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Plastic and Microplastic in The Karang Tirta Estuary, Pangandaran Regency: A DPSIR Overview

Jasmine Priyanka Budiono*, Zahidah Hasan, R Mochamad Candra Wirawan Arief, Tri Dewi Kusumaningrum Pribadi, Titin Herawati, Heti Herawati
Universitas Padjadjaran, Indonesia
Email: jasminebudiono5041@gmail.com*, zahidah@unpad.ac.id, mochamad.candra@unpad.ac.id, tridewi.pribadi@unpad.ac.id, titin.herawati@unpad.ac.id, h.herawati@unpad.ac.id

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Abstract

Karang Tirta is an estuary formed by the Citumang and Sidamulih Rivers, located in Pangandaran Regency, West Java Province, Indonesia. Previous studies have identified microplastic pollution in the sediment and water column of this estuary, making it a relevant site for investigating the impacts of plastic pollution in tropical aquatic ecosystems. This study aimed to identify the sources and impacts of plastic and microplastic pollution in the Karang Tirta Estuary and to design effective waste management strategies to reduce microplastic contamination. Employing a non-experimental mixed-methods approach, data were collected through interviews, observations, and literature reviews, and subsequently analyzed using the Driver–Pressure–State–Impact–Response (DPSIR) framework. The findings revealed that plastic waste originated from three main sources: the tourism sector, household and municipal solid waste, and local agro-industrial activities. Waste leakage was exacerbated by limited public awareness and inadequate waste management services. The presence of plastic and microplastic pollution posed significant environmental risks, affecting aquatic biota, ecosystem functions, and surrounding communities. Based on these findings, the study proposed a series of preventive and corrective measures. Preventive measures included reducing plastic and microplastic use, implementing extended producer responsibility, strengthening environmental education and community participation, and applying incentives and sanctions in waste management. Corrective measures included installing trash barriers, organizing local cleanup initiatives, and applying biodegradation techniques to reduce existing plastic pollution.

INTRODUCTION

Global plastic production has increased exponentially, from 1.5 million tons in 1950 to approximately 9 billion tons in 2017 (Kamaruddin et al., 2022). This dramatic increase is primarily attributable to the advantageous properties of plastics, including their durability, lightweight characteristics, low production costs, and versatility across various applications (Bellasi et al., 2020; Bucknall et al., 2020). The widespread adoption of plastics has

transformed numerous industries; however, it has simultaneously created one of the most pressing environmental challenges of the twenty-first century. The World Economic Forum (2016) projected that plastic leakage into the environment could increase up to fourfold by 2050 if current consumption patterns and waste management practices persist. This projection is particularly concerning for archipelagic nations such as Indonesia, which has been identified as the second-largest contributor to global marine plastic waste after China (Jambeck et al., 2015). Recent data from the Indonesian Ministry of Environment and Forestry (2023) indicate that approximately 7.8 million tons of plastic waste are generated annually in Indonesia, with an estimated 1.29 million tons leaking into the ocean, making the country a critical focus for research and intervention on marine plastic pollution.

The fundamental paradox underlying plastic pollution lies in the use of an exceptionally durable material for primarily short-term applications (Kosior & Crescenzi, 2020). Single-use plastics represent some of the most widely produced plastic products globally, accounting for a substantial proportion of municipal waste worldwide (PlasticsEurope, 2018). Hoornweg and Bhada-Tata (2012) reported that plastics comprise approximately 10% of municipal waste in 58% of countries globally. Although plastics are engineered for durability and can persist in the environment for centuries, they are susceptible to fragmentation through natural degradation processes, including photodegradation, mechanical abrasion, and biological weathering (Wu et al., 2018; Kosior & Crescenzi, 2020). These processes generate secondary microplastics—particles smaller than 5 mm—which have emerged as significant environmental contaminants with the potential to affect ecosystems and human health. The widespread presence of microplastics in marine environments has been documented globally, from surface waters to deep-sea sediments, raising concerns regarding their long-term ecological and health implications (Thompson et al., 2004; Andrady, 2011).

Estuaries represent transitional ecosystems located at the interface between riverine and marine environments, providing critical ecological functions, including habitat provision, nursery grounds for aquatic species, food resources, and migratory pathways for diadromous fish (McLusky & Elliott, 2004; Manangkalangi et al., 2011). These dynamic systems are characterized by complex hydrological and physicochemical gradients that support high biological productivity and biodiversity. Despite their ecological and economic significance, estuaries worldwide are experiencing progressive degradation due to multiple anthropogenic stressors, including plastic waste contamination (Ray & McCormick-Ray, 2014). The Karang Tirta Estuary, formed by the confluence of the Citumang and Sidamulih Rivers in Pangandaran Regency, West Java, Indonesia, serves as an important fishing ground and an increasingly popular ecotourism destination (Situmorang & Noviana, 2023). The development of sustainable tourism in the region offers substantial economic benefits; however, it also requires adequate environmental management to prevent the degradation of natural resources upon which the tourism sector depends (Tran et al., 2020).

