and may subsequently become associated with food consumed by humans. Xu et al [35] reported potential physiological and metabolic disturbances associated with microplastic contamination in marine organisms and highlighted concerns regarding human exposure through contaminated organisms. Liu et al [43] further discussed the potential for bioaccumulation and biomagnification associated with microplastic contamination and substances carried by these particles. However, the extent to which microplastics themselves biomagnify across trophic levels remains an active area of scientific investigation and should not be generalized across all particle types and ecosystems.

Overall, the findings indicate that microplastic pollution represents a potential human health concern because environmental contamination creates multiple pathways for exposure. The atmospheric occurrence of microplastics adds an additional dimension because airborne particles can be inhaled directly or deposited through rainfall into environments associated with food and water resources [17]. Ingestion, particularly through contaminated food and drinking water, represents an important pathway that warrants further investigation. At the same time, the potential for gastrointestinal uptake and translocation highlights the need to understand the biological behavior of particles with different sizes and physicochemical properties.

Therefore, the health implications of microplastics should be addressed through a precautionary and evidence-based approach. Efforts to reduce exposure should prioritize the reduction of plastic waste at its source, improved waste-management systems, reduced dependence on single-use plastics, appropriate use of alternative materials, and continued monitoring of microplastics in food, drinking water, and atmospheric environments. Public education is also important because individual consumption and waste-disposal practices contribute to the generation and environmental dissemination of plastic particles [16]. At the scientific level, further research is required to establish exposure thresholds, toxicological mechanisms, long-term health effects, and the relative contribution of different exposure pathways. Such evidence will be essential for developing effective policies to protect both environmental quality and human health.

## d. Community and Government Responses to Microplastic Pollution

The increasing occurrence of microplastics in atmospheric, terrestrial, freshwater, and marine environments indicates that mitigation cannot rely solely on environmental clean-up activities. Effective management requires interventions that address plastic pollution at its source, improve waste-management practices, strengthen public awareness, and promote collaboration among government institutions, communities, private sectors, and other relevant stakeholders. The findings of this study indicate that community participation and government intervention are complementary components in reducing the generation and environmental dissemination of microplastics.

One of the most important strategies is reducing the amount of plastic entering the environment. Plastic waste can gradually fragment into smaller particles through exposure to sunlight, mechanical abrasion, and other environmental processes. Therefore, source reduction is more effective than relying exclusively on the removal of microplastics after they have entered environmental compartments. Tanjil et al [15] emphasized the importance of reducing plastic waste as part of broader efforts to control microplastic pollution. This approach can be implemented through reducing single-use plastics, encouraging reusable materials, improving waste segregation, and strengthening recycling systems.

