**Water Emerging Contaminants & Nanoplastics**

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# A review on the presence of microplastics in environmental matrices within Southeast Asia: elucidating risk information through an analysis of microplastic characteristics such as size, shape, and type

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## Abstract
Microplastics' ecotoxicological potential in almost all ecosystems makes them a global environmental issue. This review evaluates Southeast Asian microplastic contamination data from 2013 to 2023. This evaluation examined 285 research publications from Scopus, Web of Science, and ScienceDirect, mostly on sediment and water matrices. Based on their size, shape, polymer type, and potential risks from polymer hazards in Southeast Asian countries, this analysis assesses microplastic pollution in biota, sediment, water, and other environmental matrices. The majority of microplastics in this region are small (46%) and large (32%). Within the biota matrix, small microplastics (SMP) and large microplastics (LMP) dominated. Fibers predominated in all matrices, particularly the

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biota matrix. Polyethylene emerged as the most abundant polymer type (22%), found in all four matrices. Despite being less abundant, polyurethane and polyamide have high hazard scores, raising ecological concerns due to their detrimental effects on environmental matrices. According to the analyzed data, Southeast Asian countries face significant risks due to high levels of microplastic contamination in water, sediments, biota, and other matrices. However, there are noticeable discrepancies in Southeast Asian data, indicating progress in microplastic research, with most data coming from Indonesia, Thailand, Malaysia, Vietnam, and the Philippines and little information in the literature regarding microplastic contamination from East Timor, Laos, Brunei, Myanmar, and Cambodia.

**Keywords:** Asia and Western Pacific, marine debris, microplastics risk, polymer hazard

## INTRODUCTION

The inadequate disposal plans, accidental loss, and fragmentation of larger plastics have contributed to the increasing accumulation of tiny plastic particles and fibers (microplastics with sizes of < 5 mm) in the environment[1]. The path of plastic leakage starts from land to a canal or a river, and then ends up in the water, sediment, biota, and also humans[2-5]. Plastic bags, fishing gear, food containers, and beverages are the most common waste ingredients that contribute to microplastic emissions in rivers[6]. Additionally, microplastics can be categorized as either primary or secondary, depending on their origin. Primary microplastics intentionally produced by humans[7], such as plastic resins and microbeads in cosmetic products, can be carried with wastewaters[8,9]. Conversely, secondary sources result from the breakdown of plastic items into smaller fragments due to processes like oxidation, ultraviolet (UV) radiation, and mechanical forces[10]. During the photodegradation of plastics, sunlight containing UV irradiation triggers oxidation, breaking down the chemical bond of the polymer chains in larger plastics[11,12]; this process also subjects the plastics to mechanical stress and biotic fragmentation[13]. In the water ecosystem, microplastic fragments are easily exposed to sunlight, and their degradation rate increases with higher levels of oxygen[14].

Microplastics exhibit a range of characteristics, encompassing diverse sizes, shapes, and polymeric compositions[15,16]. To illustrate, they are typically classified into two categories based on their dimensions: large microplastics (LMP), ranging from 1 to 5 mm, and small microplastics (SMP), ranging from 0 μm to 1 mm[4]. Various shapes are observed among microplastics, including fragments, fibers, pellets, films, and foam. Certain shapes may predominate in specific water columns[17]. Microplastics in the fragment form, for example, are mostly found on the water surface[18,19], whereas fibers and pellets are found to be dominant in the sediment[20]. Furthermore, as microplastics become smaller in size in the ocean, the potential for microplastics to be ingested by marine organisms increases, with their availability in both pelagic and benthic habitats[21,22]. Microplastics in the aquatic ecosystem take much longer to degrade than those on land due to the presence of salt and the lower temperature[23]. They can also be distributed in specific water columns due to their polymer density[24], and can enter the aquatic food chain from the highest to the lowest trophic levels due to this condition. Consequently, microplastics have been found in a variety of biota[25], including microscopic organisms like zooplankton[26], small marine organisms like barnacles[27], lugworms, mussels[28], and large marine organisms such as pelagic fish[10,22], which inadvertently ingest these particles mistaking them for food.

However, microplastics can leach out chemicals depending on various factors such as the type of plastic, environmental conditions, and the presence of additives[29], raising concerns about potential ecological and human health impacts[30]. When microplastics are ingested by organisms, there is the possibility that the leached chemicals could be transferred through the food web[31]. Therefore, based on the chemical compositions of the plastic polymers, plastic hazard scores have been developed to calculate the risk assessment on the polymer hazard index towards the environmental matrices[32]. Additionally, different polymers have different chemical compositions, and some may contain additives that could be of concern. For example, acrylonitrile butadiene styrene (ABS) and polyvinyl chloride (PVC) may contain additives (i.e., polyisobutylene, polyacrylates, polymetacrylates, oil-soluble polymers and copolymers of allyl and vinyl monomers, derivatives of alkyl naphthalene, and alkylphenols) that are known to be toxic and pose a high risk[32,33]. Hence, polymer risk assessment of microplastics is crucial for several reasons, as it helps understand and reduce the potential environmental and human health impacts associated with the presence of these contaminants in various ecosystems. The lack of such assessments in Southeast Asia poses several challenges and concerns. This region, known for its biodiversity, ecosystems, and high population density, is particularly susceptible to microplastic pollution. Currently, there are limited reports available on polymer risk assessments in Southeast Asia. For instance, the microplastics in surface seawater from the shore of the Rayong province in Thailand were found to contain polypropylene (PP), polyethylene (PE), and polystyrene (PS) polymer, which fell within the medium-risk category[34]. Additionally, research conducted in concentrated and peatland areas of Vietnam detected concentrations of PVC, polycarbonate (PC), and PP, where PVC, extensively utilized in industrial processes, fell into the extremely dangerous risk category[35]. However, there is a gap in reported data on polymer risk assessments in other Southeast Asian countries. Addressing this gap is crucial for developing strategies to protect the ecosystems and biodiversity of these countries from the harmful effects of microplastic polymers. Polymer risk assessments contribute to the development of effective waste management strategies. By understanding the risks posed by specific polymers, authorities can implement targeted measures to reduce their environmental presence.

Plastics found in the world's oceans have been a cause for concern; however, it is only quite recently that attention has turned to plastic waste in various environmental matrices[36,37]. Rivers in Southeast Asia notably contribute to the influx of plastic pollution into the marine environment[38-40]. Over half (58%, $n$ = 29) of the estimated top 50 plastic-emitting rivers in the world are located in Southeast Asian nations[41]. Malaysia, along with the Philippines, Indonesia, and Singapore, is one of the four megadiverse countries in the tropical Associations of Southeast Asian Nations (ASEAN) region, producing an enormous 0.5-1.9 kg/capita/day of municipal solid waste (MSW), with plastic wastes accounting for an estimated 25% of the overall composition[42]. Nonetheless, the field and environmental data on the prevalence of plastic pollution in the marine environment particularly in Southeast Asia is limited, which is one of the continents with the least amount of study on microplastic contamination[38]. This review aims to identify the diverse characteristics of microplastics in different environmental matrices, such as size, shape, and type of microplastic polymers, drawing from various studies reported in Southeast Asia over the last decade. With the compilation of the data, we then evaluate the potential toxicity effects of microplastic polymer in all matrices by conducting polymer risk assessment based on their polymer hazard score. To the best of our knowledge, this is the first scientific paper that estimates how much microplastic research may be under or over-estimating current levels of microplastics based on the impact of microplastics on the environmental matrix, and also provides recommended reporting criteria and a way forward for future improvements on microplastics mitigation frameworks in Southeast Asia.