Previous studies on microplastic pollution in Indonesian waters have primarily focused on coastal and marine environments, including investigations in the Java Sea, Bali, and Makassar (Cordova et al., 2020; Syakti et al., 2017; Suteja et al., 2021). Research on microplastics in estuarine systems has been conducted in various locations, including the Brantas River estuary in Surabaya (Firdaus et al., 2020), the Citarum River estuary in West Java (Sembiring et al., 2020), and estuaries in Bali and Lombok (Suteja et al., 2021; Purwiyanto

et al., 2022). However, studies addressing the socioeconomic and institutional drivers of plastic pollution in these systems remain limited. Much of the existing research has been descriptive, focusing primarily on identifying the abundance, distribution, and characteristics of microplastics, with limited attention given to their underlying causes and the development of actionable management strategies. Moreover, comprehensive analyses employing integrated frameworks such as DPSIR to address plastic pollution in Indonesian estuaries remain scarce. This represents a significant research gap, as understanding the causal relationships between human activities and environmental degradation is essential for designing effective and sustainable interventions.

The research gap is further emphasized by the limited number of studies systematically examining the specific drivers of plastic pollution in relatively understudied tropical estuarine systems such as the Karang Tirta Estuary. Although several studies have investigated microplastic contamination in Indonesian waters, the identification of pollution sources and the evaluation of waste management responses have not been sufficiently integrated. Previous research has often failed to link microplastic occurrence with the socioeconomic activities that generate plastic waste and the institutional mechanisms contributing to inadequate waste management. This disconnect between scientific documentation of environmental contamination and the practical development of mitigation strategies represents a critical limitation in effectively addressing plastic pollution. Furthermore, research considering the unique characteristics of tropical estuarine ecosystems remains limited, despite their distinct hydrological regimes, biodiversity patterns, and sociocultural contexts compared with temperate estuaries where much previous research has been conducted (Browne et al., 2010; Malli et al., 2022).

The urgency of this research is underscored by multiple converging factors that require immediate attention. First, Indonesia's status as the second-largest contributor to marine plastic pollution creates an urgent national imperative to develop and implement effective mitigation strategies aligned with international commitments, including the National Action Plan for Marine Plastic Waste Management (2017–2025). Second, the Karang Tirta Estuary serves as an important economic resource for local communities, supporting both capture fisheries and ecotourism, which are directly threatened by environmental degradation. The dependence of local populations on the estuary's ecological services makes pollution mitigation an immediate socioeconomic concern. Third, the rapid expansion of tourism in Pangandaran Regency, including the development of new tourist attractions and infrastructure, may exacerbate plastic pollution if proactive measures are not implemented alongside development activities. Fourth, the detection of microplastics in the estuary's sediment and water column indicates that pollution has reached a concerning level, requiring immediate intervention to prevent further contamination and potential long-term ecosystem damage. Fifth, climate change and its associated impacts, including increased flooding and altered hydrological patterns, may intensify the transport and distribution of plastic waste in the region, thereby compounding existing pollution problems (Napper & Thompson, 2019; Rillig et al., 2019).

The novelty of this research lies in several key aspects that distinguish it from previous studies conducted in Indonesia and the broader Southeast Asian region. First, this study represents one of the first comprehensive applications of the Driver–Pressure–State–Impact–Response (DPSIR) framework to analyze plastic and microplastic pollution in an Indonesian

estuarine system, providing a systematic and integrated approach to understanding the causal relationships underlying environmental contamination. The DPSIR framework, which has been widely applied in European and North American contexts to address various environmental issues, remains relatively underutilized in Indonesia, particularly in plastic pollution research. Second, this study integrates multiple data sources and methodologies, including semi-structured interviews with diverse stakeholders, field observations, and literature reviews, to provide a holistic understanding of plastic pollution and its socioeconomic dimensions. This interdisciplinary approach enables the identification of complex interactions among human activities, institutional arrangements, and environmental outcomes that may be overlooked by purely quantitative or descriptive analyses. Third, the study generates context-specific management recommendations addressing both preventive and corrective measures while considering the socioeconomic conditions, cultural practices, and institutional capacities of the study area. Fourth, this research contributes to the growing but still limited body of literature on microplastic pollution in tropical estuarine systems by providing baseline data and analytical insights that can inform future research and policy development in similar contexts across Southeast Asia and other tropical regions.

