Sustainable Environmental Insight

Review
Volume 2(1), 2025, 24–39
https://doi.org/10.53623/sein.v2i1.659

Microplastic Pollution in Malaysia's Coastal Areas: Impacts, Challenges, and Sustainable Solutions

Woo Jun Fui[1], Syahrun Neizam Mohd Dzulkifli[2*], Umi Kalthsom Parjo[3], Dzunnur Zaily Mohd Dzulkifli[4], Muhammad Noor Hazwan Jusoh[1]

[1]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia.
[2]Department of Chemical Engineering Technology, Faculty of Engineering Technology, Univerisiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Johor.
[3]SMK Tengku Mahkota, Jalan Temenggong Ahmad, Kampung Parit Besar, 84000 Muar, Johor, Malaysia.
[4]School of Global Foundation Studies, Educity International College, 79200 Iskandar Puteri, Johor, Malaysia.

*Correspondence: syahrun@uthm.edu.my

SUBMITTED: 15 April 2025; REVISED: 13 May 2025; ACCEPTED: 15 May 2025

ABSTRACT: Microplastic contamination became a serious environmental problem in Malaysia’s coastal areas, endangering marine life and human health. This review provided an overview of the status of microplastic pollution, focusing on its sources, spatial distribution, and ecological effects in Malaysian marine habitats from a holistic perspective. The article summarized key findings from recent research, which showed high levels of microplastics in coastal sediments and fauna, with fibers identified as the predominant type of contaminant. The paper compared several remediation methods, including biodegradation by indigenous bacterial strains and advanced electrocoagulation, which achieved a removal efficiency of 96.5%. However, significant challenges remained, such as limited waste management infrastructure, a lack of public education, and technological constraints in scaling up effective solutions. Three key recommendations were made: (1) enactment of strict national waste management regulations and infrastructure, with strong emphasis on recycling facilities and collection systems; (2) funding for localized research and development in cost-effective remediation technologies; and (3) national campaigns to promote reductions in plastic use. The study emphasized the necessity of a comprehensive strategy that integrated scientific innovation, policy reform, and community participation to address this growing environmental crisis. The findings of this review offered valuable information for policymakers and environmental practitioners in efforts to conserve marine biodiversity in Malaysia and served as a potential guide for developing countries facing similar challenges.

KEYWORDS: Microplastics; marine pollution; coastal ecosystems; environmental health; waste management; southeast Asia

1. Introduction

Malaysia, situated at the core of Southeast Asia, boasted a unique geographical position, with the majority of its territory surrounded by vast water bodies, and only the northern tip of the Peninsular connected to the Asian mainland through Thailand (Figure 1). Despite occupying merely 0.2% of the global landmass, Malaysia's rich biodiversity earned it the 12th spot among the world’s 17 megadiverse countries, as recognized by the National Biodiversity Index [1]. The country's waters stretched approximately 453,186 km^2, presenting a marine environment that, due to its equatorial location, experienced warm waters and perennial sunny conditions [2]. This tropical marine climate was characterized by two distinct monsoon seasons: the Northeast and Southwest monsoons.

Figure 1. Location of Malaysia in Southeast Asia [2].

Recognizing the intrinsic value and delicate balance of its marine ecosystems, the Malaysian government took commendable steps to conserve its marine wealth. A total of 50 Marine Protected Areas (MPAs) were designated across the nation, 42 in the Peninsular, five in Sabah, and three in Sarawak [2]. These MPAs collectively spanned about 1.4% of the country's waters. Malaysia's marine resources not only contributed significantly to its ecological diversity but also played a crucial role in driving its economy. As the guardian of one of the world's busiest international shipping routes, Malaysia heavily relied on ocean-based sectors such as shipping and tourism to bolster its economic trajectory [3].

However, rapid terrestrial development, expanding industrial activities, and factors such as increasing population density, rising tourism, coastal conversions for aquaculture, and land reclamation exerted unprecedented stress on Malaysia's marine environment [4]. These mounting challenges underscored the urgency for balanced growth and conservation strategies amid rapid development. As a megadiverse country with high marine biodiversity, Malaysia was also confronted with serious environmental threats posed by microplastic pollution. With its 7,350 km-long coastline and heavy dependence on seafood, the country remained especially exposed and vulnerable to these risks. This study aimed to evaluate the current status of microplastic contamination along Malaysia's coast, assess its environmental and public health impacts, and explore environmentally friendly remediation technologies alongside relevant policy initiatives.

1.1.Overview of the present status.

Plastics had become an integral part of modern life, offering convenience, durability, and versatility. However, their pervasive presence and resilience had also turned them into a pressing environmental issue, especially in aquatic ecosystems (Figure 2). In Malaysia, plastics found their way into the environment through multiple sources, including everyday items, industrial byproducts, wastewater treatment discharges, and even plastic degradation. Once in the water, these plastics posed a myriad of ecological challenges. One of the most pressing concerns in recent years had been the rise of microplastics—tiny plastic particles with a diameter of less than 5 mm. Microplastics were categorized into two main types based on their origin: primary and secondary [5]. Primary microplastics, such as synthetic plastic pellets, beads, fibers, and powders, were directly manufactured for various purposes, including as raw materials for plastics and industrial products. Secondary microplastics, on the other hand, emerged from the breakdown of larger plastic items, undergoing processes like weathering, photolysis, abrasion, and microbial decomposition [6]. The fragmentation and release of these microplastics into the environment were significantly influenced by their physicochemical properties and environmental conditions. For instance, microplastics tended to degrade more slowly in water than on land. Their interaction with other constituents in the environment—such as sorption and aggregation—changed as their specific surface area and oxygen-containing functional groups increased [5]..

