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Present Status of Microplastic Pollution Research Data in Sri Lanka and Microplastic Risk Mitigation Solutions; Lessons from a Global Policy Context

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Abstract
The emergence of microplastics (MP) as a pollutant in natural environments including aquatics has been increasingly recognized worldwide. This review focuses on the status of MP pollution research in Sri Lanka, and MP risk mitigation solutions, as lessons from a global MP policy context. The methodology involves a comprehensive literature review divided into three main sections: 1) a simple understanding of the plastic cycle and risk factors, 2) a comprehensive review of MP pollution research trends in Sri Lanka, 3) a comprehension of global trends of MP regulation policies and adaptable solutions for national scale. There was less attention given to MP research in Sri Lanka, until the recent X-Press Pearl disastrous incident. In addition to that, we highlight the less attention paid to MP pollution in inland waters and lands compared to marine. Considering the widespread MP issue, the paper highlights the importance of a policy approach for MP pollution control. Finally, the paper discusses the future directions for MP pollution research in Sri Lanka and emphasizes the need for more detailed quantitative data for effective policy formulation. The overall study presents a sound case for understanding a national context in MP pollution and suggesting necessary policy instruments in pollution regulation.

Keywords: emerging contaminant, microplastic, microplastic impact, mitigation, policy

Introduction

Microplastics (MP) have been identified as emerging contaminants because they are pervasive, harmful, and persistent. Worldwide plastic production remarkably rose 216 times, from 1.7 million tons in 1950 to 368 million tons in 2019 [1]. According to a report published by the United Nations Environment Programme (UNEP), Asia is the largest producer of plastic in the world, accounting for approximately

60% of global production [2]. China alone produces over a quarter of the world's plastic [3]. MP are defined as any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which is insoluble in water [4]. The MP are formulated by the degradation of other plastic forms, i.e. meso (5-25 mm), and macro (>25 mm) plastics [5].

Microplastic pollution has recently received increasing global attention due to its vast volume, pervasiveness in the environment, and toxic impacts. MP pollution is evident in different environments including marine ecosystems [6], terrestrial environments [7], riverine ecosystems [8], mountains [9], and surprisingly in typical cryospheric regions of the earth [10]. Novel entities including MP have exceeded the safe planetary boundaries to date [11]. MP inclusion in food webs and bioaccumulation are already evident demonstrating the depth of the issue [12]. Researchers widely discussed negative impacts of MP on the environment and human health. However, the precise effects of MP on the biosphere are not well understood scientifically yet [13], probably due to several challenges such as; inconsistency of physical and chemical properties of MP, multiple sources of origin, multiple pollution pathways, insufficient availability of detection, and other laboratory methods [14, 15]. The fundamentals in data collection standards, quality control, data storage, data sharing, and reporting ought to be improved to compare and merge MP related data from all over the world [16].

According to the literature there are several scientifically gray areas regarding MP [17], scholarly attention has been given to some extent mostly focusing on MP occurrence, environmental distribution, fate, transport, bioaccumulation, the effects on ecosystems, and MP analytical strategies. Can-Güven, (2021) reviewed research conducted in 87 countries and noticed an increasing trend in MP research, from 2006 to 2020 [18]. Certain countries, particularly Canada and the USA, have marked the detection, and characterization of MP as a priority section for research funding to avoid further environmental damage by accelerating the policy implementation process [19]. Additionally, the contradictions in access to our current state of understanding of marine litter to the general public and stakeholders have been decreased by generating guidelines for sampling and reporting as well as by homogenizing the available data [20]. Moreover, considering optimizing the research funding outcomes for policymaking, it is recognized and highlighted the importance of findability, accessibility, interoperability, and reusability (FAIR) of data [19].