## METHODS

### Study area

Southeast Asia consists of 11 countries, namely Brunei Darussalam, Cambodia, Indonesia, Laos (the only land-locked country), Malaysia, Myanmar, the Philippines, Singapore, Timor-Leste, Thailand, and Vietnam. With about 25,000 islands and 150,000 km of coastline, Southeast Asia is a wealthy and biodiverse region that is home to 25%-33% of the world's mangrove forests and 34% of its coral reefs, which are home to a variety of tropical marine animals[43]. Southeast Asian countries share several geographical and environmental characteristics that can contribute to common challenges related to the sources and transport of pollution, including microplastics. Many Southeast Asian countries are connected by the South

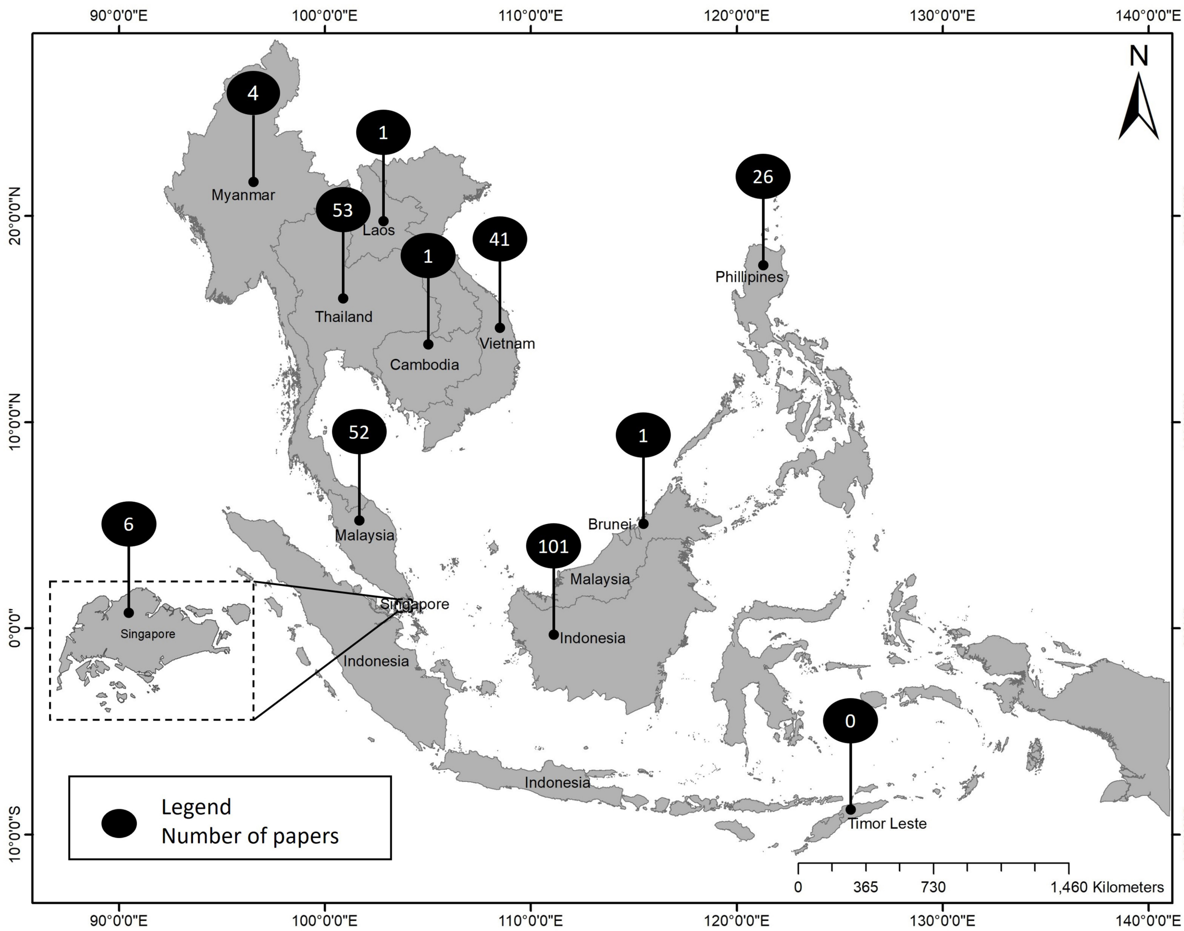


**Figure 1.** Numbers of reported microplastic pollution papers in Southeast Asian countries (2013-2023).

China Sea, which plays a central role in the region's maritime connectivity[44]. Additionally, the Mekong, Irrawaddy, and Chao Phraya rivers link several countries in Southeast Asia[9,45]. They serve as transportation routes for both plastic debris and microplastics, carrying these pollutants from upstream sources to downstream areas and ultimately to the sea. The countries in Southeast Asia face common environmental challenges, such as deforestation, agricultural runoff, and industrial discharges[46]. These activities can contribute to the introduction of microplastics into aquatic ecosystems. Additionally, Southeast Asia has some of the highest rates of marine plastic pollution in the world; estimates place the combined contributions of Indonesia (10%), the Philippines (6%), Vietnam (6%), Thailand (3%), and Malaysia (3%) to the world's oceans at 30%[47-49]. Four different types of matrices were included in this study, comprising biota, sediment, water, and others [Supplementary Table 1]. Biota samples consist of any living organisms such as fish, bivalves, crustaceans, mussels, and seagrass. Sediments encompass marine, freshwater, beach, and river sediments. Meanwhile, others comprise of atmospheric, face wash, toothpaste, human, and sea salt samples. The numbers of reported studies on microplastic pollution in Southeast Asian countries from 2013 to 2023 are shown in Figure 1. The collected data from a reported study on microplastic pollution in Southeast Asian countries aims to provide information about various characteristics of microplastics. These characteristics typically include size, shape, and types, and the study might investigate these attributes in different environmental matrices.

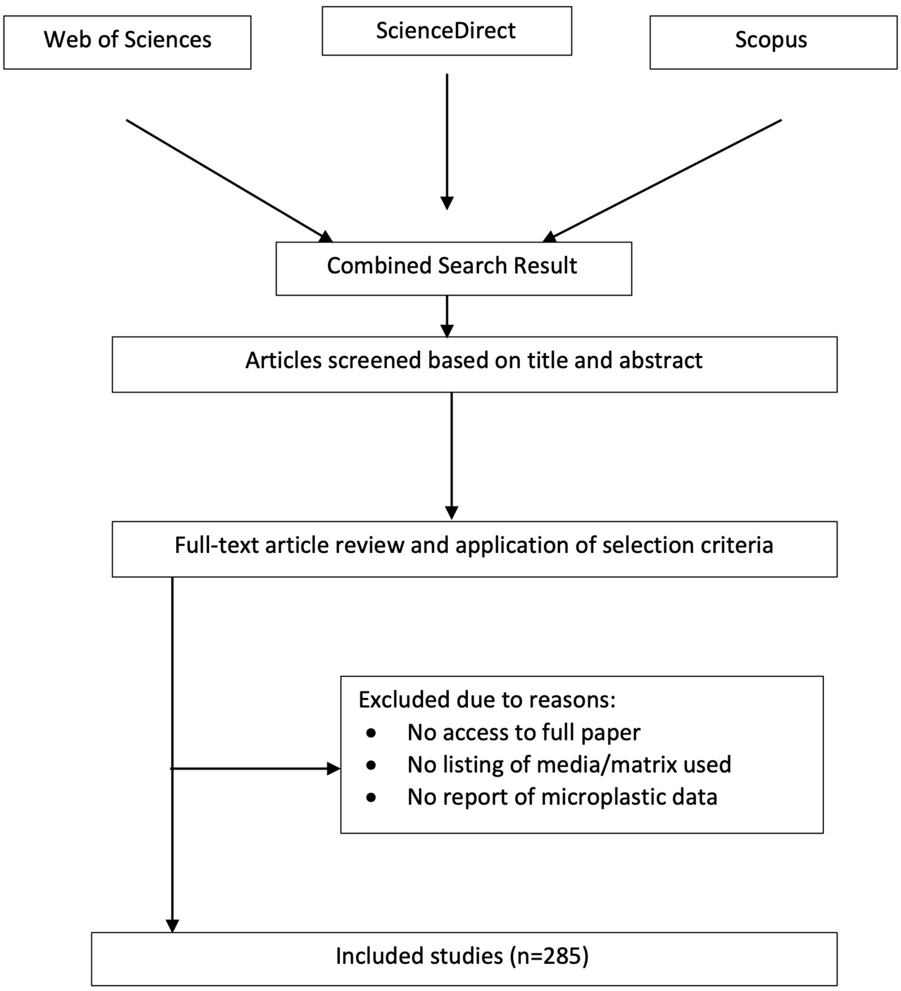


**Figure 2.** Flow diagram of studies selection including the process of literature identification, screening, and eligibility.

