

Microplastics and Pollution in Indonesia's Marine Environment: Oceanographic Perspectives

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ABSTRACT: Microplastic pollution is an emerging global concern due to its persistence, ubiquity, and potential ecological and socioeconomic impacts. Indonesia, as the world's largest archipelagic nation with extensive coastlines, diverse ecosystems, and high population density, is particularly vulnerable to marine microplastic contamination. This review synthesizes recent research on the sources, distribution, ecological consequences, and human and socioeconomic implications of microplastics in Indonesian waters, highlighting research gaps and future directions. Microplastic inputs originate from land-based sources, including domestic waste, urban runoff, rivers, tourism, aquaculture, and fisheries, as well as sea-based sources, such as fishing gear, shipping, coastal industries, and offshore aquaculture. Their transport is influenced by hydrodynamic processes, including tides, currents, monsoonal winds, and the Indonesian Throughflow, leading to spatial and seasonal heterogeneity in surface waters, sediments, and biota. Ecological impacts include ingestion by fish and invertebrates, trophic transfer, and interaction with chemical pollutants such as heavy metals and persistent organic pollutants, posing risks to marine biodiversity and ecosystem functioning. Human and socioeconomic consequences arise from seafood contamination, health risks, fisheries and aquaculture productivity losses, and impacts on tourism. Significant research gaps remain, including regional bias towards western Indonesia, lack of standardized sampling and polymer identification methods, limited integration of oceanographic modeling, and insufficient long-term and interdisciplinary studies. Future research should integrate oceanographic, ecological, and socio-economic approaches, leverage remote sensing, modeling, and molecular identification technologies, and support policy and management strategies to mitigate pollution. This review provides a comprehensive synthesis to guide future research, monitoring, and sustainable management of microplastic pollution in Indonesia's marine environment.

KEYWORDS: Microplastics; Indonesia; marine pollution; oceanography; ecological and socioeconomic impacts

1. Introduction

Microplastics are generally described as plastic particles smaller than 5 mm in size. They originate either as deliberately manufactured small particles, known as primary microplastics, or as secondary microplastics formed through the breakdown of larger plastic debris by physical, chemical, and biological processes [1]. These particles appear in various shapes, including fragments, fibers, films, pellets, and foams, and consist of common polymers such as polyethylene, polypropylene, polystyrene, and polyethylene terephthalate. Because of their small size and resistance to degradation, microplastics can persist in marine environments for long periods and interact with both oceanographic processes and marine organisms [2].

Marine microplastic contamination has emerged as a major global environmental concern. With the rapid expansion of plastic production and consumption, microplastics have been detected in nearly all marine compartments, including surface waters, the water column, seabed sediments, and marine biota—from coastal zones to deep-sea environments [3]. Their widespread distribution is strongly influenced by oceanographic dynamics, including surface currents, vertical mixing, wind-driven transport, and density-related sinking and resuspension processes [4]. These mechanisms enable microplastics to travel considerable distances, leading to accumulation not only along densely populated coastlines but also in remote oceanic regions far from direct pollution sources [3, 4].

The significance of marine microplastics is further underscored by their potential ecological and human health impacts. Research has shown that microplastics are ingested by a wide range of marine organisms across multiple trophic levels, from plankton and benthic invertebrates to fish, seabirds, and marine mammals [2,5]. Such ingestion can result in physical obstruction, impaired feeding, oxidative stress, and inflammatory responses. In addition, microplastics may function as carriers of hazardous chemicals and pathogenic microorganisms [2]. Through trophic transfer within food webs, these particles can ultimately reach humans via seafood consumption, raising concerns about food safety and possible long-term health effects [4, 5].

Within this global context, Indonesia represents a critical region for studying marine microplastic pollution. As the world's largest archipelagic country, Indonesia consists of more than 17,000 islands and possesses one of the longest coastlines globally. Its marine environment encompasses a wide range of ecosystems, including estuaries, mangroves, seagrass meadows, coral reefs, and deep-ocean basins, many of which are characterized by high biodiversity and productivity. Indonesia is also located within the Coral Triangle, a globally significant marine biodiversity hotspot that supports complex ecological interactions and provides essential ecosystem services [6].

Indonesia's geographical position between the Pacific and Indian Oceans exposes its waters to complex oceanographic circulation systems, including the Indonesian Throughflow, monsoonal currents, and strong tidal mixing. These processes play a key role in controlling the transport, dispersion, and accumulation of microplastics across different marine zones [3, 7]. Riverine inputs from densely populated catchments further contribute to microplastic loading in coastal and estuarine environments, where particles may subsequently be redistributed to offshore waters or deposited in sediments depending on hydrodynamic conditions [1, 7].