Sri Lanka, an island in the Indian Ocean, has a local plastic processing industry with a current capacity of close to 140,000 MT per year [21]. Ministry of Environment, Sri Lanka stated that Sri Lanka produced 938.42 MT of plastic waste per day in 2020 and 68% of that falls under uncollected plastics (e.g.: direct discard to water, illegal dumping, etc.) [22]. However, MP control has been the major focus in Sri Lanka. There has been attention given to MP pollution and its effect by the National Aquatic Resources Development Agency (NARA) and the Ministry of Health in Sri Lanka, even though the MP pollution was widely discussed after the X-Press Pearl accident followed by the massive disaster in May 2021 [23, 24]. The X-Press Pearl cargo ship in May 2021 on the west coast of Sri Lanka spilled nearly 1680 tons of

MP and nurdles, drawing the attention of authorities and researchers to investigate more about MP pollution [25]. Considering the ubiquitousness of MP across different landforms and sources, and the multifaceted nature of the problem, it needs a national or regional level policy intervention for risk mitigation. Because, properly formulated public policies, policy instruments targeted on the correct stakeholders can steer stakeholder behavior towards a targeted outcome, i.e. MP risk reduction [26]. Considering the importance of mitigating the MP risk on humans, the environment, and water, this paper focuses on 1) comprehending MP distribution and potential risk in the Sri Lankan context; 2) evaluating the current status of MP research carried out in Sri Lanka, and 3) suggest policy solutions to manage MP risk in Sri Lanka with the lessons learned from Globe.

Materials and Methods

The methodology typically consists of a literature review, that includes mainly three sections; 1) a simple review to understand the plastic cycle and risk factors, major MP pollution incidents as well as the MP risk on fauna and flora species, 2) a systematic review on MP pollution research in Sri Lanka, and 3) review global and national trends of MP regulation policies.

Method Followed for the Systematic Literature Review for MP Pollution Research in Sri Lanka

The methodology for conducting a systematic literature review on MP pollution research directions in Sri Lanka involved several key steps (Figure 1). Firstly, the Scopus database was selected as the primary source for the literature search, covering the period from 2018 up to 2023. The search was conducted using the keywords "microplastics" and "Sri Lanka" (n=20). Then the identified papers were further screened based on the type of paper where only the peer-reviewed journals were considered for further analysis (n=11). Then the identified papers were coded based on a few criteria i.e. year, objective, sampling duration and location, target system, sources of MP, sink/pathway, shape, size, color, polymer, reported concentration, policy recommendations, data availability statement details, journal; to develop a comprehensive understanding of the current state of knowledge on MP pollution in Sri Lanka.

Understanding MP Policies and Potential Policy Solutions with Relevance to Sri Lanka

At the stage of full-text coding, all the potential policy solutions for the Sri Lankan MP sector were coded. In addition to that, all the plastic pollution regulation laws in Sri Lanka were reviewed. At the same, we referred to the available major MP policy directives worldwide to understand global trends and strategies in MP risk regulation. With the understanding of available plastic policies in Sri Lanka, MP potential policy solutions to Sri Lanka, and the global MP regulation trends, a policy guideline for MP pollution risk regulation and mitigation in Sri Lanka was formulated.