### Methodology for literature search - identification of suitable publications

Dataset hunting was attempted using Scopus, ScienceDirect, and Web of Science indexes. The pursuit was directed utilizing the accompanying terms: "Microplastic Southeast Asia" OR "Microplastic" AND "microplastics" OR Malaysia OR Indonesia OR Brunei OR Vietnam OR Thailand OR Cambodia OR Laos OR Philippines OR Singapore OR Myanmar. Following the information base quests, 397 records were found from 2013 until 2023; Microsoft Excel was utilized to arrange the articles. Duplicates were removed, resulting in 285 papers to be evaluated for reasonable titles and abstracts [Figure 2 and Supplementary Table 1]. Several articles from Southeast Asia were examined across multiple matrices, leading to variations in the number of articles and matrices in this review.

The screening interval for the articles on microplastics in Southeast Asia over the last ten years was chosen to provide an up-to-date understanding of the current situation in the region. The abstracts indicate that plastic pollution is a pressing environmental issue in Southeast Asia, with severe impacts on aquatic life, ecosystems, and human health. By focusing on the last ten years, researchers can assess the increasing trends, levels of contamination, sources, and impacts of microplastics in Southeast Asia, providing valuable insights for policy-making, research prioritization, and allocation of resources. This screening interval allows for a comprehensive understanding of the current state of microplastic contamination in the region and helps identify key knowledge gaps that need to be addressed.

### Recovery articles and data extracted

The number of recovery articles based on the collection criteria in Southeast Asian countries is shown in Figure 2. Data extracted from the articles included basic information such as author's names, publisher, country, and year of publication. Other materials extracted include the matrices used, abundance, size, shape, and polymer composition of microplastic. Most of the studies were published from 2017 onwards, with the highest number of publications reported in 2023 at 72 articles [Figure 3]. This is also consistent with the timeline of when the term "microplastics" became very significant in the regional context due to the information from[47]. It is important to highlight that, within the context of this analysis, the inclusion of alternative keywords such as "plastic particles" was not taken into account due to their failure to adhere to the specified size parameters for microplastics.

A datasheet was prepared by using Microsoft Excel for the systematic extraction of data. The size of the microplastics was recorded into two categories - SMP (0.1-1,000 µm) and LMP (1,001-5,000 µm). Furthermore, the shape of microplastics was categorized into fragment, fiber, film, foam, and pellet. The most observed polymer composition was PE, PP, PS, polyethylene terephthalate (PET), polyamide/nylon (PA), polyester (PES), and polyurethane (PU). The types of matrices were categorized into sediment, biota, water, and others. However, some studies within the reviewed literature failed to provide information on critical characteristics such as size, shape, and polymer type. Thus, the missing data from the studies was remarked as not available (N/A) in Supplementary Table 1.

### Polymer hazard index assessment

To evaluate the polymer hazard index (PHI) of microplastics in sediments, water, biota, and other environmental matrices, data on the chemical composition of microplastic polymers were extracted from each relevant article. The chemical toxicity of different polymer types of microplastics was considered to evaluate their ecological harm[32]. The PHI of microplastics in water[33,50], sediment[51], biota[52,53], and others[54] was calculated using Equation (1):

$$PHI = \sum S_n \times P_n \qquad (1)$$

In Equation (1), "*PHI*" represents the computed Polymer Hazard Index resulting from microplastics, where "$P_n$" corresponds to the percentage of specific polymer types obtained at each sampling location, and "$S_n$" signifies the hazard scores associated with the polymer types of microplastics as derived[32].

## RESULT AND DISCUSSION

### Matrices used

The environmental matrices investigated in Southeast Asian countries consisted of water (35%) - being the most studied matrix in the region - followed by sediment (31%), biota (20%), and others (14%) [Figure 4]. Water surfaces serve as a common reservoir for microplastics due to the transport of these particles from land and other sources[55]. Rainfall, wind, and water currents can carry microplastics from urban areas, industrial zones, and river systems into surface water bodies[56,57]. In contrast, sediments act as sinks for microplastics as they can capture and retain these particles over time[58]. Once microplastics enter the water, they may settle and accumulate in sediments due to gravity or interactions with other particles[59]. Microplastics in sediments are of environmental concern because they can persist in the ecosystem for extended periods. Organisms living in or near the water and sediments, including corals, plankton, marine invertebrates, fish, and whales, may come into contact with microplastics, which subsequently enter the

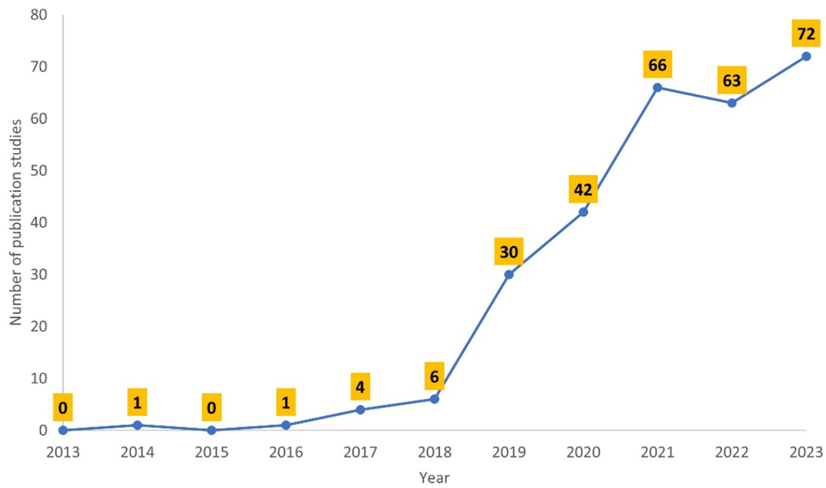


**Figure 3.** The total number of evaluated articles published in Southeast Asian countries from 2013 until 2023.

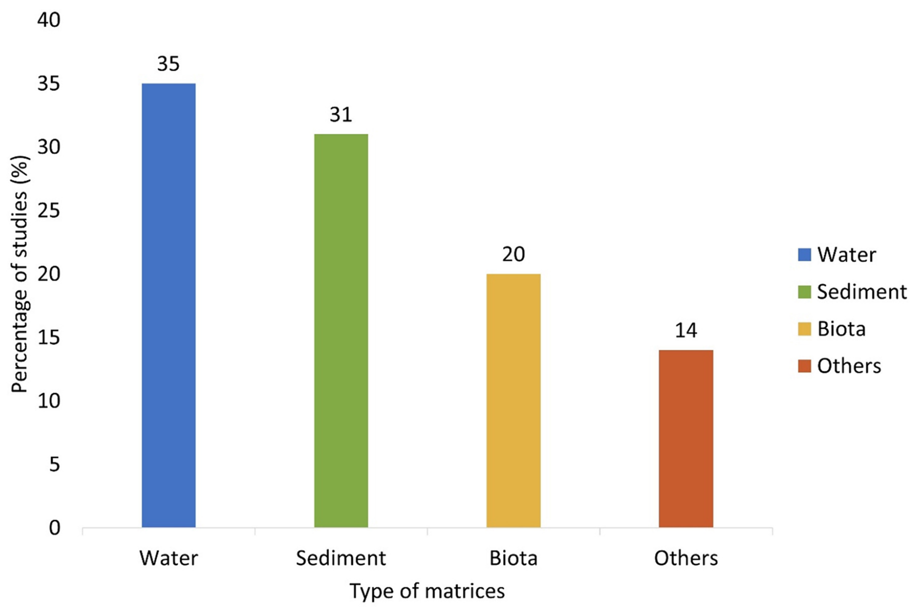


**Figure 4.** Percentages of different matrices used in the studies.

food chain[60]. When these organisms ingest microplastics, it poses potential ecological and health risks, as the plastics may carry contaminants and affect the feeding behavior of marine life. Moreover, humans are exposed to microplastic pollutants through both ingestion and inhalation pathways[61,62]. Microplastics can enter the human body through the consumption of contaminated food and water[63]. Seafood, for example, may contain microplastics that originate from the ocean. Additionally, microplastics may be present in the air, especially in urban areas with high population density, leading to their potential long-distance atmospheric transport before being deposited onto aquatic surfaces or reaching remote areas[64]. As such, dust and airborne particles that contain microplastics can be inhaled into the respiratory system and cause negative effects on human health[65].