Several recent studies have identified Indonesia as one of the major contributors of plastic waste to the marine environment, primarily due to rapid coastal development, high population density, and insufficient waste management infrastructure in some regions [6, 8]. Once plastic

debris enters Indonesian waters, it undergoes fragmentation, generating large quantities of secondary microplastics that contaminate surface waters, subsurface layers, and sediments [7]. Observations of microplastics in subsurface waters of the Indonesian archipelago indicate that these particles are not confined to the surface but are vertically transported and retained within the water column, increasing their bioavailability to pelagic organisms [7].

The ecological implications of microplastic pollution are particularly concerning for Indonesia, given the reliance of coastal communities on marine resources for food security and livelihoods. Fisheries, aquaculture, and marine tourism form important economic sectors, all of which may be affected by microplastic contamination of marine habitats and organisms [5, 8]. Despite increasing research efforts, however, existing studies are often fragmented, focusing on specific locations or environmental compartments, and lack integration with oceanographic processes that govern microplastic fate and transport.

Therefore, the aim of this review is to synthesize current knowledge on microplastic distribution and impacts in Indonesian waters, with a particular emphasis on oceanographic aspects influencing their transport, accumulation, and interaction with marine ecosystems. By integrating physical oceanography, environmental monitoring, and ecological perspectives, this review seeks to provide a comprehensive understanding of microplastic pollution in Indonesia and to identify critical knowledge gaps that should be addressed in future research and management strategies.

2. Methodology

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparency, reproducibility, and methodological rigor in synthesizing existing literature on the sources, transport, distribution, and impacts of microplastics in Indonesian marine environments [1]. The PRISMA framework was adopted to systematically identify, screen, and evaluate relevant peer-reviewed studies and to minimize selection bias during the review process.

A comprehensive literature search was performed using the Scopus, Web of Science, and ScienceDirect databases to identify relevant journal articles published between 2020 and 2026. The search strategy employed a combination of keywords related to microplastics, oceanographic processes, and Indonesian waters, using Boolean operators as follows: (“microplastic*” OR “plastic debris”) AND (“Indonesia” OR “Indonesian waters” OR “archipelagic waters”) AND (“oceanography” OR “monsoon” OR “current” OR “sediment” OR “biota”). Only English-language peer-reviewed journal articles with Digital Object Identifiers (DOIs) were considered. Eligible publication types included original research articles, systematic reviews, and short communications that addressed marine or coastal microplastic pollution within the Indonesian context.

Studies were included in the review if they focused on marine, coastal, or estuarine environments in Indonesia and reported data on microplastic occurrence, sources, transport pathways, spatial distribution, or ecological and human impacts. Eligible studies employed field-based sampling, laboratory analyses (e.g., spectroscopic polymer identification), numerical modeling, or integrated methodological approaches. To ensure data reliability and comparability, only studies providing clear methodological descriptions and quantitative or well-defined qualitative results were retained. Studies were excluded if they focused exclusively on freshwater systems without direct marine relevance, were non-peer-reviewed

publications (such as conference proceedings, theses, or technical reports), or lacked essential methodological information such as polymer identification or sampling procedures.

Following database searches, duplicate records were removed prior to screening. Titles and abstracts were initially screened to assess relevance to the review objectives, after which full-text articles were evaluated against the inclusion and exclusion criteria. Data extraction was conducted systematically to capture key information from each eligible study, including sampling locations and environmental compartments (surface waters, sediments, or biota), microplastic concentrations, particle sizes, shapes, and polymer composition, identified sources and transport pathways, and reported oceanographic conditions such as currents, monsoonal circulation, and tidal influences. Information on ecological effects, trophic interactions, and socioeconomic implications was also extracted where available. The synthesized data were then analyzed qualitatively to identify dominant patterns, knowledge gaps, and emerging trends in microplastic research within Indonesian marine systems (Table 1).

Table 1. PRISMA Selection Process.