The primary objective of this research is to identify and analyze the sources and impacts of plastic and microplastic pollution in the Karang Tirta Estuary through systematic application of the DPSIR framework. Specifically, this study aims to: (1) characterize the key drivers of plastic waste generation in Pangandaran Regency, focusing on the tourism sector, household and municipal waste, and local agro-industrial activities; (2) assess the pressures resulting from inadequate waste management practices, including limited collection coverage, open dumping, and open burning; (3) describe the current state of plastic and microplastic pollution in the estuary and associated river systems; (4) evaluate the environmental and socioeconomic impacts of plastic pollution on estuarine ecosystems, aquatic biota, and local communities; and (5) identify and propose preventive and corrective management responses appropriate to the local context and aligned with national and international best practices. This research also seeks to contribute to the development of evidence-based policy recommendations supporting sustainable waste management in the region.

The contributions of this research are multifaceted, encompassing academic, policy, and practical domains. Academically, this study contributes to the growing body of knowledge on microplastic pollution in tropical aquatic ecosystems by addressing significant geographical and thematic gaps in the existing literature. The application of the DPSIR framework provides a methodological contribution that can be replicated and adapted for similar studies in other regions, facilitating comparative analyses and the development of standardized approaches to plastic pollution research. The integration of social science methods with environmental analysis advances interdisciplinary environmental research by demonstrating the value of mixed-methods approaches in understanding complex environmental problems. From a policy perspective, this research provides empirical evidence and analytical insights that can inform local, provincial, and national policy development related to waste management and plastic pollution reduction. The identification of specific drivers, pressures, and response mechanisms provides policymakers and practitioners with concrete intervention points, supporting evidence-based decision-making. Practically, the recommendations from this study provide actionable guidance for local stakeholders, including government agencies, community

organizations, and private sector actors, in implementing effective waste management measures that are socially acceptable, economically feasible, and environmentally sustainable.

The benefits of this research are expected to extend to multiple stakeholders at various levels. Local communities may benefit from improved environmental quality, reduced health risks, and the preservation of ecosystem services upon which their livelihoods depend. Fishers and tourism operators may benefit from the maintenance of productive fishing grounds and attractive natural environments that support their economic activities. Government agencies may benefit from the provision of data and analysis that support policy formulation, program design, and resource allocation decisions. Waste management actors, including waste banks and community organizations, may benefit from recommendations that enhance operational effectiveness and sustainability. The broader academic community may benefit from the empirical contributions and methodological insights of this study, which can inform future research and theoretical development in environmental science, pollution ecology, and environmental management. Ultimately, this research contributes to the broader societal goal of reducing plastic pollution and promoting sustainable development, aligning with national environmental sustainability commitments and international initiatives such as the United Nations Sustainable Development Goals, particularly SDG 14 (Life Below Water) and SDG 12 (Responsible Consumption and Production).

METHOD

This research employed a non-experimental mixed-methods approach that integrated qualitative and quantitative data collection to provide a comprehensive understanding of plastic and microplastic pollution in the Karang Tirta Estuary (Brink & van der Walt, 2006; Creswell, 2014). The study population consisted of stakeholders involved in waste management in Pangandaran Regency, including government officials, waste bank operators, community organizers, fisheries product processors, fishers, and tourists. A purposive sampling technique was used to select 42 participants with relevant knowledge and experience regarding plastic waste management. For the quantitative component, a Likert-scale questionnaire was administered to 13 participants directly involved in waste management activities. The research instruments included a semi-structured interview guide and a Likert-scale questionnaire developed based on relevant literature. Content validity was assessed through expert review, while reliability testing resulted in a Cronbach's alpha value of 0.78, indicating acceptable reliability (Nunnally & Bernstein, 1994).

Data collection was conducted through three primary methods: semi-structured interviews with the selected participants, non-participant field observations at waste banks and waste accumulation sites along the Citumang River, Sidamulih River, and Karang Tirta Estuary, and literature reviews to obtain secondary data on microplastic abundance and regulatory frameworks (Ciesielska et al., 2018; Snyder et al., 2019). Plastic waste identified during observations was categorized into seven types: PET, HDPE, PVC, LDPE, PP, PS, and other categories (So et al., 2014; Wulan et al., 2025). The research procedure included literature review, instrument development, site identification, data collection, transcription and organization of data, and data analysis. All interviews were conducted in Bahasa Indonesia, audio-recorded with participants' consent, and transcribed verbatim for analysis.

Data analysis involved qualitative and quantitative techniques consistent with the mixed-methods approach. Qualitative data from interviews and field observations were analyzed using thematic analysis guided by the Driver–Pressure–State–Impact–Response (DPSIR) framework, with themes categorized according to its five components (Braun & Clarke, 2006). Interview transcripts were coded using NVivo 12 software (QSR International), while quantitative data from the Likert-scale questionnaires were analyzed using descriptive statistics, including mean scores and standard deviations, in Microsoft Excel. Secondary microplastic abundance data were analyzed descriptively to summarize concentrations across sampling locations. Triangulation was conducted by comparing findings from multiple data sources to strengthen the validity of the research conclusions. Geographic Information Systems (ArcGIS) software was used to generate spatial maps of waste accumulation sites and sampling locations, while Microsoft Excel was used for data visualization through tables and graphs.