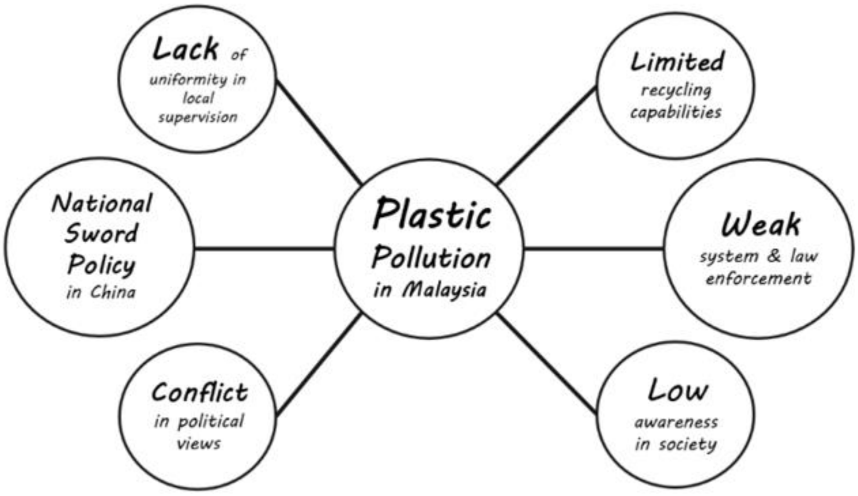


Figure 2. Plastic pollution issue in Malaysia [2].

2. Abundance and Distribution of Microplastics in Malaysia

Microplastics' entry into aquatic systems was facilitated through hydrodynamic and adhesive forces, subsequently posing threats to marine life. Numerous studies documented the ingestion of microplastics by a variety of marine species. Hossain et al. [7] found evidence of microplastics in the gastrointestinal tracts of shrimps, while Van Cauwenberghe et al. [8] and Cho et al. [9] reported similar findings in marine invertebrates such as mussels and bivalves. Notably, smaller marine organisms appeared more susceptible to microplastic contamination, likely due to their increased surface interaction with their habitats. Sfriso et al. [10] postulated that the physical resemblance of microplastics to natural food sources might also have played a role in this phenomenon. Table 1 presents a summary of microplastic abundance in various regions of Malaysia, according to Sulaiman et al. [11].

However, the issue was not limited to the ingestion of these particles. Plastics were known to contain a cocktail of additives, many of which were toxic. Fillers, plasticizers, flame retardants, colorants, stabilizers, and lubricants were routinely added during the plastic manufacturing process. Over time, these additives could leach into the aquatic environment, potentially wreaking havoc on ecosystems. The health implications of microplastic ingestion spanned a broad spectrum. Chemical risks included the leaching of estrogenic chemicals such as Bisphenol A, which had been linked to various metabolic disorders in mammals. Physical risks pertained to the movement of microplastics through the gastrointestinal tract, with potential accumulation in different parts of the body, leading to physiological disorders. There was also the threat of microbial pathogens, as gut microbiota dysbiosis had been observed in fish, compromising their immune systems.

Table 1. Abundance summary of microplastics in various regions of Malaysia.