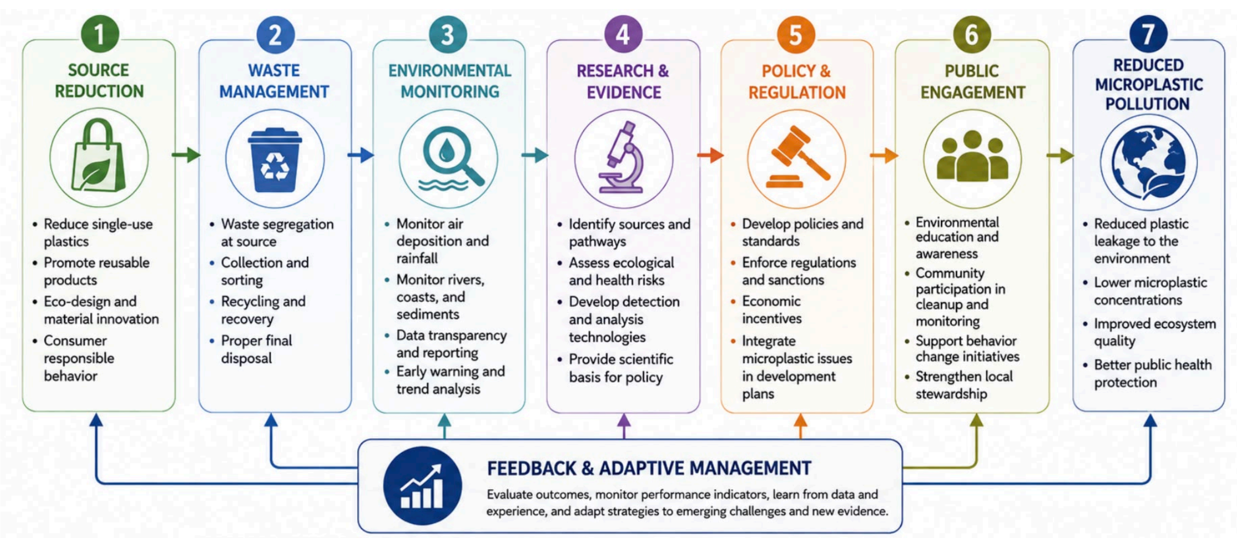


**Figure 9.** Integrated Framework for Community and Government Responses to Microplastic Pollution in Jakarta

Figure 9 illustrates an integrated framework in which microplastic mitigation begins with source reduction and continues through improved waste management, environmental monitoring, research, regulation, and public participation. The framework emphasizes that these components should not operate independently. For example, reducing single-use plastic consumption will have limited long-term effects if waste collection and recycling systems remain inadequate. Similarly, environmental regulations require monitoring and community participation to ensure effective implementation. Research also plays an important role by providing evidence regarding pollution sources, distribution patterns, ecological impacts, and potential health implications. This evidence can subsequently support policy refinement and adaptive management. Therefore, the management of microplastics should be understood as a continuous cycle rather than a single intervention. The integration of upstream prevention, environmental monitoring, stakeholder participation, and policy evaluation can provide a more sustainable approach to reducing plastic pollution in Jakarta.

Public education represents another important component of microplastic mitigation. Socialization and environmental outreach can increase community knowledge concerning the sources and potential impacts of plastic waste. Altunışık [24] emphasized the importance of educating communities about practical waste-sorting practices, particularly the separation of organic and inorganic waste at the household level. Such education becomes more effective when theoretical information is accompanied by practical examples. Communities can, for example, separate kitchen waste for composting while collecting plastic waste for reuse or recycling.

Community participation is important because household consumption and waste-disposal behavior directly influence the amount of plastic entering the environment. Educational programs can encourage individuals to reduce unnecessary plastic consumption, use reusable products, separate waste at its source, and participate in community-based recycling activities. Sin et al [5] highlighted the importance of increasing community awareness and literacy regarding the environmental and health risks associated with microplastics. Consequently, environmental education should not be limited to explaining the definition and dangers of microplastics but should also provide practical behavioral alternatives that can be implemented in daily life.

The main community and policy strategies identified from the literature and findings of this study are summarized in Table 3.

**Table 3.** Community and Policy Strategies for Reducing Plastic and Microplastic Pollution

| Strategy | Main objective | Key activities | Primary stakeholders | Expected outcome |
|---|---|---|---|---|
| Reduction of single-use plastics | Reduce plastic generation at source | Promote reusable bags, bottles, and food containers; restrict unnecessary single-use plastics | Government, businesses, communities | Reduced plastic consumption |
| Household waste segregation | Prevent mixing of recyclable and non-recyclable waste | Separate organic, recyclable, and residual waste | Households, local communities | Improved waste recovery |
| Recycling and reuse | Reduce plastic disposal and fragmentation | Collection, sorting, recycling, and reuse of plastic materials | Communities, private sector, recycling facilities | Reduced plastic leakage |

| Strategy | Main objective | Key activities | Primary stakeholders | Expected outcome |
|---|---|---|---|---|
| Environmental education | Increase public awareness and behavioral change | Socialization, workshops, school programs, campaigns | Government, schools, NGOs, communities | Increased environmental literacy |
| Plastic waste monitoring | Identify pollution sources and distribution | Monitoring of rivers, beaches, air, and coastal areas | Government, researchers, communities | Improved environmental information |
| Regulatory intervention | Control plastic production, use, and disposal | Restrictions, standards, enforcement, and sanctions | Local and national government | Improved compliance |
| Circular economy | Reduce dependence on virgin plastic materials | Product redesign, reuse, recycling, and recovery | Private sector, government | Reduced plastic waste generation |
| Community-based programs | Strengthen local participation | Clean-up activities, waste banks, recycling initiatives | Communities, local government, NGOs | Increased participation and local capacity |

Table 3 demonstrates that reducing microplastic pollution requires interventions at several stages of the plastic life cycle. Regulatory measures are necessary to establish standards and restrictions, but regulation alone may not produce sustainable outcomes without community participation and appropriate infrastructure. Household waste segregation, for example, can improve the recovery of recyclable materials and reduce the amount of plastic entering uncontrolled disposal systems. Recycling and reuse can further reduce the availability of plastic materials that may eventually fragment into microplastics [9]. Meanwhile, environmental education provides the behavioral foundation for these interventions by improving community understanding and encouraging responsible consumption. The private sector also has an important role in redesigning products and packaging to reduce unnecessary plastic use. Consequently, an integrated approach involving regulation, infrastructure, education, economic incentives, and community participation is more appropriate than relying on a single mitigation strategy.