## Different sizes of microplastics in Southeast Asia

Based on the dimensions, microplastics can be divided into large and small sizes. Figure 5 demonstrates that

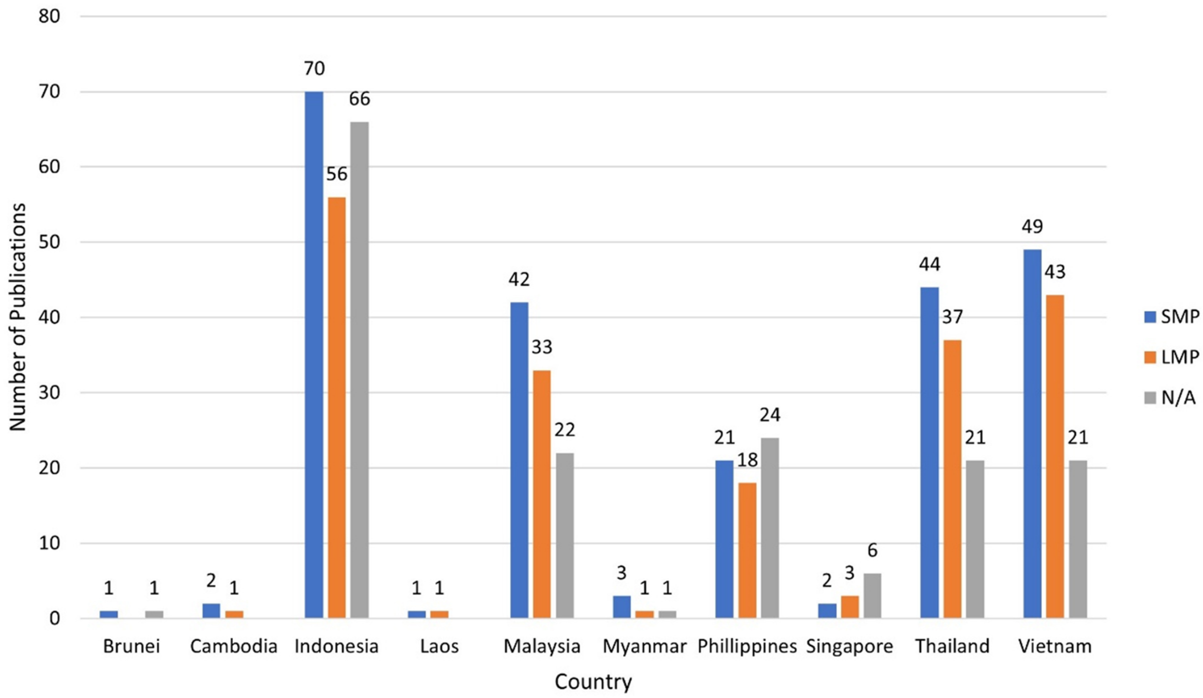


**Figure 5.** Number of published articles with size measurement. N/A denotes publication without size measurement.

SMP are prominent in practically all Southeast Asia nations. However, some published articles do not indicate the size measurement. Indonesia has the most SMP relative to LMP, followed by Vietnam, Thailand, Malaysia, the Philippines, Singapore, Myanmar, Laos, Cambodia, and Brunei, consistent with the number of published research studies. This study has analyzed the percentage of SMP (0.1-1,000 μm) at 46%, followed by 32% of LMP (1,001-5,000 μm), and 22% of unspecified reports on microplastics [Figure 6A]. According to these published studies, it is evident that the presence of SMP is widespread in the natural environment and corresponding matrices are significantly more abundant than LMPs. Figure 6B shows that SMP occupy the highest percentage at 46%, compared to LMP (37%) in biota samples. This review also demonstrated SMP constituted the majority, accounting for 43% in sediment and 47% in water, followed by LMPs at 29% and 33% in sediment and water, respectively [Figure 6C and D]. While in the other matrices, the percentage of SMP (53%) was also higher than LMP (31%) [Figure 6E]. Nevertheless, comparing the data proved challenging as the various samples found in other matrices were influenced by distinct pathways of microplastic pollutants, resulting in differences across matrices.

It is worth noting that size is one of the important factors that could affect the vertical distribution of the microplastics in water columns[66]. However, in rivers, various degradation processes such as photodegradation, mechanical-physical breakdown, weathering, and biodegradation can lead to a natural decrease in size[67]. As a result, the longer plastic trash is subjected to these degrading processes, the smaller it becomes. The size of the microplastics might have a variety of effects according to their categories. LMP particles may pose a concern to the water treatment plants (WTP) as the majority of water intake is from the river[68]. As such, the high loading of LMP in the water source potentially affects the performance of primary and secondary stages in the WTP. For instance, it was documented that in terms of size fraction, the efficiency of particle removal shows an ascending trend, with filtration playing a crucial role in achieving higher removal rates, particularly for particles sized ≥ 500 μm[69]. Although the abundance of microplastics is decreased by the treatment plant, a significant portion escapes in the treated effluent, especially for the

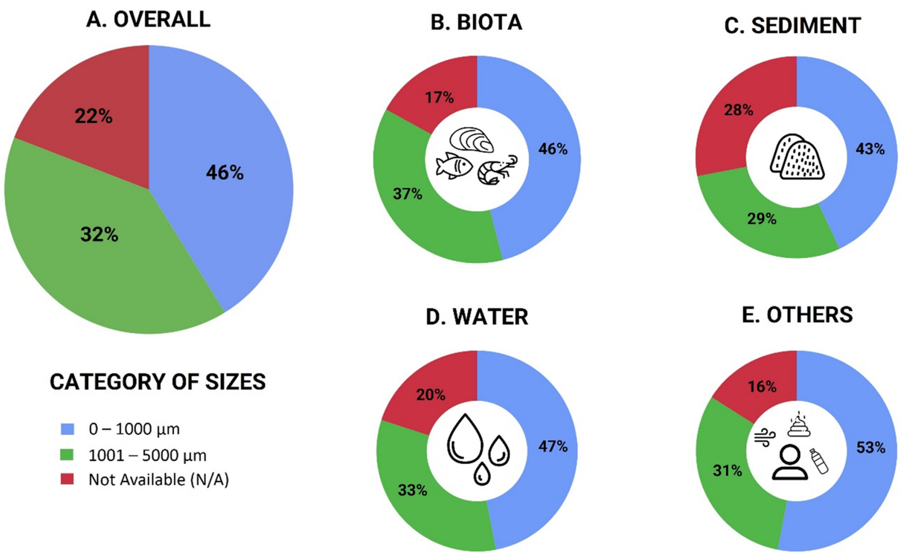


**Figure 6.** Percentage of microplastic sizes. (A) Overall; (B) Biota; (C) Sediment; (D) Water; (E) Others. N/A indicates the absence of microplastic polymer data in numerous studies.

smaller size fractions. It is reported that microplastics smaller than 2,000 μm tend to be easily mistaken as food and ingested by the marine biota[70,71]. Microplastics of sizes below 1,000 μm were found to be the most abundant in fish intestines, which can translocate across the digestive system to the lymphatic systems of mammals and humans[25].