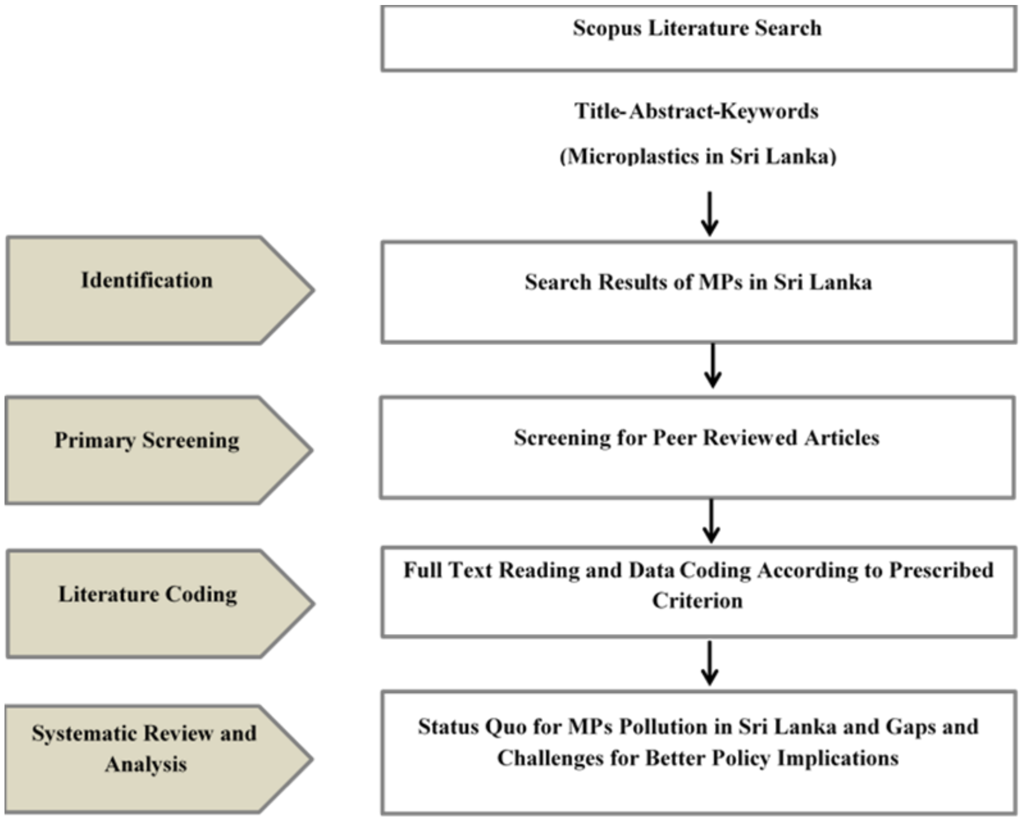

Figure 1. Schematic diagram of literature review for MP pollution research directions in Sri Lanka

Results and Discussion

Microplastic Pollution

Typical Life Cycle of Plastics and Fate

The refined crude oils are used to produce a range of petrochemicals that would act as the building blocks for plastic production [27]. Among the myriad of plastics of various compositions, commonly used plastics are polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), nylons, polystyrene (PS), polyurethane (PU), and polyvinyl chloride (PVC) [28]. Among different types of MP, microbeads in personal care and cosmetic products (PCCPs), synthetic textiles (polyester, nylon, and modacrylic), plastic packaging materials, single-use items such as bags, food containers, domestic laundry, unsustainable coastal fisheries, harbor operations, and fishing gears are the major types of MP associated with high pollution risks [29]. Despite their convenience and numerous uses, plastics, including personal protective equipment like masks, gloves, and face covers, have become a significant source of MP during the COVID-19 pandemic, as they are often discarded, incinerated, or recycled through inefficient and unsustainable methods [30].

Over time, plastics can also degrade due to exposure to light, heat, and other environmental factors such as weathering and erosion [31], leading to MP formation [32]. However, once MP are formed, they can be released into the environment through a range of pathways such as; the shedding of microfibers from apparel textiles during washing, i.e., textiles made out of PET, nylons, and PU, or abrasion of plastic materials during the manufacturing process [33]. In this regard, by considering the mode of their origin, MP can also be categorized as primary MP and secondary MP. Primary MP are initially introduced into cleansers, cosmetics, and medical drugs as abrasives [34], while secondary MP are created through external forces such as physical, chemical, and biological processes when larger plastic fragments are broken down [35]. Once added to the environment, the aging of MP in the environment is a complicated process, leading to physical changes such as protrusions and cracks on their surface and changes in their physicochemical properties. Consequently, these changes can facilitate the absorption and further release of pollutants (e.g. heavy metals) and additives from the environment [36]. The MP can get circulated through the environment by wind, water currents, and the movement of organisms. This can lead to their distribution in various ecological habitats such as oceans, rivers, lakes, and soil [37]. Once released, MP can accumulate in multiple ways, such as forming sediment or being ingested by organisms [38]. These tiny pieces of plastic pose an immense environmental and economic threat to coastal and marine ecosystems around the world [39]. Biofilms use MP as an artificial adhesion surface, thus potentially changing certain properties of the MP. These biofilms are unique and form a distinct ecological niche due to the dynamic and highly regulated process that distinguishes them from the natural environment [40]. Wu et al., (2022) discovered that biofilms enhance the adsorption of heavy metals onto MP, and the size of the MP is a critical factor in biofilm colonization [41]. The MP have been found to absorb numerous contaminants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dioxin-like chemicals, polybrominated diphenyl ethers (PBDEs), toxic metals, pharmaceuticals, pesticides, and herbicides [42].