Community-based recycling initiatives can provide an additional mechanism for transforming plastic waste from an environmental burden into a recoverable resource. The activities described in the existing community programs demonstrate that collected plastic waste can be sorted and processed into useful products. Xiang et al [40] emphasized that the characteristics and types of polymers used in recycling processes can influence the quality of the resulting products. Therefore, appropriate sorting and identification of plastic materials are important components of recycling programs. Such activities can simultaneously improve environmental awareness, provide practical waste-management skills, and create potential economic value from plastic waste.

In addition to community initiatives, government intervention is essential because microplastic pollution involves multiple environmental compartments and administrative sectors [17]. Local governments have responsibilities related to waste collection, environmental monitoring, public education, and enforcement, while national institutions can provide broader regulatory frameworks and technical standards. Coordination is particularly important in Jakarta because plastic waste can move across administrative and environmental boundaries through drainage systems, rivers, atmospheric transport, and coastal currents.


**Figure 10.** Implementation Flowchart for an Integrated Microplastic Management Strategy in Jakarta.

Figure 10 shows that microplastic management should be implemented through an adaptive process consisting of problem identification, baseline assessment, strategy development, implementation, monitoring, evaluation, and policy adjustment. This approach is particularly relevant because microplastic pollution is dynamic and influenced by changing environmental and socioeconomic conditions. Monitoring should therefore be conducted periodically to determine whether interventions reduce plastic inputs and environmental contamination [18]. If the expected targets are not achieved, policies and implementation strategies should be reviewed and modified. This feedback mechanism can prevent environmental management from becoming a static program that is unable to respond to emerging pollution pathways. In Jakarta, the approach could integrate monitoring of atmospheric deposition, rainfall, rivers, coastal areas, and waste-management systems. The resulting evidence can then be used to identify priority sources and evaluate whether interventions are producing measurable improvements.

The effectiveness of this approach depends strongly on cooperation among stakeholders. Government institutions have an important role in policy development, regulation, enforcement, infrastructure provision, and environmental monitoring. Communities contribute through responsible consumption, waste segregation, recycling, and participation in environmental programs [20]. The private sector can contribute through environmentally responsible product design, reduction of unnecessary plastic packaging, recycling investment, and implementation of circular-economy principles. Academic and research institutions can provide scientific evidence and technological innovations, while civil society organizations can strengthen environmental education and community engagement.

**Table 4.** Stakeholder Roles in Microplastic Pollution Management in Jakarta

| Stakeholder | Main role | Examples of contributions | Expected contribution |
|---|---|---|---|
| Local government | Regulation, coordination, and implementation | Waste infrastructure, environmental monitoring, public campaigns | Effective local environmental governance |
| National government | Policy and regulatory support | National standards, technical guidance, funding, and policy coordination | Consistent environmental policy |
| Academic and research institutions | Research and evidence generation | Microplastic monitoring, risk assessment, technological development | Evidence-based intervention |
| Private sector | Source reduction and innovation | Sustainable packaging, recycling, product redesign | Reduced plastic generation |
| Local communities | Behavioral change and waste management | Waste segregation, recycling, clean-up activities | Reduced plastic leakage |
| NGOs and civil society | Advocacy and public engagement | Education, campaigns, community empowerment | Increased public participation |
| Media | Information dissemination | Environmental reporting and public awareness campaigns | Increased awareness and accountability |

Table 4 highlights that no single stakeholder can address microplastic pollution independently. Local government provides the institutional foundation for implementation, whereas national government support can ensure regulatory consistency and technical capacity. Academic institutions contribute evidence necessary for identifying pollution sources and evaluating environmental risks. The private sector has a particularly important position because many plastic products originate from commercial production and consumption systems [38]. Changes in packaging design, material selection, and recycling practices can therefore reduce plastic generation upstream. Communities remain essential because waste-management systems ultimately depend on household and individual behavior. NGOs and media can further strengthen public awareness and accountability. Collaboration among these stakeholders can create a governance structure in which scientific evidence, policy instruments, infrastructure, and community behavior reinforce one another.