Previous studies have indicated that SMP tend to dominate due to their strong affinity for natural colloids, leading to increased precipitation rates with sediments over time[72,73]. The concentration of microplastics in sediment samples was determined using sediment properties, sedimentation rates, and the capacity of the microplastics to adsorb or adhere to sediment particles[74]. The predominance of SMP over LMP found in this review may be due to the fact that one LMP can split into numerous SMP (considering the particle abundance that was commonly reported in microplastic studies, not the mass abundance), leading to a steady-state distribution with SMP outnumbering LMP over time. However, the counting of SMP may be underestimated due to variations in the lower size limit and instrument limitations used in different studies, resulting in the exclusion of numerous SMP.

Small-sized plastic particles (< 5,000 μm) tend to be transported over large distances, which ultimately can be transferred along the food chain[75]. The size of microplastics has a significant impact on their mobility in the aqueous environment and whether they may be consumed by animals, which is strongly connected to biosafety[76,77]. Microplastics with particle sizes smaller than 1 mm are found in greater abundance in sediments[78], whereby the likelihood of microplastic abundance in environmental matrices increases as the size of microplastics decreases[79]. Size significantly influences the impact of microplastics on organisms; thus, reporting the size of microplastics is necessary to quantify their potential to interact with the organisms, which intensifies as plastic size decreases[80]. Aquatic organisms such as invertebrates, fish, seabirds, and mammals have all been shown to ingest microplastics, which often comes with negative health consequences[81]. Furthermore, microplastics can absorb concentrated pollutants from the ambient environment, such as polychlorinated biphenyls (PCBs), pharmaceutical and personal care products (PPCPs), and heavy metals onto their surface, and thus can act as a potential carrier for microbial communities, which in turn can accumulate in fish and other organisms, and migrate to the human bodies throughout the food web due to their small size, strong hydrophobicity, and very low density[23,82]. They may then have adverse effects on animals and humans by affecting the body via the skin pores, digestive tract, and respiratory system, causing chemical and physical hazards and inducing neurotoxicity and oxidative damage[83,84].

## Different shapes of microplastics in Southeast Asia

The potential negative effects of microplastics differ depending on particle shape. This study focused on the reported shapes of microplastics such as fragment, fiber, pellet, film, and foam. The shapes that were mentioned most commonly in the published articles in Southeast Asia were fiber (28%), fragment (27%), pellet (19%), film (13%), and foam (5%). Another 8% of the articles did not report on the shape data [Figure 7A]. Among them, fragments were the most common shape reported in water (31%) and sediment (34%) samples, while fibers were found to be dominant in biota (35%) and other matrices (28%). The shape of microplastics is significant as it can serve as a basis for traceability and a source of information[85]. Furthermore, the particles can be influenced by the initial structure of the primary microplastics, the surface erosion and degradation mechanisms, and the duration of time the plastic particles remain in the environment[68,86]. Some studies have revealed that the influence of microplastics on adsorption, desorption, and ecological effects can be attributed to the different shapes[87,88]. This current review shows that the data are primarily dominated by secondary microplastics from the breakdown of larger low-density plastics through weathering processes such as fragmentation and fiber formation[89]. In addition, shapes may be used to trace the source of microplastics[90]. Synthetic fibers usually emanate from effluent generated by fishing activities and the textile industry[7]. Fragments and foams are from plastic containers including single-use plastics such as bottles, cups, and food storage containers[91,92], while pellets usually originate from cosmetic products and personal care items[93]. Films, for instance, are made from plastic bags and plastic packaging; however, because they are tiny and translucent, they readily shatter when exposed to sunlight, subsequently producing smaller film particles[94]. Additionally, the proximity of many Southeast Asian countries to rivers and coastal areas facilitates the transport of mismanaged waste to water bodies. For instance, Indonesia, Malaysia, and Thailand have shorelines that are 91,363, 4,809, and 3,150 km long, respectively[95,96]. However, the inconsistent or insufficient regulatory frameworks for waste management in Southeast Asian countries may contribute to ineffective waste disposal practices, which can result in inadequate control over plastic waste[97,98]. Plastic waste carried from the land can undergo fragmentation during transportation, eventually reaching rivers and seas, resulting in microplastics of different shapes[99].

In the biota and other matrices, the shape of microplastics observed followed the order of fiber > fragment > film > pellet > foam [Figure 7B]. Meanwhile, in sediment and water matrices, the order of microplastic shapes can be characterized as fragment > fiber > film > foam > pellet [Figures 7C and D]. However, fibers are also prevalent in both surface water and sediment, as well as other matrices [Figure 7E], making it likely for them to be present in biota as they come into direct contact with these environmental matrix components. The elongated and flexible structure of fibers, as highlighted in[100], makes them more susceptible to ingestion or incorporation by organisms. Synthetic fibers, including those from textiles and effluents from the textile industry, as well as those released during domestic washing machine activities[101], contribute significantly to the composition of microplastics. Due to the lightweight and floating nature of microplastics, pelagic fish are more prone to consuming them compared to demersal fish. For instance, the prevalence of fibers in pelagic fish may be attributed to their thin size, allowing them to float on the water's surface, or their form that resembles their natural prey[102]. Interestingly, microplastics exhibit diverse distribution patterns in aquatic environments, dispersing across distinct compartments such as the water surface, water column, and sediment. This dispersion is influenced by variations in shape and density, impacting the availability of microplastics to species at different trophic levels and within different habitats[37,79]. Pelagic organisms, such as phytoplankton[103] and small crustaceans like zooplankton[42], are

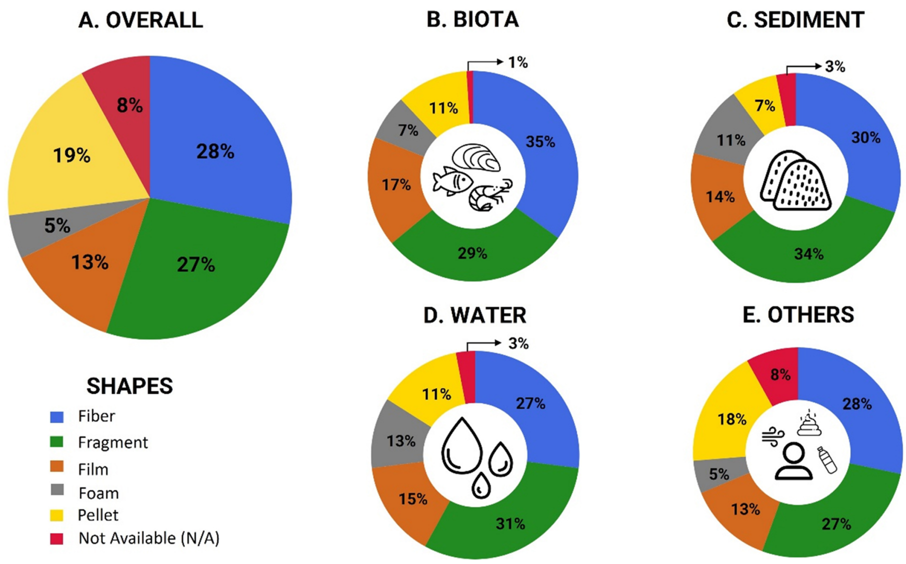


**Figure 7.** Percentage count of microplastic shapes. (A) Overall; (B) Biota; (C) Sediment; (D) Water; (E) Others. N/A indicates the absence of microplastic polymer data in numerous studies.

more likely to encounter less dense, floating microplastics. In contrast, benthic organisms such as amphipods[104], polychaete worms[105], tubifex worms[106], and echinoderms[107] are more prone to encountering microplastics denser than water. It is widely reported that microplastics can be consumed directly or indirectly by both benthic[17] and pelagic fish[10], where they become part of the prey. Furthermore, these fibers sourced from textiles and other origins can be transported through both air and water before settling in the sediment, leading to widespread distribution and potential ingestion by a variety of organisms including humans through food consumption[79].