Location/Ecosystem	Sample	Microplastic Abundance	Characteristic of Microplastic
Setiu Wetlands, Terengganu, Malaysia	Ingestion by benthic organisms	0.000090547 particles/m³ (0.12–9.5 mm)	Filaments, transparent, PE and PA
Setiu Wetlands, Terengganu, Malaysia	Surface water	0.00036 particles/m³ (200 µm)	Transparent, film, and filament
Setiu Wetlands, Terengganu, Malaysia	Sediment	0.00000597 particles/m³ (200 µm)	Transparent, film, and filament
Terengganu Coastal Waters, Southern South China Sea	Ingestion by benthic organisms	0.03–2.04 particles/m³ (0.02–1.168 mm)	Fragment, fiber, PA
Terengganu Coastal Waters, Southern South China Sea	Surface water	0.000090547 particles/m³ (0.02–1.168 mm)	Fragment, fiber, PA
Terengganu Coastal Waters, Southern South China Sea	Sediment	0.00304–0.00306 particles/m³ (>125 µm)	Fiber, black; Seasonal
Terengganu estuary and offshore waters, Malaysia	Ingestion by benthic organisms	291–812 particles/m³ (96.8–361.7 µm)	Offshore: fiber; Estuaries: fiber; PP, PE, and PA
Terengganu estuary and offshore waters, Malaysia	Surface water	211.2–421.8 particles/m³ (96.8–361.7 µm)	Offshore: fiber, fragment, and pellets
Tanjung Penyabung, Mersing and Pantai Remis, Johor	Ingestion by benthic organisms	5.17–9.88 particles/m³ (0.063–5 mm)	Black, blue, PE, PP, acrylonitrile butadiene styrene (ABS), PS and PET
Pulau Pangkor, Perak, Malaysia	Ingestion by benthic organisms	0.000015 particles/m³ (0.5 to 2 µm)	Fiber, black, PE and poly(methyl methacrylate) (PMMA)
Klang River estuary, Malaysia	Ingestion by benthic organisms	0.00000005–0.00000175 particles/m³ (300–1000 µm)	Fiber, black, polyethylene-propylene-diene (PE-PPD) and PES
Sungai Dungun, Terengganu, Malaysia	Surface water	0.1771 particles/m³ (200 µm)	Fiber, fragment, black and transparent, PP, polyacrylonitrile (PAN) and rayon
Cherating river and Cherating mangrove, Pahang	Surface water	0.0051–0.0070 particles/m³ (0.5 to 1.0 mm)	Fragment, white color
Kuala Nerus, Terengganu and Kuantan, Pahang	Surface water	0.00013–0.00069 particles/m³ (200 µm)	Fragment, filament, irregular black grey, PA and PP, PES, PS
Skudai and Tebrau Rivers, Malaysia	Surface water	0.20–0.68 particles/m³ (1000 to 5000 µm)	Not mentioned
Bangi, Selangor, Malaysia	Surface water	17 particles/m³ (200–50 µm)	Not mentioned

The plastics industry undeniably played a significant role in Malaysia's economy. According to the Malaysian Plastics Manufacturers Association (MPMA), the sector contributed RM30.98 billion to Malaysia's GDP in 2018, accounting for a substantial 4.7% [11]. However, the nation grappled with waste management challenges. With a population exceeding 32 million, Malaysia generated a staggering 38,000 metric tonnes of waste daily, of which only 24% was recycled. The remainder ended up in landfills. The COVID-19 pandemic further exacerbated the plastic waste issue. With the surge in the use of personal protective equipment (PPE) made from plastics, there was a marked increase in plastic medical waste. Khoo et al. [12] and Jędruchniewicz et al. [13] highlighted the environmental pollution associated with discarded disposable gloves and other PPE. Moreover, despite the high domestic generation of plastic waste, Malaysia imported a significant 333.5 million kilograms of plastic waste in 2019, according to United Nations Comtrade data excluding illegal imports [11]. Thus, while plastics undeniably benefited society, their environmental repercussions especially in the context of Malaysia's aquatic ecosystems, demanded urgent attention and action (Figure 3).

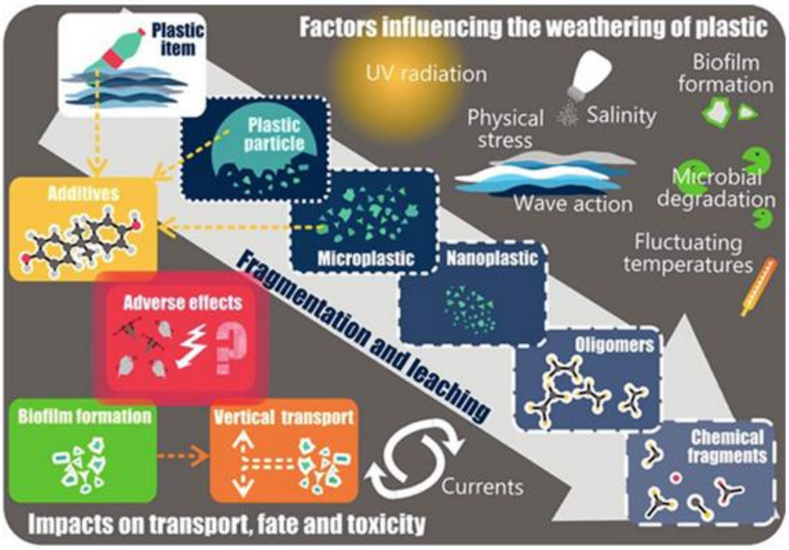


Figure 3. Fate of weathering of plastics [31].

Malaysia, with its extensive coastline and rich marine biodiversity, faced a growing environmental concern: microplastic pollution. Microplastics, tiny plastic particles less than 5 mm in size were pervasive, and their impact on aquatic ecosystems and human health became increasingly evident. In recent years, several studies were conducted in Malaysia to map the distribution of microplastics across various environments. For instance, Saipolbahri et al. [14] reported the presence of microplastics in estuarine sediments in the South and North Setiu Wetlands along the South China Sea, discovering concentrations of 0.00000597 particles/m^3 in dry sediment. Similarly, Hamza et al. [15] found microplastic concentrations ranging from 0.00304 to 0.003058 particles/m^3 on sea turtle nesting beaches in Terengganu. Notably, the majority of these microplastics were fibers, comprising 96.18% of the total, with black being the most common color, accounting for 35.64%. Such distributions were not confined to coastal zones. In Kuching, Sarawak, Noik and Tuah [16] detected varying concentrations of microplastics at two sandy beaches, Santubong and Trombol, reporting 0.0000000358 and 0.0000017343 particles/m^3, respectively (Figure 4). The Baram River, one of Sarawak's largest rivers surrounded by industrial activity, exhibited microplastic concentrations ranging between 0.0000005188 and 0.00000087 particles m−3 in its sediments. Even areas relatively isolated from direct human interference, such as the mangrove forests in Kapar, Selangor, were not spared; Govender et al. [17] reported a significant concentration of 0.418 particles/m^3 of microplastics.