Microplastics can be found in ocean water, sea beds, and beach sediment, as well as in the stomachs of aquatic organisms, leading to a variety of health and ecological issues. They will include affecting the feeding behavior of aquatic organisms, altering the nutrient cycling of ecosystems [43], and increasing the toxicity of pollutants [44]. MP that enter marine environments pose a significant risk to marine organisms due to their potential bioavailability and/or bioaccumulation. As MP interact with plankton and sediment particles, both suspension and deposit feeders may be at risk of accidentally or deliberately ingesting the debris. The ingestion of MP by organisms can result in smothering, blockage of the digestive tract, or the uptake of associated toxins (Figure 2). Furthermore, MP can be ingested by marine animals, eventually entering the food chain. These characteristics of aged MP can have significant implications on the health of marine wildlife and humans [1]. Not only in marine ecosystems, but also soil ecosystems have been severely affected by MP. Plastic waste built up in agricultural areas is found to possess significant environmental issues that can have direct impacts on food sources and indirect impacts on organisms in various levels of the food chain [45]. Exposure to MP through contaminated food or water sources, as well as inhalation of airborne particles, presents a potential risk to human health [46]. Additionally, the presence of MP in the environment may lead to the introduction of non-native species, as well as altered microbial communities and increased disease transmission [47].