The origins of microplastic fragments in the sediment and water ecosystems might be traced back to items such as bags, containers, food wrappers, waste related to tourism, and fishing nets or "ghost nets"[42,108]. Hence, the higher prevalence of microplastic fragments in sediment and water matrices can be ascribed to the gradual breakdown of larger plastic items during their transportation across extensive distances through weathering processes, mechanical abrasion, chemical degradation, and human activities[109]. These broken-down pieces could also sink into the bottom from the surface water and might be the reason for the higher occurrence of fragments in sediment. Additionally, sediment acts as a natural filter, capturing and retaining particles of various sizes of microplastics. Microplastic fragments, being smaller, may be more efficiently trapped and retained in sediment matrices compared to larger plastic items. Additionally, birds and animals[110] that feed on aquatic creatures or inhabit aquatic environments are known to ingest microplastics. The global presence of microplastics in practically all marine and freshwater ecosystems, including in protected and isolated areas around the region, underscores the widespread and potentially harmful nature of these pollutants.

### Polymer composition

The overall microplastic polymers observed in environmental matrices of Southeast Asia are illustrated in Figure 8A, and shown in Supplementary Figure 1. In general, PE is the most abundant (22%) microplastic polymer composition in all matrices, followed by PP (17%), PET (10% ), PS (10%), PA (9%) and other polymers (12%). Additionally, 13% of publications did not provide polymer identification. Specifically, in biota, the polymer follows the order of PE > PP > PA > PET > PS > PES > PU [Figure 8B], while the order of

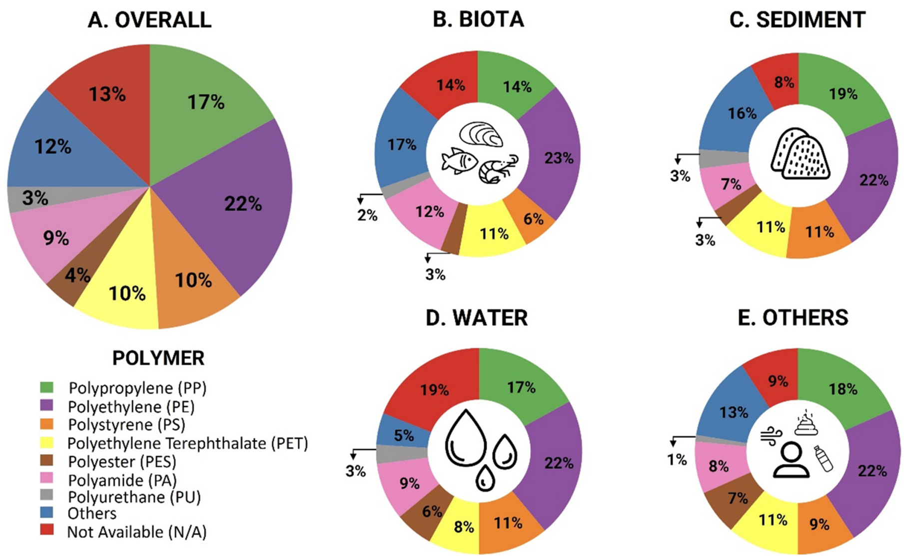


**Figure 8.** Percentage of seven main polymer compositions. (A) Overall; (B) Biota; (C) Sediment; (D) Water; (E) Others. N/A indicates the absence of microplastic polymer data in numerous studies.

abundance in the sediment matrix is PE > PP > PET > PS > PA > PES >PU [Figure 8C]. The water matrix revealed the microplastic composition of PE > PP > PS > PET > PA > PES > PU [Figure 8D], and the other matrices displayed the abundance in the order of PE > PP > PET > PS > PA > PES > PU [Figure 8E].

PP is a fiber-based material that is commonly used in garments, blankets, and other fiber-based items, as well as food packaging, pipelines, and chemical containers[50]. Fiber PE is widely utilized in the production of films, hollow items, fibers, and everyday necessities such as plastic bags[111]. Since PE and PP stand as the predominant polymer classes in both surface water and sediment, their existence in biota and humans is not surprising[5,112]. In addition, both polymers are known as the most widely produced in the world, satisfying 48.7% of the European plastic demand[89]. Thus, the high demand in the market for PE and PP is the cause of the high detection of these plastics in various environmental matrices in Southeast Asia[2,72,113].

PES, often known as polyester, is found in a wide range of products. The majority of the microplastics found in this investigation were fibers. PS is commonly found in foam products and disposable lunch boxes[114]. It is also utilized in light industrial manufacturing and as a decorative material. PA and PES in the environment mostly originate from the effluents of washing clothes and the usage of fishery tools[115]. PVC is utilized as a film in agricultural cultivation due to its inexpensive cost, and PU is used in adhesives, foams, food-grade coatings, insulators, tyres, sponges, and many more products[116].

Moreover, microplastics can also be distributed in specific water columns according to their polymer density[117]. This enables the penetration of microplastics into aquatic food chains, from the lowest to the highest tropical levels, due to their density-dependent distribution[118-120]. PE, PP, PU, and PS are examples of low-density polymers[121]. These polymers tend to float on the surface water and are likely to be consumed by pelagic species, while benthic species tend to consume dense plastics such as PES, PET, PA, and PVC, as they typically settle on the seabed. Interestingly, high-density polymers such as PET are also found in the surface water rather than in the sediment[4,122]. This can be due to environmental factors such as temperature, wind turbulence, tides, and waves[123]. These denser plastic particles could have also been resuspended from deeper water to the surface[121]. Furthermore, after degradation, aggregation, and biofouling processes, low-density polymers can also reach the seafloor[122]. Biofouling is defined as the accumulation of biological matter on surfaces, which creates biofilms by microorganisms[124]. Subsequently, this may cause an increase in microplastic density, thus resulting in microplastic sinking. The types of biofouling formations on the surface of the microplastic substrates are determined by the local environment in the aquatic habitats and the species of microorganisms.

### PHI of microplastics in Southeast Asia

Plastics, a category of polymers comprised of monomers, have been engineered to meet the specific qualities demanded by many applications[125]. The occurrence of incomplete polymerization reactions leads to the existence of hazardous monomers that remain in the polymer, thus impacting its characteristics and also its environment[126]. Furthermore, plasticizers found in plastics, such as phthalates and bisphenols, have been shown to affect hormones[127]. These chemicals are frequently employed to improve the flexibility and durability of plastics such as PVC. While residual monomers in plastics may pose a risk, the presence of plasticizers is another concern because they possess the ability to disrupt hormones. Prospective risk assessment of microplastic particles is critical for determining when and where the ecosystems and human health issues can be anticipated. A study published in 2011 evaluated the environmental and health risks of plastic polymers based on their chemical composition[32]. On a monomer basis, 55 plastic polymers were graded and analyzed. The most hazardous polymers are those that are produced from mutagenic or carcinogenic monomers. Polymers that ranked in this category belong to the families of PU, PVC, epoxy resins, and styrene copolymers due to their high hazard scores[32]. Hence, this study evaluated the environmental toxicity of microplastic polymers in the risk assessment, which includes both environmental exposure and ecotoxicity. This method was used for the hazard score of each polymer, and the value of PHI was calculated based on Equation (1).

The overall hazard categories of Southeast Asia in all four matrices were IV (danger; PHI: 100-1,000) and V (extreme danger; PHI: > 1,000) [Supplementary Table 2]. Singapore, however, was the only country that did not report the type of polymer detected in all four types of matrices; therefore, the value of PHI for Singapore could not be determined [Table 1]. The high PHI value in Malaysia across all environmental matrices, compared to other countries, is due to the presence of polymers with high hazard scores, such as PU, PA, and PS, with hazard scores of 7,384, 47, and 30, respectively [Table 2]. Meanwhile, a low PHI from Brunei may reflect the limited number of studies from this country [Figure 5]. PU is a polymer used to make flexible foams, and has a high hazard score compared to daily plastics used such as PE and PP. As shown in Table 2, PU is composed of carcinogenic propylene oxide monomers that are hazardous to both humans and aquatic organisms. Each year, around millions of tonnes[32] of this polymer are reportedly produced, which may cause it to become more concentrated in the sediment due to its density properties. Meanwhile, the least harmful monomers for the environment are ethylene in PE and propylene in PP, resulting in a low hazard score[32]. Therefore, it is extremely important to identify and chemically characterize the microplastics based on polymer types, not only because each polymer poses different hazard levels, but also because it could be a source of great pollution, since each plastic product uses specific polymers and additives. Thus, this study provides valuable information about the origin of microplastics found in environmental matrices.