Stage	Process Description	Number of Records (n)
Identification	Records identified from Scopus	112
	Records identified from Web of Science	84
	Records identified from ScienceDirect	76
	Total records identified	272
	Duplicate records removed	58
	Records after duplicates removed	214
Screening	Titles and abstracts screened	214
	Records excluded at screening stage	138
Eligibility	Full-text articles assessed for eligibility	76
	Full-text articles excluded (freshwater only)	8
	Full-text articles excluded (non-peer-reviewed)	7
	Full-text articles excluded (insufficient methodological detail)	9
	Full-text articles excluded (outside 2020–2026 range)	3
	Full-text articles excluded (other reasons)	3
Included	Studies included in qualitative synthesis	46

3. Sources and Pathways of Microplastics in Indonesia

Microplastic pollution in Indonesian marine environments originates from a complex interplay of land-based and sea-based human activities combined with hydrodynamic transport processes that redistribute plastic debris across coastal and offshore systems. Due to Indonesia's rapid coastal urbanization, dense population, and extensive river networks, land-based sources are widely recognized as the dominant contributors of microplastics to its marine waters [9]. Domestic waste mismanagement, particularly the widespread use of single-use plastics, results in large quantities of plastic debris entering drainage systems and urban runoff pathways, where plastics undergo fragmentation before being transported into rivers and coastal waters [9, 10].

Urban runoff and river discharge serve as critical pathways linking terrestrial plastic sources to marine environments. Studies conducted in Java Island rivers and estuaries have consistently detected microplastics in both water and sediments, with fragments and films dominating particle shapes, indicating their origin from degraded packaging materials and household waste [9]. Riverine transport intensifies during periods of high rainfall, when

increased surface runoff mobilizes plastic debris from urban landscapes and informal disposal sites, resulting in elevated microplastic fluxes toward coastal zones [10]. Seasonal observations from the Greater Jakarta area demonstrate a strong relationship between precipitation patterns and microplastic release into Jakarta Bay, highlighting the importance of hydrological forcing in governing land-based microplastic inputs [10].

Tourism, aquaculture, and fisheries activities further contribute to land-derived microplastics in Indonesia. Coastal tourism generates plastic litter from recreational activities, food packaging, and consumer goods, which may enter marine waters directly or indirectly through runoff and river systems. Similarly, aquaculture and small-scale fisheries operating near river mouths and coastal settlements release plastic materials such as feed bags, ropes, and containers that fragment into microplastics over time [9]. These sources reinforce the land-sea continuum as a key mechanism through which terrestrial activities influence marine microplastic contamination.

In addition to land-based inputs, sea-based sources represent a significant but often underestimated contribution to microplastic pollution in Indonesian waters. Marine fishing gear, including synthetic nets, lines, and floats, constitutes one of the primary sea-based sources, particularly in regions with intensive fishing activity [11]. Loss, abandonment, and degradation of fishing gear release fibers and fragments directly into the marine environment, where they can persist and disperse over large spatial scales. Shipping and maritime transport also contribute plastics through accidental loss of materials, packaging waste, and operational discharges, which subsequently degrade into microplastics under mechanical and environmental stress [11]. Coastal industries and offshore aquaculture installations further exacerbate sea-based inputs by introducing plastic components that fragment through prolonged exposure to ultraviolet radiation, wave action, and biofouling.

Once microplastics enter Indonesian marine systems, their distribution is strongly influenced by physical transport pathways driven by rivers, tides, currents, and seasonal monsoon circulation. Rivers deliver large quantities of microplastics into estuaries, where tidal mixing determines whether particles are retained locally, deposited in sediments, or transported offshore [9]. Surface currents and wind forcing then redistribute floating microplastics across the archipelago, while denser or biofouled particles may sink and accumulate in nearshore or benthic environments.

Oceanographic processes play a particularly important role in shaping microplastic pathways in Indonesia due to its location between the Pacific and Indian Oceans. Studies in the tropical Northwestern Pacific and Indonesian seas demonstrate that regional current systems, including the Indonesian Throughflow, facilitate long-distance transport of microplastics across basins and contribute to spatial heterogeneity in concentration patterns [11]. Seasonal monsoons further modulate these pathways by reversing prevailing wind and current directions, leading to temporal variability in microplastic accumulation zones. During certain monsoon phases, floating debris may be driven toward coastal and semi-enclosed seas, while in other periods it is transported toward open ocean regions [12].