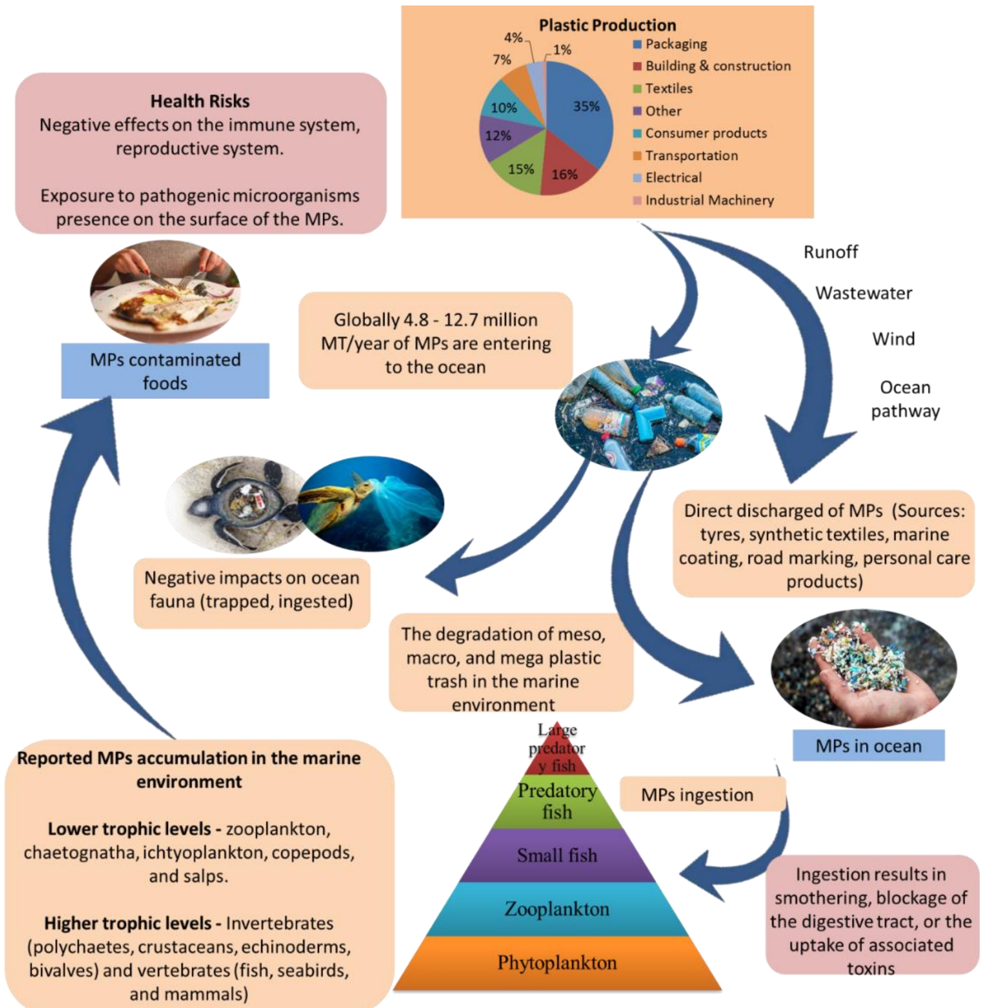

Figure 2. Fate and impacts of MP

Toxic Consequences of MP

As summarized in Table 1, MP are a major environmental concern due to their potential to cause toxic effects on humans, animals, and ecosystems. They are capable of absorbing and carrying persistent organic pollutants, such as pesticides, flame retardants, and heavy metals, which can be ingested by humans and animals and cause a range of health problems [48]. Importantly, MP can be used as a vector for the spread of invasive species, allowing them to be transported to new environments where they can outcompete native species [43]. MP may cause human conditions such as early-stage inflammation, breast cancer, blood infection, and early-onset puberty [48, 49]. Accumulation of MP in animals can lead to various adverse effects, including bleeding, obstruction of the gastrointestinal tract, starvation, decreased body mass, a decrease in hatching rate, and elevated malondialdehyde levels in the liver, brain, intestine, and gizzard [50-52].

Table 1. Toxic consequences of MP on humans, animals, and the ecological environment

Impact group	Impact	MP type	Toxic concentration	Geographical location	Reference
Human	Early-stage inflammation	PS	500 μg/mL	Korea	[53]
Human	The immune system was stimulated, and potential hypersensitivity to PP particles was enhanced by an increase in cytokine and histamine levels in Human peripheral blood mononuclear cells (PBMCs), Raw 264.7, and HMC-1 cells.	PP	N/A	Korea	[48]
Human	Breast cancer, blood infection, and early onset puberty and genital defects	Additives such as Phthalates, Bisphenol A, and Bisphenol S		-	[49]
Human	Cytotoxicity, immunotoxicity, reproductive toxicity, carcinogenicity, and developmental toxicity.	PE, PP, Polyamide (PA), PVC, PS, Rubber, and PET	N/A	-	[46]
Migratory birds	The lower digestive tracts of all bird species contained fiber, fragments, and beads.	PE, PET, nylon, and PVC	N/A	USA	[54]
Aquatic birds	Bleeding, blockage of the digestive tract, ulcers, or perforations of the gut. a false feeling of being full, leading the bird to not eat and, therefore, starve.	N/A	N/A	Portugal	[50]

Terrestrial bird	Decrease in body biomass, increase in malondialdehyde production in the liver, brain, intestine, and gizzard. In addition, hepatic nitric oxide production and superoxide dismutase activity were suppressed in both the liver and intestine.	PS	N/A	Brazil	[52]
Zebrafish larvae	Decrease in hatching rates, an increase in malformation rates, and a decrease in calcified vertebrae.	MP + Butylated hydroxyanisole (BHA)	N/A	China	[51]
Rotifers species	Exposed to Cr (VI) coupled with MP, the survival rate of water fleas was significantly reduced while the burrowing ability of polychaetes was inhibited.	PS	100 particles L^{-1}	Korea	[55]
Oysters (Crassostrea gigas)	MP exposure induced metabolic changes in oysters, including alterations in energy metabolism and inflammatory responses.	PE/PET	10 and 1000 μg L^{-1}	China	[56]
Nile Tilapia (Oreochromis niloticus)	Anemia, and perturbations may lead to mortality.	N/A	100 mg/L	Egypt	[57]
Freshwater algae	Detrimentally affected by chlorophyll concentrations	PP/PVC	>250 mg/L	China	[58]