In the biota matrix, the majority of the countries were rated as extremely dangerous (red), whereas Vietnam was determined as dangerous with PHI values ranging from 100 to 1,000 [Table 1 and Figure 9A]. This is attributed to the lowest number of hazardous polymers detected in Vietnam in contrast to other countries, which affected the value of PHI evaluated. The sediment matrix showed that most of the countries were extremely dangerous (red), with PHI values of more than 1,000 [Figure 9B]. Sediments have the capacity to serve as a sink for microplastics, which can be permanently stored and have an impact on the

**Table 1. The value of PHI in all matrices among Southeast Asia countries**

| Matrices | Malaysia | Indonesia | Vietnam | Philippines | Thailand | Cambodia | Laos | Myanmar | Brunei | Singapore |
|---|---|---|---|---|---|---|---|---|---|---|
| No of study | 43 | 63 | 27 | 15 | 34 | 3 | 2 | 3 | 2 | 0 |
| Biota | 1,016*** | 47,800*** | 850** | 32,525*** | 1,321*** | 0* | 0* | 0* | 0* | 0* |
| Sediment | 18,744*** | 1,508*** | 25,798*** | 1,198*** | 1,130*** | 148,600*** | 148,600*** | 46,650*** | 1,100*** | 0* |
| Water | 31,975*** | 9,835*** | 1,376*** | 23,500*** | 30,861*** | 0* | 0* | 0* | 0* | 0* |
| Others | 29,688*** | 786** | 775** | 0* | 0* | 1,260*** | 0* | 1,140*** | 867** | 0* |

*Classified as minor risk category; **Classified as dangerous risk category; ***Classified as extremely dangerous risk category; ****"0" represents "no PHI value" due to no reported polymer. PHI: Polymer hazard index.

**Table 2. Detailed information for microplastic polymers detected in this study, including monomer, density, usage, and score**

| Polymer | Monomer | Number of articles corresponding to the polymer | Main/common application | Score |
|---|---|---|---|---|
| Polyethylene | Ethylene | 180 | Toys, bottles, pipes, house ware, *etc.* | 11 |
| Polypropylene | Propylene | 246 | Food packaging, *etc.* | 1 |
| Polyamide | Adipic acid | 75 | Bearings, automotive applications, *etc.* | 47 |
| Polystyrene | Styrene | 96 | Plastic cup, food packaging, spectacles frame, *etc.* | 30 |
| Polyethylene Terephthalate | Ethylene glycol | 98 | Packaging and textile production | 4 |
| Polyester | Monoethylene glycol | 47 | Fabrics, textiles production, *etc.* | 3 |
| Polyurethane | Propylene oxide | 15 | Upholstery, sports mats, packaging bags, *etc.* | 7328 |

environment[76]. Moreover, the majority of the countries in the water matrix have also been indicated as extremely dangerous (red) due to high concentrations of microplastics in each country, whereas others, such as Cambodia, Myanmar, Brunei, and Laos, did not report the polymer identified in this sample matrix [Figure 9C]. The predominant risk level (orange) was reported for other matrices depicted in Figure 9D, where a low number of microplastic studies were reported in each country; this indicates that the majority of the countries are considered to be in danger. However, Malaysia, Cambodia, and Myanmar stand out as areas classified as extremely hazardous (red) based on the PHI. The microplastics that were found could have come from other regions. This is due to the fact that microplastics can travel large distances by wind, water currents, and even migratory animals[128]. As a result, nearby areas may be subjected to similar sources of microplastic contamination, such as rivers, ocean currents, and industrial activity. From the evaluation that has been made, we have concluded that higher hazard scores of the polymers may result in higher values of PHI, even if the microplastic concentration is low. Nevertheless, we cannot overlook the significance of the lowest hazard scores linked to polymers like PP, PE, and PET, given their widespread presence in environmental matrices. When evaluating the risk of microplastic pollution, even materials with lower hazard scores must be considered, as their potential environmental impact becomes significant when they are in high concentrations and/or abundances. This, in turn, contributes to a certain level of environmental risk as reflected in the PHI, while PHI alone cannot be the dominant parameter for ecological assessment and in calculating the hazard index of microplastics. This is because microplastics can also absorb persistent, bioaccumulative, and toxic contaminants from the environment, thus potentially leading to hazards from co-pollutants. These contaminants may include plastic additives, which are chemicals added during the manufacturing of microplastics[129]. The ingestion of microplastics and the accumulation of these contaminants have been a concern for the potential hazards of microplastics in aquatic environments, especially marine environments[1,130]. However, adverse effects of microplastic

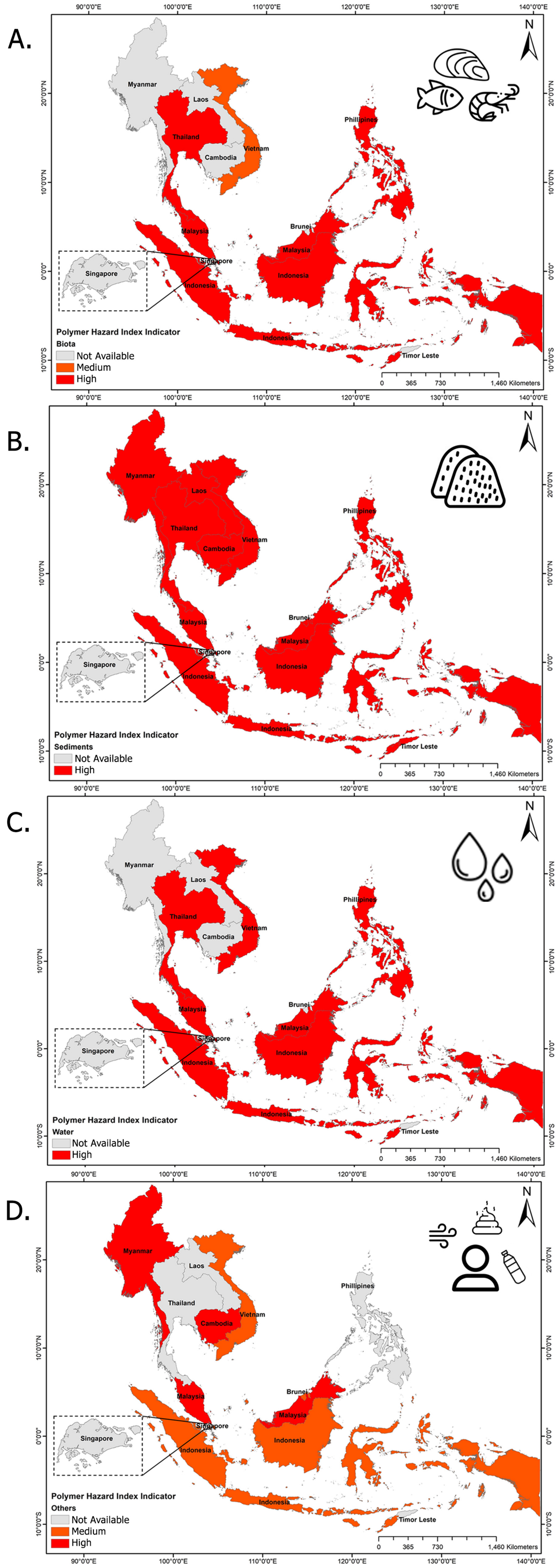


**Figure 9.** Visualized hazard scores based on Polymer hazard index in environmental matrices. (A) Biota; (B) Sediment; (C) Water; (D) Others.

ingestion have only been observed in laboratory conditions at high exposure concentrations. Further research is needed to fully understand the contribution of plasticizers to the hazard of microplastics, as well as incorporating other related risk assessment calculations such as measured environmental concentration (MEC) and predicted no-effect concentration (PNEC) that are widely used for chemical compounds.