The findings also suggest that public participation should be treated as an integral component of environmental governance rather than merely as an additional supporting activity. Community participation can improve the effectiveness of waste-management programs because local residents possess direct knowledge of waste-generation patterns and environmental conditions [39]. Community-based monitoring may also help identify locations where waste accumulates or where waste-management services are inadequate. When communities are actively involved in planning and implementation, environmental programs may obtain stronger local legitimacy and greater continuity.

Overall, the management of microplastic pollution in Jakarta requires a combination of prevention, regulation, environmental monitoring, scientific research, community participation, and stakeholder collaboration. Reducing single-use plastic consumption, strengthening waste segregation and recycling, improving environmental monitoring, and expanding public education should be implemented simultaneously rather than separately [42]. The findings also support an adaptive management approach in which environmental data are continuously used to evaluate policy effectiveness and identify necessary improvements. Such an approach is consistent with the principle that environmental governance must respond to changing pollution pathways and emerging scientific evidence.

Therefore, the long-term reduction of microplastic pollution cannot depend solely on downstream clean-up activities. Interventions should prioritize preventing plastic waste from entering the environment, strengthening institutional capacity, and developing a circular system in which plastic materials are reduced, reused, recovered, and recycled [2]. Through coordinated action among government, communities, private sectors, researchers, and civil society, Jakarta can develop a more comprehensive strategy for reducing plastic leakage and limiting the formation and redistribution of microplastics.

## Conclusion

This study concludes that microplastic pollution in Jakarta represents a multidimensional environmental issue that extends beyond terrestrial and aquatic ecosystems to the atmospheric environment. The findings indicate that atmospheric microplastics can originate from diverse anthropogenic activities, including plastic waste fragmentation, synthetic textile fibers, vehicle tire abrasion, and plastic waste combustion. The relatively high concentrations reported in Jakarta, particularly in Central and South Jakarta, demonstrate the importance of urban activities in contributing to atmospheric microplastic contamination. The dominance of fragments and fibers further indicates the contribution of both degraded plastic materials and synthetic products to airborne microplastic pollution.

Rainfall represents an important pathway for transferring atmospheric microplastics to terrestrial and aquatic ecosystems. Through wet deposition, airborne particles can reach soil, rivers, sediments, and coastal waters, thereby connecting atmospheric pollution with other environmental compartments. This interconnected pathway increases the potential for microplastics to accumulate in different ecosystems and interact with terrestrial and aquatic organisms. Microplastic exposure may affect soil properties, sediment quality, aquatic habitats, and organisms such as plankton, fish, shellfish, and other marine biota. The potential transfer of microplastics through food webs further demonstrates that the environmental consequences may extend beyond individual ecosystems.

The study also highlights potential implications for human health. Microplastics may reach humans through ingestion, inhalation, and direct environmental contact, with food and drinking water representing important potential exposure pathways. Their potential interaction with intestinal tissues, translocation through biological barriers, and association with chemical contaminants raise concerns regarding possible oxidative stress, inflammation, cellular damage, and metabolic disturbances. However, these health implications should be interpreted cautiously because the magnitude of human health risks and the mechanisms underlying long-term exposure remain areas requiring further toxicological and epidemiological investigation.

Addressing microplastic pollution in Jakarta therefore requires an integrated and adaptive management strategy. Source reduction, restrictions on unnecessary single-use plastics, improved waste segregation and recycling, environmental monitoring, public education, and stronger regulatory enforcement should be implemented simultaneously. Effective mitigation also requires collaboration among local and national governments, communities, private sectors, academic institutions, and civil society organizations. Community participation is particularly important because sustainable plastic reduction depends not only on regulatory intervention but also on changes in consumption, disposal, and recycling behavior.

Overall, this study emphasizes that microplastic pollution should be addressed as a connected environmental governance issue rather than an isolated waste-management problem. An integrated approach that links source control, waste management, atmospheric and environmental monitoring, scientific research, policy implementation, and community participation can provide a stronger basis for reducing microplastic leakage and protecting Jakarta's terrestrial, aquatic, and coastal ecosystems. Future research should strengthen empirical monitoring of atmospheric and rainfall-associated microplastics, establish more robust exposure and risk assessments, and evaluate the effectiveness of specific governmental interventions to support evidence-based and sustainable microplastic management.

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