Plants	Humans are consuming an estimated 80 g/day of MP through the ingestion of fruits and vegetables that accumulate MP through uptake from polluted soil.	N/A	N/A		[59]
Soil	The addition of MP to the soil increased the bioavailability of metals (Cu^{2+} and Ni^{2+}), resulting in greater toxic effects on earthworms.	PE	N/A	China	[60]

PS = polystyrene; PP = polypropylene; PE = polyethylene; PA = polyamide; PVC = polyvinyl chloride; PET polyethylene terephthalate

MP Pollution in Sri Lanka

The amount of plastic consumed in Sri Lanka each year is increasing by 16%, with a currently estimated amount of 265,000 tons [61]. It is estimated that 69,427 tons of plastic are being washed into the sea annually, resulting in a per capita contribution of 3.3 kg [61]. Few studies have been conducted to identify MP pollution in coastal Sri Lanka. For example, *Pitipana* Beach in *Negombo*, an area on the western shore, was surveyed by Athawuda et al. (2020), who discovered MP in the beach sand and 36 items/m^3. They also conducted 91 km of further coastal surveys in the south, and tested surface water samples for MP. They discovered that every single water sample included at least one form of plastic [62]. Koongolla and research team found that *Ambanalthota* and *Dondra* Harbors had high MP counts and aggregate weights, particularly in the water; 15 and 29 items/m^3, respectively [63]. Polystyrene foam particles were dominant in 60%. Local fishermen use bait boxes, fish storage boxes, and buoys made of PS, which is likely why these harbors have high MP counts. Nawalage and Bellanthudawa conducted a study that uncovered several environmental concerns that have arisen from the addition of MP to personal care and cosmetic products (PCCPs). Toothpaste was the most widely used product (95.8%), followed by face cleansers (21.8%). In Sri Lanka, the four PCCPs; shampoo, face cream, toothpaste, and face cleanser products are responsible for releasing a total of 21.4 trillion MP particles into the environment on an annual basis [64].

The X-Press Pearl incident released over 1680 tons of plastic nurdles, one of the biggest nurdle pollution events in the Indian Ocean near the Sri Lankan coastline [25]. Here, several phenomena influenced the dispersed distribution of MP over the coast of Sri Lanka, such as; monsoons, tidal, wind, wave, thermohaline gradients, and an upwelling pattern in the southern sea and activities of *Hambantota* and *Godawaya* harbors [1]. In addition, the intensity of wave and current interactions with rocky and sandy surfaces near-shore areas may amplify the process of secondary MP generation [65].

Moreover, in another study, it was found that the concentrations of airborne MP were higher indoors (0.13–0.93 particles/m^3) than outdoors (0.00–0.23 particles/m^3) [66]. This was attributed to the types of indoor MP being generated from indoor sources and the lifestyle of the occupants. The highest outdoor MP abundance was found near an industrial zone, followed by urban and inland locations in high-density areas.

MP Pollution Research Directions in Sri Lanka

Yearly Distribution of Research on MP in Sri Lanka

According to literature the world-focused research on MP started five decades back [67], all peer-reviewed articles have been published within the last 6 years in Sri Lanka. In each of the years 2018, 2020, and 2021, three research papers were published, while eight papers were published in the year 2022. The X-Press Pearl incident in 2021 has highlighted the need for more research on the effects of MP on the environment in Sri Lanka. Not only that, it also sheds a red light on the need for strong MP policies in Sri Lanka. It is also raises the concern that this heightened attention might have influenced the publication of more studies on the topic, potentially leading to a bias where the severity of the incident could have caused an overrepresentation of studies focusing on its aftermath. The focus on the immediate effects of the incident might have skewed the research landscape, leading to an imbalance in the types of studies being conducted and published. However, a closer examination of the research objectives of studies published after 2021 reveals that only three publications directly address the objectives related to the X-Press Pearl accident.