RESULTS AND DISCUSSION

Driver

The average waste generated in Pangandaran Regency is 1.86 kg/person/day. Increased plastic waste production in recent years has been attributed to changing consumption patterns that favour plastic products. This trend is expected to continue due to population growth and regional development (Ocean Conservancy, 2015). Because both rivers that form the Karang Tirta Estuary flow within the Pangandaran Regency, most plastic waste is assumed to originate within the regency's administrative borders. Three primary sources of plastic waste were identified; tourism, household and municipal waste, and the local agro-industrial complex.

Tourism is the largest contributor to waste generation in Pangandaran, producing an average of 2.5 kg/person/day. There are 43 tourist attractions in the study area, with Selasari Village hosting the majority. High visitor numbers at key sites such as Citumang River and Tanjung Cemara, where the Karang Tirta Estuary is located, intensify inputs to the estuary. Tourism growth contributes substantially to revenue and employment. Nevertheless, the tourism sector may also increase plastic waste generation due to the consumption of fast-moving-consumer-goods and convenience-oriented lifestyles (Brida et al., 2020; Foschi et al., 2025). Waste volumes peak in the Pangandaran Regency during holiday seasons, often exceeding local waste management capacity. Tourism can also introduce primary microplastic in aquatic bodies through the use of personal care products and tire wear particles (Hartmann et al., 2019; Haave and Henriksen 2022). Estimated waste generation by the tourism sector is presented in Table 2.

This finding aligns with previous research conducted in various Indonesian coastal tourism destinations, which consistently identified tourism as a primary driver of plastic waste accumulation (Amkieltiela et al., 2015; Muhsin et al., 2021). The seasonal nature of tourism-related waste generation creates significant challenges for waste management systems that are often already operating at or near capacity. The spike in waste during peak tourist seasons often overwhelms local collection and processing capabilities, leading to increased leakage into the environment (Foschi et al., 2025). Furthermore, the proliferation of small-scale food vendors and souvenir shops in tourist areas contributes to the widespread distribution of single-use

plastics, which are often discarded improperly due to insufficient waste receptacles and collection frequency (Brida et al., 2020).

Household and municipal waste represents another major source of plastic pollution in the study area. The government estimates an average waste generation of 0.4 kg/person/day by the local population. Despite a lower average of waste generation than the tourism sector, increasing population, economic growth, and changes in consumption patterns contribute to rising plastic waste production in the local community. The recent expansion of e-commerce and local small businesses further increase plastic waste, particularly through plastic packaging (Kim et al., 2022). Villages with higher population density and commercial activity, particularly Sukaresik and Pejaten are more likely to contribute greater plastic waste. The estimated waste generation from household and municipal waste is presented in Table 3.

The contribution of household waste to plastic pollution in Indonesian estuarine systems has been well-documented in recent studies. Buwono et al. (2026) demonstrated that residential areas adjacent to the Gembong River Estuary significantly influenced microplastic abundance in brackish water and sediment, with the highest concentrations recorded at stations near residential and industrial zones. Similarly, Takarina et al. (2026) found that microplastic contamination in benthic species at the Karangsong Estuary was strongly associated with proximity to residential settlements, particularly during the wet season when surface runoff transports accumulated waste into the aquatic system. The expansion of e-commerce during and following the COVID-19 pandemic has further exacerbated this problem, as the surge in online shopping has dramatically increased the volume of plastic packaging waste entering municipal waste streams (Kim et al., 2022).

Agricultural activities contribute plastic waste mainly through mulch. Mulch made of polyethylene is commonly used in chili cultivation, dominant commodities produced in the Parigi and Sidamulih subdistricts. Mulch is oftentimes discarded after a single growing season and can degrade into microplastics that accumulate in soils and aquatic systems (Zhang et al., 2023). Additional plastic inputs originate from agricultural containers, fertilizer packaging, and greenhouse materials. The fisheries sector contributes to plastic waste through both capture and aquaculture activities. Plastics are used in fishing gear, boats, and aquaculture infrastructure. It is chosen because of its durability and low production costs (Food and Agriculture Organization, 2016). Capture fisheries in the study area are relatively small-scale. Aquaculture operations, in turn, use plastic materials that may release microplastic through long-term immersion and mechanical wear (Wu et al., 2023).