4. Distribution and Oceanographic Patterns

Microplastic distribution in Indonesian marine environments reflects the interaction between anthropogenic inputs, particle characteristics, and complex oceanographic processes. Given Indonesia's archipelagic setting and dynamic circulation systems, microplastics are

heterogeneously distributed across surface waters, sediments, and biota, with pronounced spatial and seasonal variability driven by monsoonal winds, river discharge, and large-scale current systems such as the Indonesian Throughflow [13,14]. Table 2 shows overview of microplastic distribution in Indonesian marine environments

Table 2. Overview of microplastic distribution in Indonesian marine environments

Compartment / Type	Key Characteristics	Drivers / Processes	Reference
Surface waters	Concentrations vary from <1 item m ³ offshore to several items L ⁻¹ in coastal/upwelling zones; fibers and fragments dominate; PE and PP most common polymers	Hydrodynamic forcing, vertical redistribution by upwelling, seasonal monsoons, river discharge, urban runoff	[13–15]
	PET and rubber-based polymers detected in regions influenced by urban and fishing activities	Local anthropogenic inputs, proximity to populated islands and semi-enclosed basins	[13,15]
	Seasonal variability: wet season increases riverine microplastic input; dry season promotes retention	Monsoon-driven wind and current patterns, water residence time	[13,14]
Sediments (coastal and estuarine)	Hundreds of particles per kg dry sediment; fragments and fibers dominate	Low-energy depositional zones, tidal flats, mangrove-fringed coasts	[16]
	Denser polymers like PET and PVC more frequent; microplastics present in remote benthic habitats	Vertical transport: biofouling, aggregation, particle settling; Indonesian Throughflow	[17]
Sediment variability	Spatial heterogeneity due to bathymetry, sedimentation rate, tidal currents; resuspension occurs	Local current regimes, storm activity, river discharge	[16]
Biota	Microplastic ingestion reported in fish, bivalves, crustaceans; fibers and fragments dominate	Bioavailability, feeding strategy, habitat type	[18]
	Trophic transfer potential; microplastics may carry chemical contaminants	Predation, food chain dynamics, adsorption/desorption of pollutants	[18,19]
	Seasonal variability affects ingestion rates	Monsoonal circulation, riverine input, local environmental exposure	[18,19]

4.1. Surface waters.

Surface waters are among the most extensively studied compartments for microplastic pollution in Indonesia. Concentrations in surface waters vary considerably across regions, ranging from less than 1 item per m³ in offshore waters to several items per liter in coastal and upwelling-influenced zones [13,15]. Studies conducted in the Maluku Sea during peak upwelling conditions reported elevated microplastic concentrations, indicating that physical oceanographic processes can enhance the vertical redistribution of particles toward the surface [13]. Such findings suggest that surface microplastic abundance is not solely determined by proximity to pollution sources but also by hydrodynamic forcing. In terms of particle characteristics, fibers and fragments consistently dominate surface microplastic assemblages in Indonesian waters [13–15]. Fibers are primarily associated with synthetic textiles and fishing gear, while fragments originate from the degradation of larger plastic items such as packaging materials. Polymer composition analyses reveal that polyethylene (PE) and polypropylene (PP) are the most abundant polymers in surface waters, reflecting their widespread use and low density, which favors buoyancy [14]. Polyethylene terephthalate (PET) and rubber-based polymers are also detected, particularly in regions influenced by urban runoff and fishing activities [13,15]. Spatial heterogeneity is evident across Indonesian seas, with higher concentrations typically reported near densely populated islands and semi-enclosed basins

where water exchange is limited [14]. Seasonal variability further influences surface microplastic distribution. During the wet monsoon season, increased river discharge and surface runoff enhance microplastic inputs into coastal waters, while changes in wind-driven circulation alter transport pathways and accumulation zones [13,14]. Conversely, during the dry season, reduced runoff but longer water residence times may promote local retention of floating microplastics.

4.2. *Sediments.*

Marine sediments act as important sinks for microplastics in Indonesian waters, particularly in estuaries, coastal zones, and benthic environments. Sediment-associated microplastics are generally more abundant in areas characterized by low hydrodynamic energy, such as tidal flats, mangrove-fringed coasts, and semi-enclosed bays [16]. Studies in the Java Sea and adjacent coastal regions report microplastic concentrations in sediments reaching several hundred particles per kilogram of dry sediment, with fragments and fibers again representing the dominant particle types [16]. Polymer composition in sediments often mirrors that observed in surface waters, although denser polymers such as PET and polyvinyl chloride (PVC) are more frequently detected due to their higher propensity to sink [17]. In deeper marine environments, including areas influenced by the Indonesian Throughflow, microplastics have been identified in deep-sea sediments, demonstrating that plastic pollution extends beyond coastal zones into remote benthic habitats [17]. Vertical transport processes, including biofouling, aggregation with organic matter, and particle settling, contribute to the transfer of microplastics from the water column to the seabed. Sediment accumulation patterns also exhibit spatial heterogeneity driven by local bathymetry, sedimentation rates, and current regimes. In regions with strong tidal currents, resuspension can occur, allowing microplastics to cycle repeatedly between sediments and overlying waters [16]. Seasonal changes in river discharge and storm activity further influence sedimentary microplastic inventories, particularly in estuarine environments.