The varied characteristics of these microplastics also warranted attention. Microplastics could be classified into different shapes, including fibers, films, filaments, fragments, and irregular forms. Size played a crucial role in their environmental impact. Research showed that plastics smaller than 1 mm could penetrate cellular barriers, cause oxidative damage, and affect reproductive and immune responses in marine organisms. Identifying the polymer type of microplastics was essential, as it determined their chemical composition. For instance, polymers like polyethylene (PE) and polypropylene (PP) had densities lower than water, allowing them to float, while others such as polystyrene (PS), polyester (PES), and polyamide (PA) were denser and tended to sink.

Despite the extensive research conducted, several challenges persisted in this field. One of the primary issues was identifying the sources of these microplastics. While some studies, such as that by Noik and Tuah [16], suggested that domestic items were the main contributors, others, like Tee et al. [18], indicated that microplastics near certain sites might have originated from domestic discharge in nearby residential areas. These differing conclusions made it difficult to pinpoint the root causes of pollution. Human activities—including fishing, tourism, and industrial operations—further complicated the matter. In the Setiu Wetland, for example, fishing and tourism were believed to contribute significantly to microplastic contamination. Fishing nets, often made of plastic fibers, added to the abundance of fiber-type microplastics in the environment. Moreover, given Malaysia's strong dependence on fisheries and tourism, mitigating pollution from these sectors without negatively impacting the economy remained a delicate balancing act.

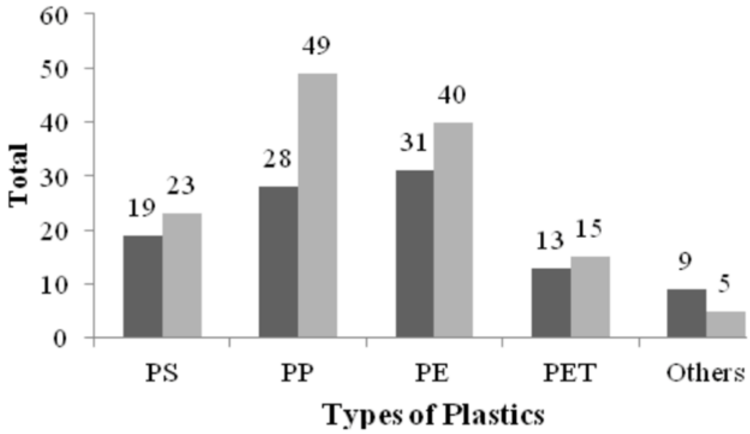
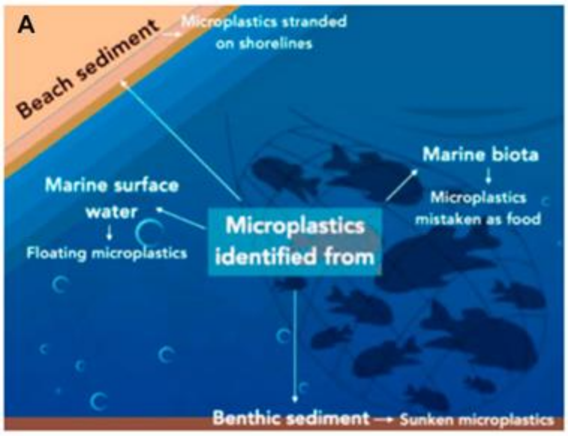


Figure 4. Count of found plastic fragments from Santubong (dark gray) and Trombol (light gray) stations [16].

Lastly, the movement of microplastics driven by natural phenomena such as tides, winds, and water currents made it difficult to trace their exact sources and predict their dispersion patterns. As noted by Ibrahim et al. [19], microplastic concentrations could vary significantly between two nearby sampling stations due to these dynamic environmental factors. Therefore, while Malaysia had made considerable progress in mapping the distribution and characteristics of microplastics, notable challenges remained. Addressing microplastic pollution required a multifaceted approach—combining scientific research, policymaking, industrial regulation, and public awareness campaigns. Given the potential ecological and health consequences, it was a challenge that demanded urgent and sustained attention.

3. Impact of Microplastics in Malaysia and Southeast Asian Countries

Microplastics, minuscule plastic fragments less than 5mm in size, have emerged as a global environmental challenge, particularly in coastal regions. Malaysia, a nation with a vast coastline and rich marine biodiversity, is significantly affected by this issue, and the same holds true for its Southeast Asian neighbors.