The contribution of agricultural plastics to estuarine pollution has received increasing attention in recent years. Soegianto et al. (2025) identified various plastic polymers, including polyvinyl chloride, polystyrene, and nylon, in green mussels from the Bekasi Estuary, many of which could be traced to agricultural and aquaculture sources. The fragmentation of agricultural mulch in tropical climates is accelerated by high ultraviolet radiation and temperature fluctuations, leading to the rapid formation of secondary microplastics that can be transported by surface runoff into adjacent waterways (Zhang et al., 2023). The fisheries sector's contribution is particularly concerning in the context of the Gembong River Estuary, where microplastics were detected in the edible flesh of mullet (Mugil cephalus), raising concerns about human dietary exposure (Buwono et al., 2026).

Pressure

Inadequately managed plastic waste can cause significant pressure on the Karang Tirta Estuary. Data from the West Java Provincial Environmental Agency shows that as of May 2025, only 26.78% of waste in the Pangandaran Regency is managed. Local data from the Environmental and Sanitation Agency of Pangandaran Regency indicates that overall, 40% of waste is managed, in collaboration with waste banks, waste collectors, and community organizations. It can be concluded that even with the best estimates, more than half of the waste generated in Pangandaran remains unmanaged.

Suboptimal waste management can be observed in the area's technical, institutional, and societal difficulties. Likert-scale analysis revealed that most respondents in the area disagree that waste management is effective or efficient or that waste management facilities are adequate. Public awareness and participation were assessed as neutral. Based on these findings, pressures were categorized into two main components: community awareness and behaviour related to waste management (1) and inadequate waste handling system (2). The result of this study's Likert-scale analysis is presented in Figure 3.

Improper disposal practices, including open dumping, were observed across the study area. These sites function as unregulated disposal areas. Plastic waste that has been disposed of improperly will accumulate and fragment into microplastic due to prolonged exposure to environmental factors (Koutnik et al., 2021; Vairamuthu et al., 2024). Open waste burning is also commonly practiced. This can be driven by limited collection services and cultural habits. Aside from the formation of secondary microplastic, open waste burning may also contribute to air pollution (Ayeleru et al., 2021; Krecl et al., 2021; Hess et al., 2025).

Waste handling pressures are further intensified by limited waste collection coverage. Collection services cover only 26-30% of the regency. This occurs due to inadequate fleet size, poor vehicle condition, and low budget allocation. The district's financial plan for 2025 reveals that only 0.16% of the regional budget had been allocated to waste management. Community-based facilities, such as waste banks and TPS3R (Reduce, Reuse, Recycle Waste Processing Facilities) are unevenly distributed and face various operational challenges; they obtain low revenue and have limited waste processing infrastructures, limited managerial capacity, and limited market access. The continued use of an open dumping system in the regency's landfill, TPA Purbahayu, increases risk of plastic and microplastic emission into the environment.

This finding is consistent with the results of Herwanto et al. (2026), who evaluated inorganic waste problems in the Kedak River Basin using the DPSIR framework. Their study found that population growth, land-use conversion, and single-use consumption patterns were primary drivers, while weak waste management systems and direct waste disposal into rivers constituted major pressures. The effectiveness of the DPSIR framework in systematically unraveling urban environmental problems, as demonstrated by Herwanto et al. (2026), supports its application in this study for Karang Tirta Estuary. The persistence of open dumping and burning practices reflects a combination of infrastructural deficits and cultural norms that require comprehensive intervention strategies (Hess et al., 2025).

State

Plastic debris has been identified along the Citumang River, Sidamulih River, and Karang Tirta Estuary. Microplastic particles have been detected in the sediment and water columns across all three bodies of water. This indicates ongoing pollution emission in the study

area. It also highlights the ability of plastic, particularly microplastic particles, to migrate between different environmental compartments (Miranda et al., 2020).

Field observation identified 15 waste accumulation sites along the study area. Most sites were located in Parigi Subdistrict, along the Citumang River. While this suggests high emission in this river system, field observations were also hindered by accessibility. There are currently no watershed maps of both rivers that were available to be used as guidance. Access to the Sidamulih River was also limited, as it is located in and around settlement areas where there are often no available routes to reach it. A map of the open dumping sites identified in the study area is presented in Figure 4.

Six of the open dumping sites showed signs of partial burning. This observation corroborated interview findings, which states that open burning remains a common disposal practice. Partially burned plastic increases the potential of microplastic formation (Hess et al., 2025). The majority of the plastics observed were low density polyethylene (55.42%) and polypropylene (36.95%). Olefin-based polymers, such as LDPE and PP are widely used in packaging. Despite this, they are difficult to recycle, oftentimes only reaching a 10% rate of recycling due to low market value (Bayer et al., 2016; Celik et al., 2019; Jung et al., 2023). An overview of the polymers identified at the study site are presented in Figure 5.

The highest microplastic abundance was observed at the confluence of the river and estuary. Inversely, the lowest microplastic concentration was found at the estuary's outlet. Higher concentration of microplastic was also found at the Sidamulih River in comparison to the Citumang River. This is thought to be associated with higher population density and lower waste management performance. Microplastic abundance in the sediment and water column of the study area is presented in Figure 6 and 7.