4.3. *Biota*

Microplastics have been widely documented in Indonesian marine biota, raising concerns about ecological impacts and food chain transfer. Ingestion of microplastics has been reported in fish, bivalves, crustaceans, and other invertebrates inhabiting coastal and estuarine environments [18]. Studies on commercially important fish species from Indonesian rivers and coastal waters indicate frequent ingestion of fibers and fragments, with particles detected in gastrointestinal tracts [18]. These findings suggest that microplastics are readily bioavailable to marine organisms across different trophic levels. The presence of microplastics in lower trophic organisms increases the potential for trophic transfer within food webs. Experimental and field-based evidence from Southeast Asia indicates that microplastics ingested by invertebrates can be transferred to higher trophic levels through predation [19]. In addition to physical effects such as gut blockage or reduced feeding efficiency, microplastics may act as vectors for chemical contaminants, including heavy metals and persistent organic pollutants, which can adsorb onto particle surfaces and desorb following ingestion [18, 19]. The distribution of microplastics in biota is influenced by habitat type, feeding strategy, and environmental exposure. Pelagic species may be more exposed to floating microplastics, while benthic feeders are more likely to ingest sediment-associated particles. Seasonal variability in microplastic

availability, driven by monsoonal circulation and riverine inputs, may therefore influence ingestion rates and ecological risk across different times of the year.

5. Ecological Impacts

Microplastic pollution in Indonesian marine environments poses multiple ecological risks to marine organisms due to both physical and chemical impacts, leading to potential bioaccumulation and trophic transfer, as well as interactions with other contaminants. These impacts have been increasingly documented in recent studies focusing on fish, invertebrates, and benthic organisms across coastal and estuarine habitats [20, 21].

5.1. Physical impacts.

Physical impacts of microplastics are primarily associated with ingestion and entanglement. Marine organisms may mistakenly ingest microplastics due to their size, shape, or resemblance to natural prey items. Studies on fish species collected from coastal Indonesian waters report that ingested microplastics can cause gut blockage, reduced feeding efficiency, internal abrasions, and reduced energy allocation [20]. Similarly, benthic organisms such as bivalves and polychaetes experience mechanical stress and reduced burrowing efficiency when microplastics accumulate in sediment layers [21]. In crustaceans, fiber-rich microplastics have been linked to impaired molting and decreased survival rates, highlighting the species-specific sensitivity to particle morphology [22].

5.2. Chemical impacts and pollutant interaction.

Beyond physical harm, microplastics also act as vectors for chemical contaminants, including heavy metals and persistent organic pollutants (POPs). These contaminants can adsorb onto the surface of microplastics in water and sediments, and subsequently desorb once ingested by organisms, leading to chemical exposure even in relatively pristine environments [23]. Studies in Indonesian estuaries have shown that microplastics collected from sediments frequently carry trace metals such as lead (Pb), cadmium (Cd), and copper (Cu), as well as hydrophobic organic pollutants like polychlorinated biphenyls (PCBs) [24]. The combined physical and chemical effects can compromise organism health, reproduction, and immune response.

5.3. Bioaccumulation and trophic transfer.

Bioaccumulation occurs when microplastics persist in organisms over time, particularly in filter feeders and benthic invertebrates. These microplastics can then enter higher trophic levels through predation, resulting in trophic transfer. Recent field studies in Indonesian waters report microplastics in both prey species (such as shrimps and mollusks) and commercially important fish, indicating the potential for biomagnification [20, 25]. Laboratory experiments corroborate these findings, showing that fish feeding on contaminated invertebrates retain microplastics in the gastrointestinal tract for extended periods, which may influence nutrient absorption and energy allocation [21]. Seasonal patterns, such as monsoon-driven riverine inputs, also influence the degree of bioaccumulation, with higher contamination observed during wet seasons due to increased plastic flux [20].

5.4. Case studies in Indonesian waters.

Several studies highlight the ecological consequences of microplastics in Indonesia. For example, fish species in Jakarta Bay were found to contain fibers and fragments in 35–60% of sampled individuals, with corresponding reductions in gut fullness and lipid content [20]. In the Java Sea, bivalve mollusks accumulated microplastics in gills and digestive tracts, leading to altered filtration rates and growth inhibition [21]. Crustaceans sampled in Makassar Strait exhibited both physical damage from fibers and chemical exposure due to heavy metals adsorbed onto the ingested plastics [22]. These studies collectively indicate that microplastic pollution can compromise organismal health, affect population dynamics, and disrupt food web structures in tropical marine ecosystems. The ecological impacts of microplastics in Indonesian marine organisms is summarized in Table 3.