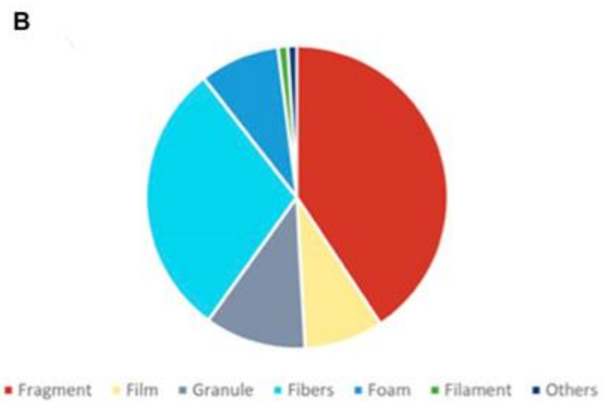


Figure 5. (A) Schematic diagram of the presence of plastics in aquatic environments. (B) Distribution of the types of microplastics in Southeast Asia [21].

Southeast Asia, boasting almost 150,000 km of coastline and over 25,000 islands, shelters roughly 34% of the world's coral reefs and between 25%-33% of global mangrove forests [3]. These pristine environments are under threat from microplastic pollution (Figure 5). Given the region's dense coastal populations in countries like Indonesia, the Philippines, and Vietnam, the susceptibility to marine plastic pollution intensifies. Astonishingly, these countries alone produce over 1.5 million metric tons of mismanaged plastics every year. Malaysia, Thailand, Vietnam, the Philippines, and Indonesia rank among the top 10 nations for mismanaged plastic generation, with Indonesia and the Philippines securing the second and third positions, respectively [20].

In Malaysia specifically, instances of waste spillage have been reported, and there has been a surge in household plastic waste [1]. Such mismanagement can often lead to the breakdown of plastics into microplastics, further exacerbating the problem. These microplastics are not just present in water bodies but have been detected in various ecosystems. For instance, microplastics have been found trapped amidst high-strand vegetation lines and within plants in countries like Thailand and Singapore [21].

The implications of microplastics are vast. Marine organisms, from the smallest plankton to the largest whales, ingest these particles, leading to potential internal injuries, malnutrition, and even death. Moreover, microplastics act as carriers for other pollutants, introducing them into the marine food chain, which subsequently affects human health. In a concerning revelation, microplastics have been detected in human bloodstreams [22], indicating the pervasive nature of the issue.

Other Southeast Asian countries echo Malaysia's challenges. In the Philippines, densely populated coastal areas contribute substantially to plastic waste, much of which breaks down into microplastics that harm marine life. Vietnam's rapid industrialization and urbanization have led to escalating plastic use, with inadequate waste management systems struggling to keep pace. The root causes of the microplastics issue in Southeast Asia can be traced back to several factors. Rapid economic growth in countries like Indonesia, the Philippines, and Vietnam over the past three decades has resulted in an exponential rise in plastic consumption. Coupled with inadequate waste management systems, especially in populous coastal regions, this has created a perfect storm for microplastic pollution. Microplastics threaten coastal ecosystems, and mangroves and coral reefs and are particularly threatened, and are essential for biodiversity and carbon sequestration [25]. In addition, microplastics have also been found in seafood, leading to threats like endocrine disruption and immune system effects [23, 24].

The response to this growing concern, however, has been fragmented. While individual nations have taken steps to curb plastic waste, a consolidated regional effort is lacking. The ASEAN Regional Action Plan for Combatting Marine Debris (2021-2025) is a commendable initiative, but the focus remains on marine waste rather than addressing the root of the problem: land-based sources of plastic waste [3]. Hence, microplastic pollution in Malaysia and Southeast Asia at large is a pressing environmental and health issue. The region's unique marine ecosystems, which are biodiversity hotspots, are under grave threat. Addressing this challenge requires a combination of local initiatives, regional collaboration, and global support.

4. Impact of Microplastics on Marine Environment and Human Health: A Case Study

Malaysia, with its 4,800 km coastline, is a treasure trove of marine ecosystems. However, the adverse effects of pollution, particularly plastic waste, pose significant threats to its environment, marine organisms, and human health.

4.1.Environmental impact.

Malaysia is an integral part of the Coral Triangle marine region. Its coastal area comprises ecosystems such as coral reefs, mangrove forests, mudflats, seagrass meadows, and pristine sandy beaches. Unfortunately, weak local law enforcement, inadequate plastic waste management, and coastal development activities have exacerbated environmental pollution. The mangrove forests, acting as a crucial barrier between land and sea, are increasingly becoming the recipients of terrestrial waste (Figure 6). The mangroves, which are known to protect coastal communities from storms, are dwindling at an alarming rate, with SEA experiencing about 30% loss since 1980. Mangroves in Malaysia, though constituting about 570,000 hectares, are under severe threat from activities like agriculture, aquaculture, and timber manufacturing.