## CONCLUSION

The objective of this study was to assess the comprehensive contamination status of microplastics in the Southeast Asia region, considering four matrices - water, sediment, biota, and others. The overall results revealed that microplastic pollution poses a high risk to water, sediment, biota, and other matrices in the Southeast Asia region. The detection of a high concentration of microplastics within an ecosystem suggests a significant environmental impact. Microplastics can enter ecosystems through various avenues such as industrial discharges, improper waste disposal, and degradation of larger plastic items. The fact that the research is conducted mainly in water, followed by sediment and biota or living organisms within the ecosystems, indicates that researchers in Southeast Asian countries are interested in understanding how microplastics are distributed in the ecosystem and how they enter the food web, especially the fate and transport of these emerging contaminants. Additionally, biota can serve as indicators of the overall health of an ecosystem, and the presence of diverse polymer types in these organisms may have implications for the entire ecosystem. The size of microplastics is indeed a crucial factor in understanding their environmental impact. SMP are the predominant size category of microplastics found in Southeast Asia, with biota matrices being the most common habitat for these particles. Additionally, fiber was the predominant microplastic shape found in Southeast Asia. Increased fishing-related activities, shipping activities, and anthropogenic activities in the coastal areas of Southeast Asia may serve as potential contributors. The findings additionally confirmed the presence of PE as the dominant type of microplastic polymer. The PHI toxicity and hazard readings of microplastics in the Southeast Asian region were found to have increased with the presence of high hazard scores of the polymers (PU, PA, and PS). Overall, our results indicated that water, sediment, biota, and others in Southeast Asia are at a high-risk level due to microplastic pollution. However, the different reporting units for microplastic abundance prevent the calculation of pollution load index (PLI) and potential ecological hazard index (PEHI) in environmental matrices within this review. Therefore, it is essential to apply specific methods to assess ecological risks across various research areas in Southeast Asian countries, to enable the identification of the pollution status in the study area, and the precise estimation of microplastics in the environment. Southeast Asia has a major issue with microplastic pollution, underscoring the critical need for effective waste disposal and consumption reduction to mitigate environmental risks and safeguard seafood in the region, as specified by the Coordinating Body on the Seas of East Asia (COBSEA) Regional Action Plan on Marine Litter and ASEAN Regional Action Plan for Combating Marine Debris. More rigorous studies and continuous monitoring are needed from all countries and authorities to establish a "safe standard" or "acceptable limit" for microplastic contaminants, as well as other related regulations for food security and environmental health. Nevertheless, it is envisioned that these data can aid in baseline assessments and address microplastic pollution at specific locations and in various regions of Southeast Asian countries.

## GAPS OF EXISTING STUDIES AND FUTURE OUTLOOK

This study highlights the variability in the units used for reporting, thus presenting challenges in establishing a standardized baseline for assessing microplastic pollution in Southeast Asian countries. For instance, the concentrations of microplastics in water may be denoted as items per liter (items/L) or items per cubic meter (items/$m^3$). Meanwhile, sediment samples may be expressed as items per gram (items/g), items per kilogram (items/kg), or items per square meter (items/$m^2$), and biota samples may be presented as items per gram tissue (items/g) or items per individual (items/individual), as discussed earlier in this review. This inconsistency poses a difficulty in applying the PLI and PEHI measurements for the evaluation of microplastic risk assessments, as both methods rely on a standardized measure of abundance for accurate comparisons. However, achieving uniformity in reporting units is rather challenging due to the inherent variations in each matrix that have been discussed earlier. Apart from the lack of consistency in reporting units, the divergence in methodologies across research papers poses a significant challenge[131-133]. Some studies attribute their methods to organizations like National Oceanic and Atmospheric Administration (NOAA), Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), or Intergovernmental Oceanographic Commission of the Western Pacific (IOC-WESTPAC), while others do not specify their sources. This discrepancy complicates the organization of data according to the methods employed, hindering our ability to compare the efficacy of various microplastic sampling methods. Furthermore, there is an inconsistency in the nomenclature of shapes; for instance, the term "pellet" is used interchangeably with "granular", "sphere", "beads", "grains", "nurdles", "nibs", and other variations. Additionally, this variation in naming conventions can lead to confusion, making it challenging to accurately categorize and analyze microplastic shapes. Furthermore, certain publications fail to specify the polymer type of the observed microplastics. Typically, the confirmation for the presence of small particles in various samples (e.g., water, sediment, human cells, air, plants) requires testing through analytical techniques such as Fourier Transform Infrared (FTIR), micro-FTIR, micro-Raman spectroscopy, or pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) to identify the associated polymers. However, studies with polymer information did not specifically identify the polymers' assignation based on the shape or color of microplastics found, which could possibly be due to the limitations in costs or resources.

Finally, there is also an absence of information regarding the variations in geological locations for microplastic sampling, which can significantly impact the chosen sampling methods. Different countries exhibit diverse geological features, influencing the design of the sampling methodologies. For instance, when comparing research on microplastics in water from mangrove and sea areas, the methodologies employed may differ. The collection of water samples in mangrove areas often involves the use of the bucket method, while a towing method is commonly employed in sea water or riverine water sampling. Consequently, the observed abundance of microplastics between these two methods may yield disparate outcomes. The lack of consistency in methods makes it difficult to develop a comprehensive picture of the distribution and quantity of microplastics. The complexity of the problem is further increased by Southeast Asia's varied ecosystems and climate, and influenced by variables including seasonal fluctuations and anthropogenic activity. Large-scale, thorough studies may be difficult to carry out in some of the region's countries due to a lack of funding and expertise in research infrastructure. For instance, while other Southeast Asian countries are making progress in microplastic research, there is no information in the literature regarding microplastic contamination in East Timor. Similarly, little information has been obtained from Laos, Brunei, Myanmar, and Cambodia.

Additionally, researchers in the Western region have discovered that risk assessments of microplastic polymers are important for assessing their risk to ecosystems and human health; however, in practice, comparing the pollution hazard index of microplastics can be difficult for several reasons, including the diverse nature of microplastics and the variety of factors that must be considered in assessments, as has been highlighted in this review. Apparently, no standardized techniques have been established to determine the ecotoxicity of microplastics in the Southeast Asia region. Different studies may use different methodologies to estimate the risks and hazards, making direct comparisons of results challenging. Moreover, the long-term effects of microplastic exposure are also unknown. While short-term studies can provide information, the long-term consequences of microplastics on ecosystems and organisms are still being studied. To address these issues, continued research should focus on developing standardized procedures for microplastic risk evaluation, understanding the toxicity of various polymer types, and taking into account the larger ecological context in which microplastics are commonly discovered. Future investigations should also prioritize the study of microplastics within terrestrial ecosystems, with a specific emphasis on agricultural land. This focus is essential for advancing our understanding of the biogeochemical dynamics of microplastics in soil-plant systems and for conserving terrestrial and agricultural ecosystems.

The aforementioned studies of microplastics in the Southeast Asian region have a number of difficulties and constraints. While the trend of microplastic research in the region is in line with other research pertaining to microplastics globally, there is also a notable lack of studies focusing on spatial, temporal, and interconnected correlational studies of the matrices within Southeast Asia's environmental ecosystems. As such, little is known about how microplastics are transported within the diverse matrices. Factors such as biological interactions, sedimentation process, and water currents might influence the microplastic distribution, transport, and fate in the region. Therefore, to overcome these limitations, there is a serious need for regional and international harmonization, for instance, in working on standardized procedures, providing more financing/funding, participating in regular monitoring, and sharing capacity in building strong research networks that will expand the knowledge of the scope and effects of microplastic pollution in Southeast Asia. This gap is significant, especially considering the devastating impacts of microplastics on marine ecosystems, health issues, and biodiversity destruction resulting from a substantial increase in plastic pollution on land and in marine environments in the Southeast Asia region. Therefore, collaboration between scientists, policymakers, and environmental organizations is critical for obtaining a thorough understanding of the potential hazards connected with microplastics and developing effective mitigation methods.

## DECLARATIONS

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### Availability of data and materials

Data will be available in Supplementary Materials and upon request.

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**Conflicts of interest**

All authors declared that there are no conflicts of interest.

**Ethical approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

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