Table 3. Ecological impacts of microplastics in Indonesian marine organisms.

Compartment / Organism	Observed Impact	Mechanism / Process	Reference
Fish	Gut blockage, reduced feeding efficiency, internal abrasions	Ingestion of fibers and fragments; mechanical stress	[20]
Bivalves & polychaetes	Reduced filtration/burrowing efficiency, growth inhibition	Sediment-bound microplastic ingestion	[21]
Crustaceans	Impaired molting, decreased survival	Fiber ingestion; mechanical stress	[22]
All organisms	Chemical exposure: heavy metals (Pb, Cd, Cu), POPs (PCBs)	Adsorption/desorption of contaminants on microplastic surfaces	[23,24]
Food web	Bioaccumulation and trophic transfer	Predation on contaminated prey; biomagnification	[20,25]
Seasonal influence	Increased microplastic ingestion during wet season	Enhanced riverine and runoff inputs	[20]

6. Human and Socioeconomic Implications

Microplastic pollution in Indonesian marine environments has significant consequences for human health, coastal livelihoods, fisheries, and tourism. Through seafood contamination, microplastics can enter the human diet, raising concerns about potential health risks [26, 27]. Additionally, their presence in coastal ecosystems affects economic activities and highlights the need for regulatory interventions.

6.1. Seafood Contamination and Health Risks.

Seafood represents a major source of dietary protein for Indonesian coastal communities and urban consumers. Microplastic particles have been detected in commercially important fish, shellfish, and other marine organisms across Indonesia, indicating widespread contamination [26, 28]. These particles can be ingested directly by humans or potentially translocate into edible tissues, creating a route of exposure [27]. Microplastics can also carry adsorbed chemical contaminants, including persistent organic pollutants (POPs) and additives such as bisphenol A (BPA), which may have endocrine-disrupting effects and other toxicological impacts [27, 29]. Case studies in Banyuwangi and Jakarta Bay show that mussels, squid, and other seafood species contain microplastics in varying abundance, suggesting that regular consumption may contribute to cumulative human exposure [28]. Seasonal variations influence contamination levels; for instance, increased microplastic flux during wet monsoon periods elevates the concentration in seafood [26]. While definitive human health outcomes are still under investigation, experimental studies suggest potential oxidative stress, cytotoxicity, and immune response disruptions resulting from microplastic ingestion [27, 29].

6.2. Coastal livelihoods, fisheries, and tourism.

Microplastic pollution also impacts coastal livelihoods. Fisheries, a key economic and cultural resource, may be affected by reduced fish health and productivity due to microplastic ingestion by target species [30]. Aquaculture operations face similar challenges, with microplastics in rearing waters and sediments potentially degrading water quality and the nutritional content of farmed fish [31]. Such effects can reduce market value and income for local communities. Tourism, another vital sector, is affected as well. Beaches and coastal areas contaminated with plastic debris become less attractive to visitors, reducing tourism revenue and increasing cleanup costs. While Indonesia-specific tourism losses due to microplastics are not yet fully quantified, global studies suggest that visible marine litter can deter tourists, disrupt ecosystem services, and indirectly affect fisheries-dependent communities [32].

6.3. Regulatory and management relevance.

Addressing these human and socioeconomic implications requires coordinated policy and community-level interventions. Indonesia has initiated programs to reduce single-use plastics and improve waste management, but microplastic-specific regulations are still emerging. Integrating microplastic monitoring into public health advisories, fisheries management, and tourism planning can support evidence-based decision-making. Moreover, transboundary cooperation is critical, as ocean currents can transport microplastics across regions, affecting multiple coastal jurisdictions [33]. Table 4 summarizes the key human and socioeconomic implications of microplastics in Indonesian marine environments.

Table 4. Human and socioeconomic implications of microplastic pollution in Indonesian marine environments.