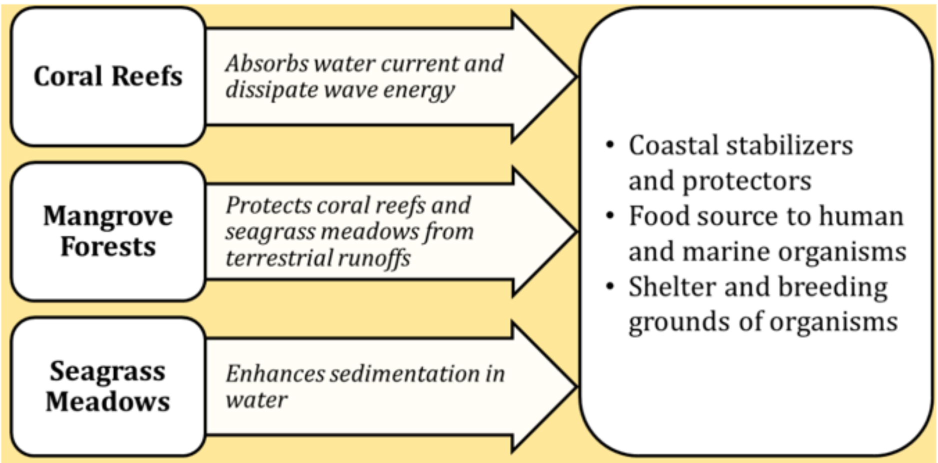


Figure 6. Significance of Malaysia's coastal ecosystem [2].

Seagrass meadows, while essential for marine organisms, act as bioengineers, dissipating energy from ocean waves and storms. Recent findings suggest that these meadows sequester approximately 10% of atmospheric carbon dioxide, playing a pivotal role in mitigating climate change [25]. However, they are at the frontline of receiving terrestrial waste and accumulating microplastics (MPs). MPs not only alter sediment composition, potentially affecting seagrass growth but also threaten the health of organisms relying on these meadows.

4.2.Impact on marine organisms.

Marine mammals, including dolphins, dugongs, and sea turtles, faced grave threats from plastics and microplastics (MPs). These mammals served as reliable bioindicators due to their position in the food web [25]. When ingesting plastics, they experienced blockages in their digestive and respiratory pathways. Although MPs did not necessarily cause suffocation, they carried toxic chemicals that damaged cells and impaired physiological functions. In Malaysia, numerous reports documented marine mammal deaths caused by plastic ingestion or entanglement. A notable case in 2015 involved a dolphin in Likas Bay, Sabah, which was found with 4.25 kg of plastic waste in its body [26].

Dugongs, herbivorous marine mammals that primarily fed on seagrasses, were at risk due to the accumulation of MPs in these meadows. An 8-month-old dugong named 'Marium' in Thailand died from ingesting plastic waste, which led to gastritis and blood infection [2]. Without enhanced efforts to protect seagrass habitats, the dugong population, currently listed as Vulnerable on the IUCN Red List, faced the risk of extinction in Malaysian waters. Sea turtles, for which Malaysia served as a critical nesting ground, were also threatened by plastic debris resembling their natural prey, jellyfish [27]. The disappearance of leatherback turtles in Malaysia highlighted the dangers of disrupted incubation temperatures, which caused imbalances in sex ratios..

4.3 Human health and socio-economic impact.

The intrusion of pollution, particularly microplastics, into the Malaysian marine ecosystem has severe implications not only for the environment but also for human health and the nation’s socio-economic well-being. The marine industry, which includes fishing and tourism, supports a significant portion of Malaysia’s population. However, the degradation of marine habitats due to pollution could lead to reduced fish catches, directly affecting the livelihoods of local fishermen. Additionally, contamination of seafood may discourage tourists, thereby impacting the country’s tourism revenue.

Recent studies have highlighted the widespread presence of microplastics in everyday consumables, ranging from drinking water to food products such as seafood and salt [28, 29]. This extensive contamination is particularly alarming for seafood-dependent countries like Malaysia. A report by the University of Newcastle revealed that an average adult could ingest up to 5 grams of plastic per week, roughly equivalent to the weight of a credit card, through commonly consumed foods and beverages [30]. In Malaysia, some commercial fish species have been found to contain microplastics, raising health concerns for consumers given that the nation’s per capita fish consumption is approximately 58 kg per person annually.

The ingestion of microplastics, as shown in Figure 7, poses three primary health risks: chemical, physical, and microbial [24]. Plastics, when subjected to certain temperatures or ultraviolet radiation, can release chemicals like bisphenol-A (BPA), which mimic the actions of natural estrogens. This can lead to endocrine disruptions resulting in metabolic disorders like obesity and diabetes. Moreover, these plastics can absorb and bind with toxic pollutants, heightening the risk of diseases like certain forms of cancers, reduced sperm count in males, and early puberty in females [32].