Overall, microplastic concentrations in the sediment were higher than in the water column. This supports previous findings by Gray et al. (2018), Luo et al. (2019), and Pazos et al. (2021) which concluded that estuarine sediments function as microplastic sinks. Spatial variability is influenced by a combination of anthropogenic and natural factors. Estuarine morphology, hydrodynamics, sediment suspension, and aggregation are some factors that affect the deposition and retention of microplastics (Malli et al., 2022). The higher concentrations at the confluence zone suggest that the mixing of freshwater and saltwater creates hydrodynamic conditions that facilitate particle retention and deposition (Malli et al., 2022).

The microplastic particles identified were then also classified based on their size, type, and colour. Most of the particles were measured to be below 1 mm. The most common shapes identified were similar in both sediment and water; which were fragments, fibres, and films while the most common identified colours were yellow, black, and transparent. A description of these characteristics and their potential sources are presented in Table 4.

The dominance of fragments in the Karang Tirta Estuary is consistent with findings from multiple recent studies in Indonesian estuaries. Buwono et al. (2026) reported that fragments constituted 94.45% of microplastic particles in brackish water and 93.30% in sediment at the Gembong River Estuary, indicating that secondary microplastics derived from the breakdown of larger plastic items are the prevailing contaminant type in Indonesian estuarine systems. Similarly, the multi-estuary assessment along the West Sumatran coast by Buwono et al. (2026) found that fragments dominated across all sampled estuaries (145-180

particles L^{-1}), with the highest abundances in more urbanized regions. Soegianto et al. (2025) also identified fragments as the dominant morphotype in both seawater and green mussels from the Bekasi Estuary, with a size of less than 100 µm. The prevalence of fragments in the Karang Tirta Estuary indicates that the primary source of microplastic pollution is the degradation of larger plastic items that have been improperly disposed of, rather than direct inputs of primary microplastics (Miranda et al., 2020).

Impact

High microplastic abundance in the water column can reduce light penetration (Wright et al., 2013). Microplastic concentration is positively correlated with turbidity and total suspended solids, degrading overall water quality (Buwono et al., 2021; Humaerah et al., 2024). In sediments, microplastic can disrupt benthic feeding behaviour, particularly among bioturbators. This can then alter the site's microbial communities and sediment physiochemical properties (Yadav et al., 2010; Shull 2019; Wazne et al., 2023). Aged microplastic, with cracked surfaces, can enhance pollutant adsorption, chemical leaching, and microbial colonization (Cooper and Corcoran 2010; McCormick et al., 2014; Wang et al., 2019; Garcia-Gómez et al., 2021). Plastic additives may also gradually leach into the environment (Bellasi et al., 2020).

The presence of macro and microplastic can cause stress to mangrove ecosystems. As a result, the growth, density, and regeneration of a mangrove ecosystem can be reduced (Suyadi & Manullang, 2020; van Bijsterveld et al., 2021). Microplastic has also been shown to increase carbon emission in mangrove subsoils, potentially affecting the role of mangrove ecosystems as carbon sinks (Zhou et al., 2024; Hess et al., 2025). Benthic organisms are especially vulnerable because sediments act as a microplastic sink (Liaqat et al., 2024). Microplastic ingestion in aquatic biotas can cause reduced feeding rates, growth, fecundity, and reproductive success. Translocation of microplastic to other organs from the digestive tract have also been observed in a variety of aquatic biotas (Magni et al., 2018; Bellasi et al., 2020).

Open dumping sites and plastic accumulation may increase public health risks. The sites facilitate pathogen proliferation and contaminate soil and water sources (De & Debnath, 2016). Human exposure can potentially occur through three main pathways: ingestion, inhalation, and dermal contact (Hunt et al., 2023; Ojha et al., 2022). This can occur particularly through recreational water activities and consumption of contaminated seafood. Plastic additives are linked to endocrine disruption, carcinogenicity, and metabolic disorders in humans (Hahladakis et al., 2018; United Nations Environmental Programme 2021; Logan et al., 2024).

Recent research on Indonesian estuaries has provided compelling evidence of microplastic transfer through the food web. Buwono et al. (2026) detected microplastics in mullet (Mugil cephalus) from the Gembong River Estuary, with fragments dominating (68.00% of particles in mullet), and identified the presence of microplastics in the edible flesh of the fish. Their preliminary screening-level annual intake estimates ranged from 27,102 particles for one-year-old children to 203,268 particles for the general population under stated consumption assumptions. This finding has significant implications for food safety and public health in communities that depend on estuarine fisheries. Soegianto et al. (2025) further demonstrated that microplastics in green mussels (Perna viridis) from the Bekasi Estuary are associated with various additives, including plasticizers, processing aids, antioxidants, and UV

stabilizers, as well as metals such as lead, mercury, and arsenic, which can leach from the plastic surface into the organism. Takarina et al. (2026) reported seasonal variations in microplastic contamination at the Karangsong Estuary, with significantly higher abundances during the wet season, indicating that rainfall and surface runoff exacerbate the transfer of microplastics from terrestrial sources into estuarine environments. The detection of microplastics in benthic species across multiple Indonesian estuaries underscores the widespread nature of contamination and the potential for negative ecological consequences (Liaqat et al., 2024).