Implication Category	Key Issues	Outcomes / Potential Effects	Reference
Seafood contamination	Microplastics in commercial fish and seafood	Human ingestion of microplastics and associated chemicals	[26, 28]
Health risks	Potential toxicity, oxidative stress, chemical exposure from plastics	Uncertain but emerging concern for human health	[27,29]
Human exposure pathways	Consumption of fish, shellfish, squid; whole-organism consumption	Hazard quotient increases with intake	[28]
Fisheries impacts	Reduced fish health, potential lower yields	Economic stress for fishers	[30, 31]
Aquaculture concerns	Microplastics in aquaculture waters and sediments	Lower nutritional quality, potential market impacts	[31]
Tourism effects	Plastic pollution on beaches and coastal areas	Reduced tourism revenue and increased cleanup costs	[32]
Regulatory relevance	Need for monitoring, policy, and risk communication	Supports public health advisories and management	[33]

7. Research Gaps and Challenges

Despite increasing attention to microplastic pollution in Indonesian marine environments, several critical research gaps and methodological challenges remain, limiting the comprehensive understanding of the scale, pathways, and impacts of plastic debris across the archipelago [34]. These gaps are particularly evident in terms of spatial coverage, methodological standardization, integration with oceanographic processes, and long-term monitoring.

7.1. Regional bias.

Most existing studies on microplastics in Indonesia have focused on western regions, such as Java, Sumatra, and Bali, which host dense populations, intensive industrial activities, and major urban centers [34, 35]. Conversely, eastern Indonesia, including the Maluku and Papua regions, remains underrepresented in the literature despite its extensive coastlines, unique ecosystems, and reliance on fisheries and aquaculture [35, 36]. This regional bias limits the generalizability of findings, as environmental conditions, hydrodynamic regimes, and anthropogenic pressures vary considerably across the archipelago. Furthermore, data gaps in eastern Indonesia impede assessments of transboundary transport via major currents, including the Indonesian Throughflow, and reduce the ability to model plastic distribution at the national scale [36].

7.2. Lack of standardized methods.

Methodological inconsistencies remain a major challenge in Indonesian microplastic research. Studies vary in terms of sampling devices, mesh sizes, sample preservation, and laboratory protocols for polymer identification [37]. For example, some investigations use manta trawls with 330 μm mesh, while others employ smaller nets or grab sampling, leading to discrepancies in particle size detection and reported concentrations [37, 38]. Polymer identification methods, including Fourier-transform infrared spectroscopy (FTIR) and Raman spectroscopy, are not consistently applied, and chemical characterization is often limited to selected polymers, preventing cross-study comparability. Without standardized protocols, it is difficult to synthesize datasets for meta-analysis or to establish baselines for policy and management [38].

7.3. Limited integration with oceanographic modeling.

Microplastic distribution is strongly influenced by hydrodynamic processes such as currents, tides, monsoon winds, and upwelling zones. However, few studies in Indonesia integrate oceanographic modeling with field observations to predict transport pathways, accumulation zones, or seasonal variability [39]. Existing research often focuses on point measurements without coupling with hydrodynamic models, which limits understanding of long-range transport, particle sinking behavior, or the influence of the Indonesian Throughflow on inter-island microplastic exchange. Improved integration of modeling and observation would allow for predictive assessments of pollution hotspots and inform management strategies.

7.4. Insufficient long-term monitoring and interdisciplinary studies.

Long-term monitoring of microplastics in Indonesia is sparse, with most studies providing short-term or seasonal snapshots [34, 39]. Continuous monitoring is crucial to detect trends, evaluate the effectiveness of mitigation measures, and understand seasonal or interannual variability. Additionally, interdisciplinary approaches combining oceanography, ecology, toxicology, and socioeconomics remain limited. Such integration is necessary to link microplastic sources, transport pathways, ecological impacts, and human health or socioeconomic consequences [36, 39, 40]. Addressing these gaps would support holistic management strategies that are grounded in robust scientific evidence. Table 5 shows the research gaps and methodological challenges in microplastic studies in Indonesian environments.

Table 5. Research gaps and methodological challenges in microplastic studies in Indonesian environments.

Research Gap / Challenge	Description	Implications	Reference
Regional bias	Most studies focus on western Indonesia (Java, Bali, Sumatra); eastern regions (Maluku, Papua) remain underrepresented	Limits generalizability; reduces understanding of transboundary transport and national-scale patterns	[34,35]
Lack of standardized methods	Variability in sampling methods (nets, mesh sizes), sample processing, and polymer identification	Hinders comparability across studies and prevents establishment of national baselines	[36,37]
Limited integration with oceanographic modeling	Few studies integrate microplastic field data with hydrodynamic and circulation models	Reduces ability to predict transport pathways, accumulation zones, and seasonal variability	[38]
Insufficient long-term monitoring	Most studies are short-term or seasonal	Limits detection of temporal trends, assessment of mitigation efforts, and understanding of interannual variability	[39]
Lack of interdisciplinary studies	Minimal integration of ecology, toxicology, socioeconomics, and oceanography	Reduces understanding of linkages between sources, ecological impacts, and human or socioeconomic consequences	[40]