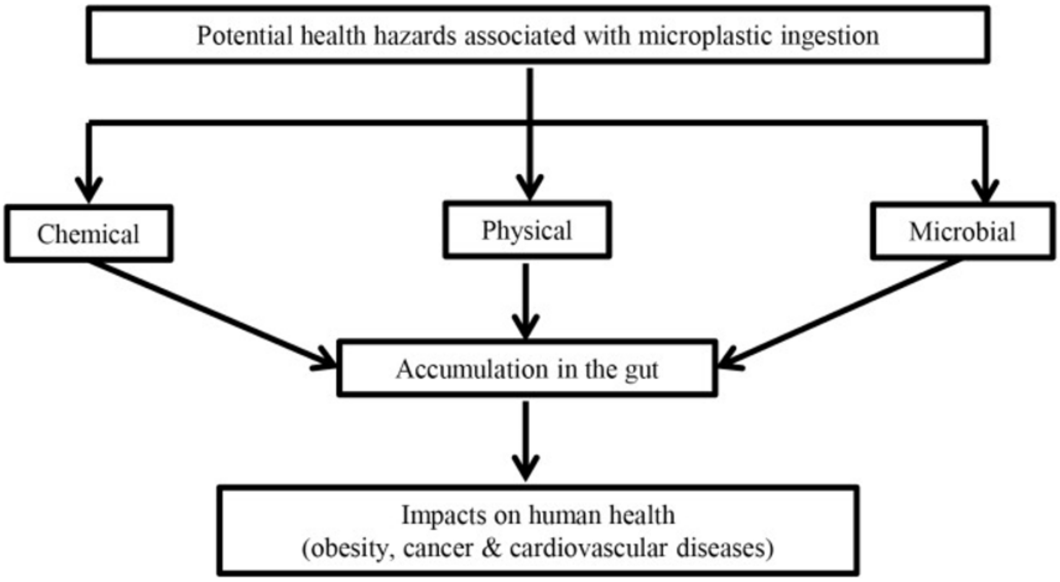


Figure 7. Health effects of microplastic ingestion [24].

Physically, while some ingested microplastics might be excreted, others could accumulate in the gastrointestinal tract or even translocate to the respiratory and cardiovascular systems. There have been indications of microplastics obstructing blood flow, leading to severe cardiac damage [33]. Inhalable microplastics might also inflame the respiratory tract, escalating the risk of cardiovascular diseases [34]. Lastly, microplastics can disrupt the gut microbiota, potentially compromising the immune system and escalating the risk of severe infections [24]. While the full scope of health implications from microplastics in humans remains under-researched, preliminary findings suggest dose-dependent adverse effects. Furthermore, the degradation of natural barriers like mangroves and coral reefs, vital for cushioning the blow from natural calamities, can expose coastal communities to heightened risks from tsunamis, storms, and coastal erosion. Their decline could result in significant loss of life and property, further accentuating the socio-economic challenges for Malaysia.

5. Addressing the Microplastic Menace: Remediation Technologies in Focus

Taken together, there is a pressing need for inventive and scalable solutions to address microplastic pollution along Malaysia's coast. Several technologies show promise in overcoming this challenge, each with trade-offs in terms of performance and versatility. For example, biodegradation employs microorganisms such as Bacillus cereus and B. gottheilii to break down common plastics like polyethylene (PE) and polyethylene terephthalate (PET) [35]. While this method is environmentally friendly and aligns with natural processes, its efficiency is limited by slow degradation rates and substrate specificity, meaning it is effective only for certain plastic types. This highlights the need for further research to improve its feasibility for industrial-scale applications.

Adsorption methods, such as those using nanoscale ferrofluids, have demonstrated the ability to effectively capture microplastics from water through magnetic removal in laboratory settings [36]. However, practical applications face challenges due to the complex marine environment, where factors like salinity and organic matter can reduce performance. Electrocoagulation, an advanced treatment process, uses an electric current to aggregate microplastics, achieving removal efficiencies up to 96.5% in wastewater treatment [37]. Despite this, the method is energy-intensive and requires substantial infrastructure, limiting its applicability in resource-poor settings.

Alternative processes such as air flotation and membrane filtration also offer potential for microplastic separation. Air flotation employs microbubbles to separate particles, achieving 69–85% efficiency for plastics like PVC [38], while membrane filtration can remove 91–96% of microplastics, though it remains unaffordable to scale up widely [38]. Each of these technologies involves trade-offs related to efficiency, cost, and practicality, indicating that no single solution is universally appropriate.

A hybrid approach combining these technologies, tailored to local conditions and supported by policy measures and community engagement, may provide the most viable path forward for Malaysia. Significant challenges remain, including scaling laboratory successes to field applications and integrating these technologies into existing waste management systems. Conducting pilot studies, cost-benefit analyses, and fostering interdisciplinary collaboration will be critical steps to overcoming these obstacles and minimizing the pervasive threat of microplastics.

6. Challenges and Prospects for Future Research on Plastic Pollution Management in Malaysia

Malaysia's endeavors to address plastic pollution, especially microplastics, are emblematic of a broader global challenge. As the nation grapples with rapid urbanization, economic growth, and changing consumption patterns, its confrontation with plastic waste offers valuable insights for many emerging economies. At the forefront of Malaysia's challenges is the existing waste management infrastructure (Figure 8). While cost-effective, conventional landfilling, primarily in open dumping areas, has proven ecologically detrimental, contaminating water sources and soil. The adverse impact of leachate from these sites further compounds the issue, echoing concerns highlighted in various studies.