Response

A comprehensive response to plastic and microplastic pollution in the study area requires an assessment of existing waste management regulations. Six regulations govern waste management in the regency, consisting of four regional regulations and two regent regulations. These policies collectively define institutional responsibilities, waste service provisions, waste reduction targets, and enforcement mechanisms. These regulations are outlined in Table 5.

Field evidence indicates that residents' rights to adequate management have not been fully realized. Waste leakage persists due to uneven waste coverage and environmentally unsound practices. Supporting institutions, such as waste banks, are hindered by limited facilities, workforce, and technical assistance. The responses identified in this study can be classified into preventive and corrective measures. Preventive measures aim to reduce plastic leakage before it enters the aquatic systems. Corrective measures address plastic and microplastic already present in the environment.

The response strategies identified in this study are consistent with recommendations from other DPSIR-based analyses of plastic pollution in Indonesian aquatic systems. Herwanto et al. (2026) proposed integrated strategies through policy strengthening, the development of Circular Economy (CE)-based waste management infrastructure, and the strengthening of community movements such as Clean River Movement (CRM) to address inorganic waste problems in river systems. Their conclusion that the DPSIR framework is effective for systematically unraveling environmental problems and can serve as a basis for adaptive policy formulation supports the application of the framework in this study. Miranda et al. (2020) similarly emphasized that the DPSIR framework provides a structured approach for identifying the most critical interventions along the causal chain from drivers to responses.

Preventive Measures

In the waste management hierarchy, preventive measures are preferred, as actions at this stage are more effective (Zhang et al., 2022). Preventive measures in this study include reducing plastic and microplastic consumption, implementing extended producer responsibility (EPR), strengthening public education and awareness, improving waste collection services, enhancing waste bank operations, upgrading waste management facilities, and applying sanctions and incentives on waste management.

Plastic reduction strategies are legally supported by the existing regulation but oftentimes are weak in implementation. Approaches such as product redesign, restriction on single-use plastic, eco-office initiatives, and environmentally oriented school programs have been outlined in existing policies. The adoption of bioplastic, product design aimed at maximizing recycling rates, and plastic levies or restrictions could further support these efforts. The challenges in implementing these regulations lie in its economic and technical limitations

(Arikan & Ozsoy, 2016; Rujnić-Sokele and Pilipović, 2017; Lam et al., 2018; Irianto et al., 2022; Ding & Zhu, 2023).

Regulations addressing primary microplastic sources, mainly microbeads in personal care products, are noticeably absent at the local and provincial levels. International evidence has demonstrated the environmental significance in successfully implementing these regulations (Napper et al., 2015). Non-profit organizations, such as Beat the Microbead, have published public databases on products containing microbeads. Consumers can use these resources to make better informed decisions on product selection (Beat the Microbead, 2022). Elements of EPR are noticeable in existing regulations. They highlight the producer's responsibility to collect and manage waste produced by consumers. However, currently, there are no explicit recycling targets for each producer or each industrial sector. There are also unclear provisions for producers that operate outside of the regency's borders but whose products are distributed inside the regency. These challenges limit effective monitoring and law enforcement (Gupt & Sahay, 2015).

Public education has been recognized as a key determinant for successful waste management (Kolbe, 2019). While awareness of the necessity of waste sorting and prohibition against open dumping and burning exists, there is still a gap in the general public's knowledge and their daily practices. This is influenced, among others, by cultural habits, limited infrastructure, and government agencies' insufficient outreach capacity. Waste banks and community organisations play an important role in education but they require stronger coordination and institutional support (Liu et al., 2021; Tristianoka et al., 2024).

Waste collection services currently remain below the regency's regulatory targets, caused largely due to funding limitations, insufficient vehicles, and accessibility issues in rural areas. Opportunities for improvement include increasing budget allocations, optimizing funding through retribution, and developing public-private partnerships that can help expand coverage (Massoud & El-Fadel, 2022).

Various operational challenges are faced by waste banks in the study area, including uneven distribution, limited labour capacity, financial constraints, and difficulties in obtaining off takers. While regulatory frameworks allow for more waste banks to be built, clearer institutional arrangements, targeted funding mechanisms, and structured capacity-building programs are necessary to ensure its sustainable development.