8. Future Directions

Mitigating microplastic pollution in Indonesian marine environments requires multidisciplinary integration across oceanography, ecology, and socioeconomics. Future research should prioritize understanding transport pathways, ecological exposure, and socioeconomic vulnerabilities, enabling evidence-based decision-making and effective management strategies [41]. Integrating oceanographic models with ecological surveys can identify microplastic accumulation hotspots, track seasonal and monsoonal variability, and predict areas at risk for high ecological and human exposure [42]. Coupling these models with socio-economic assessments facilitates prioritization of interventions in communities reliant on fisheries, aquaculture, and coastal tourism [43].

The application of advanced monitoring and identification technologies is essential. Remote sensing and high-resolution satellite imagery can detect macro- and meso-plastic accumulations, providing spatially extensive data to complement in situ sampling [44]. Hydrodynamic particle-tracking models can simulate microplastic dispersal under complex currents such as the Indonesian Throughflow, enabling forecasts of accumulation zones and ecological risk [42]. Molecular and spectroscopic techniques, including pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS), Raman spectroscopy, and Fourier-transform infrared spectroscopy (FTIR), allow precise identification of polymer types, supporting source attribution and understanding of degradation pathways [45].

Effective policy and management strategies are equally critical. Strengthening waste management infrastructure, promoting circular economy initiatives, and regulating the disposal of fishing gear and single-use plastics can reduce new inputs of microplastics [46]. Community-based approaches, such as participatory beach cleanups and sustainable fisheries practices, enhance local engagement and stewardship [41]. Establishing national long-term monitoring programs and integrated databases can support adaptive management and policy evaluation, ensuring that interventions are guided by robust scientific evidence [46].

4. Conclusions

Microplastic pollution in Indonesian waters represents a complex and growing environmental challenge, driven by a combination of anthropogenic inputs, dynamic oceanographic processes, and insufficient regulatory control. Land-based activities, including domestic waste

mismanagement, urban runoff, tourism, aquaculture, and fisheries, contribute substantially to microplastic inputs, while sea-based sources such as lost fishing gear, shipping, and coastal industries exacerbate contamination. Once introduced into marine systems, microplastics are transported and redistributed by rivers, tides, currents, and seasonal monsoons, resulting in spatially and temporally heterogeneous distributions in surface waters, sediments, and marine organisms. Fibers and fragments dominate particle types, with polyethylene and polypropylene as the most abundant polymers, reflecting their widespread use and buoyancy characteristics. Ecological impacts are significant, with microplastics ingested by fish, bivalves, crustaceans, and other invertebrates, facilitating trophic transfer and serving as vectors for adsorbed chemical contaminants, including heavy metals and persistent organic pollutants. These ecological effects, in turn, have human and socioeconomic implications. Coastal communities relying on fisheries and aquaculture are vulnerable to productivity losses and economic impacts, while seafood contamination poses potential health risks. Tourism and coastal livelihoods are also affected, emphasizing the need for integrated management approaches. Despite growing research efforts, major knowledge gaps persist, including regional biases favoring western Indonesia, lack of standardized sampling and polymer identification methods, limited integration of hydrodynamic modeling, and insufficient long-term interdisciplinary monitoring. Addressing these gaps requires coordinated research combining oceanography, ecology, and socioeconomics, alongside advanced monitoring tools such as remote sensing, molecular polymer identification, and predictive modeling. Policy interventions, improved waste management, and community engagement are essential to reduce microplastic inputs and mitigate ecological and socioeconomic risks. By integrating multidisciplinary research with proactive governance, Indonesia can advance sustainable management strategies that protect marine ecosystems, human health, and the socioeconomic well-being of coastal communities.

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Author Contributions

Ahmad Pratama Wijaya conceptualized the study, performed the literature review, and prepared the original draft. Olufemi Adekunle Balogun contributed to methodology design, data interpretation, and manuscript revision. Neema Rehema Mkwawa provided expertise on environmental and oceanographic analysis, assisted in data validation, and contributed to the final manuscript editing. All authors read and approved the final version of the manuscript.

Competing Interest

The authors declare that they have no competing interests in relation to this study.

Data Availability

All data generated or analyzed during this study are included in this published article and its supplementary information files. Additional datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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