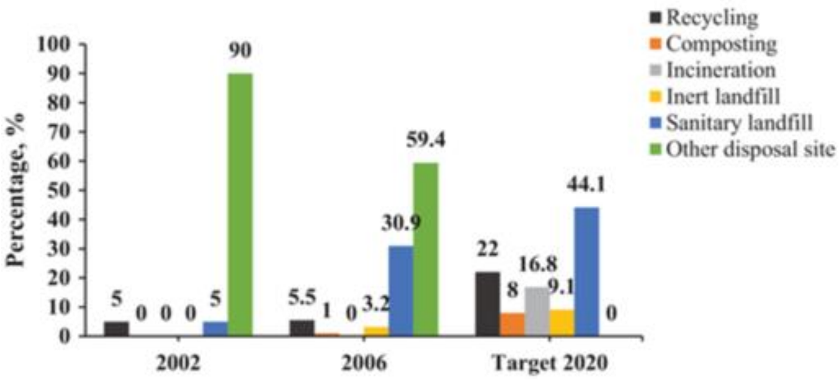


Figure 8. Methods of microplastics waste management in Malaysia [4].

The nation's recycling landscape further highlights the challenges ahead. Despite a recent increase in recycling rates, Malaysia still lags behind global leaders in this area. The recycling industry's growth is hampered by a heavy reliance on easily recoverable plastics such as PET, alongside a preference for imported recycled plastics rather than domestic sources. Given these obstacles, the ambitious target set by SWCorp to reach a 40% recycling rate by 2025 remains a formidable challenge [39]. Although policy initiatives like Malaysia's "No-Plastic Bag Day" campaign and the Roadmap to Zero Single-Use Plastics demonstrate strong intent, they have yet to achieve the desired impact [11]. This gap largely stems from difficulties in implementation and entrenched public behaviors. While environmental education efforts have successfully raised awareness, converting that awareness into sustained, proactive behaviors remains elusive.

On the remediation front, existing sewage treatment plants are inadequate in capturing microplastics, adding complexity to the problem. However, there is cause for optimism. Adopting a circular economy mindset offers a promising pathway forward. By treating plastics as renewable resources, Malaysia can revolutionize its approach to waste management. This vision—where plastics are continuously recycled and reused—is already being advanced through innovative technologies like Unilever's CreaSolv Process [11].

Technological progress is key to future success. Chemical recycling, which breaks plastics down into their basic monomers for reuse, exemplifies the potential of cutting-edge solutions. Partnerships such as that between PETRONAS Chemical Group and Plastic Energy Ltd. demonstrate the feasibility of scaling such transformative technologies [24]. Bioplastics, derived from renewable feedstocks, provide another hopeful alternative, reducing greenhouse gas emissions while substituting conventional fossil-based plastics. Furthermore, collective domestic and international collaborations can magnify the impact of individual efforts. Campaigns like the 'Straw Ban' and industry partnerships illustrate the power of united action [11].

Thus, while Malaysia faces significant challenges in combating plastic pollution, they are far from insurmountable. A multifaceted approach—blending research, technological innovation, sound policies, and collective initiatives—can steer the nation toward a sustainable future. This journey, though demanding, reflects Malaysia's enduring commitment to a greener, more eco-friendly tomorrow.

7. Conclusion and Recommendations

Microplastic contamination represented a serious threat to the coastal ecosystems, marine biodiversity, and human health in the waters of Malaysia. Microplastics were found in water, sediments, and marine organisms, highlighting the urgent need for action. Despite advancements in research and policy-making in the country, poor waste management, lack of public awareness, and the absence of implementable remediation technologies continued to pose significant challenges. To address microplastic pollution adequately, Malaysia needed to focus on several key measures. These included enforcing waste management laws by adopting stricter measures for plastic production, collection, and recycling, and developing recycling systems to minimize waste washouts into the environment. Investment in research and technology was necessary to fund pilot studies aimed at developing, refining, and testing remediation techniques such as biodegradation and electrocoagulation for scalable solutions. It was also important to promote sustainable replacements by encouraging industries and consumers to use biodegradable materials through incentives like tax breaks and awareness campaigns to reduce the use of single-use plastics. Strengthening monitoring and enforcement by establishing long-term systems to track trends in microplastic pollution and ensuring the effective implementation of environmental laws was essential. Additionally, promoting regional cooperation with Southeast Asian neighbors to create joint strategies for mitigating marine plastics, which transcend political borders, was crucial. By implementing these changes, Malaysia would have been able to mitigate microplastic pollution, protect its marine environments, and set an example for effective coastal management. The way forward required a commitment from all parties involved, government, industry, researchers, and the general public, to secure a cleaner, healthier future for Malaysia's coastal environment.

Acknowledgments

We thank all researchers and institutions whose work contributed to this study. Special appreciation to field teams and local communities for their invaluable support in data collection and environmental conservation efforts.

Author Contribution

All authors equally participated in shaping the study's concept, designing the methodology, collecting and analyzing data, and drafting the manuscript. We have all reviewed and given their approval for the final version submitted.

Competing Interest

The authors declare that they have no competing interests.

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