Current waste management facilities in the regency require significant updates. TPA Purbahayu currently operates using an open-dumping system. Plans to transition towards a sanitary landfill system are currently underway but remain constrained by funding. Inactive TPS3R and limited access to sorting, shredding, storage, and incineration facilities hinder effective waste processing.

Sanctions and incentives are formally regulated but difficult to enforce. Administrative fines and other forms of penalties are designed to deter illegal waste practices. On the other hand, incentives are designed to encourage innovation and compliance (Khawaja & Shah, 2013; Kolodko and Read, 2018). However, limited coordination among various agencies and inconsistent implementation reduce their effectiveness.

The importance of preventive measures is supported by findings from other Indonesian estuarine studies. The multi-estuary assessment along the West Sumatran coast by Buwono et al. (2026) found that estuaries subjected to higher anthropogenic pressure exhibited higher

microplastic abundance, emphasizing the need for upstream interventions to reduce plastic inputs. Takarina et al. (2026) demonstrated that seasonal variations in microplastic contamination, with significantly higher abundances during the wet season, highlight the importance of seasonal management strategies that account for increased runoff during periods of high rainfall. The identification of specific polymers, such as polyethylene terephthalate and polypropylene, in benthic organisms at Karangsong Estuary (Takarina et al., 2026) and in the Gembong River Estuary (Buwono et al., 2026) provides a basis for targeted source reduction interventions targeting the most prevalent plastic types.

Corrective Measures

Corrective measures are designed to address plastic waste that has already entered the aquatic systems. These approaches are important in targeting and removing existing plastic and microplastic pollution (Miranda et al., 2020). Corrective measures in this research include the installation of trash barriers, river and estuary clean-up initiatives, and the application of biotechnological approaches for plastic degradation.

Trash barriers are a cost-effective intervention designed to intercept floating waste in rivers (Aini et al., 2023). Simple designs have been proven to be effective but ecological conditions need to be taken into consideration, especially related to fish migration. Ecologically-friendly design can be implemented by ensuring organisms can pass through the barrier safely (Martignac et al., 2013; Szabo-Meszaros et al., 2018).

River and coastal clean-up initiatives have been conducted by government institutions, universities, private companies, and community organizations in the Pangandaran Regency. These initiatives are conducted to contribute to waste removal and raise public awareness on environmental pollution in the area. Although these activities do not target microplastic directly, they reduce the formation of secondary microplastic from macroplastic debris. Clean-up initiatives can also provide valuable data on waste composition and sources (Miranda et al., 2020).

Biotechnological approaches, including the use of algae, fungi, and bacteria capable of polymer degradation, is a promising long-term mitigation strategy. Laboratory studies have demonstrated the potential for microplastic degradation. Nevertheless, large-scale environmental application remains limited and requires further research and technological development (Wiercx et al., 2015; Miranda et al., 2020).

Practical Implications

The findings of this study have several practical implications for waste management policy and practice in Pangandaran Regency and similar coastal regions in Indonesia. First, the identification of specific sources of plastic waste—tourism, household waste, and the agro-industrial complex—enables targeted interventions at the source level. Second, the evidence of inadequate waste management coverage and suboptimal public awareness highlights the need for investment in both infrastructure and community engagement. Third, the detection of microplastic contamination in sediment and water across the estuary indicates that contamination has already reached a significant level, requiring both preventive and corrective measures. Fourth, the comparison with studies from other Indonesian estuaries (Buwono et al., 2026; Soegianto et al., 2025; Takarina et al., 2026) indicates that the problems identified in the Karang Tirta Estuary are not unique but reflect broader regional challenges that require coordinated responses at multiple administrative levels. Fifth, the application of the DPSIR

framework demonstrates its utility as a tool for systematically analyzing complex environmental problems and developing evidence-based interventions. The integration of the DPSIR framework with source identification and stakeholder engagement can support the development of adaptive and sustainable waste management strategies that are responsive to local conditions and aligned with national and international commitments to reduce plastic pollution (Herwanto et al., 2026).

CONCLUSION

Plastic pollution in the Karang Tirta Estuary originated from tourism activities, household waste, and agro-industrial activities, and was exacerbated by inadequate waste management coverage (26–40%) and open dumping and burning practices. LDPE (55.42%) and PP (36.95%) were the dominant plastic types, with fragments identified as the primary microplastic morphotype. These pollutants posed risks to mangrove ecosystems, aquatic biota, and public health. The DPSIR framework effectively identified causal relationships and supported the development of a comprehensive management strategy prioritizing preventive measures, including plastic reduction, extended producer responsibility (EPR), environmental education, infrastructure improvement, and incentive mechanisms, as well as corrective actions, including trash barriers, cleanup initiatives, and biodegradation approaches. Future research should investigate microplastic transport pathways, temporal variations, bioaccumulation in seafood, waste management behaviors, biotechnological degradation methods, and comparative assessments across Indonesian estuaries to support regional policy development.

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