Target Journals, Research Institutions, and Objectives of Reviewed Research Studies

Due to the scarcity of research papers on pollution among Sri Lankan MP, whether approached qualitatively or quantitatively, it is noteworthy that a majority of these articles, specifically 64%, have been published in the Marine Pollution Bulletin journal. Articles were with the objectives of identifying available MP from widely used personal care products and investigating the level of awareness of MP [64], analyzing and quantifying the MP contamination in salts in Sri Lanka [29], generating MP baseline data to investigate the extent of contamination, and guide further research on the ecological impact of MP contamination [68], and monitor the environmental pollution along the coastline of Sri Lanka [25, 63, 65, 69]. Environment Pollution, Science of Total Environment, and Journal of Hazardous Materials are the journals where the rest of the research papers were published with the objectives of, quantitative and qualitative analysis of MP in beach sediments, investigating the effect of X-Press Pearl incident, analysis of potentially toxic elements using sampling, identify the fate of MP in the deep sea and the factors influencing and investigate occurrence of MP in commercial marine dried fish in Asian countries [1, 39, 47, 69]. Furthermore, research keywords identified include MP, maritime accidents, potentially toxic elements, pellet pollution index, coastal pollution, the Eastern Indian Ocean, sediments, sources, grain size, plastic debris, heavy metals, marine pollution, toxic contamination, the Indian Ocean, and polluted sand.

Among peer-reviewed articles, when considering the institute that carried out the research, it is evident that seven (07) Sri Lankan universities and three (03) Sri Lankan government institutes have paid attention to MP pollution in Sri Lanka, while the most actively engaged institutions are the University of Uva Wellassa and University of Ruhuna. Out of the eleven (11) research papers studied, five (05) publications had foreign collaborations with the USA, India, China, and Taiwan. Seven (07) studies have conducted laboratory research in Sri Lankan laboratories while three (03) studies have done their laboratory research in India, China, and Taiwan research institutes. For all the laboratory analyses, researchers collected samples from fields while sample separation and MP identification were carried out in major laboratories. Out of the total studied, only two (02) studies have studied species in risk [39, 47]. This finding emphasizes the need for more research studying the effect of MP on species in future studies.

Target Systems and Sample Types Investigated in Studies

Among the articles studied for this review, 73% of articles investigated the presence of MP in the marine/coastal environment while the rest 27% of articles were concerned with MP pollution with products as illustrated in Figure 3a. As shown in Figure 3b, out of the studied 73% of the studies analyzed MP in sample types such as water, sand, product, soil, and sediments, 27% of the papers analyzed MP in products (cosmetics and food) such as saltern samples from *Puththalam*, *Hambanthota*, and *Elephant pass*; dried fish, toothpaste, soap, shampoo, handwash, and face cream.

Out of the total products reviewed, it is evident that the highest levels of MP were recorded in salt samples and salt samples from *Hambantota* saltern recorded the highest value as 3345.7±311.4 items/kg. Also when it comes to personal care products it is estimated that 21.4 trillion MP are released into water bodies each year from four different products; shampoo, face cream, toothpaste, and face cleanser products. Shampoo is the largest contributor, with 10.6 trillion MP particles, while face cream comes in second with 7.1 trillion MP particles [64]. Although in the Sri Lankan context, the sample that was collected was narrowed to the types shown in Figure 3b, concerning the Asian context it is evident that biota and organisms such as fish, crustaceans, and insects were also taken into consideration [8]. This will allow the identification of new research approaches to investigate in the Sri Lankan context.

Types, Shapes, and Colors of MP Identified in Sri Lanka

MP types and shapes are significantly important because they directly influence the distribution of MP, removal, and interactions between other organisms and contaminants [31]. Also, as a morphological characteristic, color provides a general idea about the source of MP. The research articles that assessed MP have conducted morphology analysis and identified shape, color, and polymer types that can be found commonly among the different MP. Figure 3c depicts the shapes of MP found in many of the studies. Fragments and filaments were found to be more common (19%) among these studies, followed by fibers (17%) and foam (14%). The other important attribute when assessing the occurrence of MP in any environment is their variety of colors. Under the Sri Lankan context, 91% of the studies have analyzed the color of the MP found in their analyzed samples, and out of them, 55% of them are differentiated into six (06) colors or more, as shown in Figure 3d.

Data Sharing Trend in Review Articles

Out of all the reviewed articles under the Sri Lankan context, 73% of the articles contained data sharing statements as shown in Figure 3e. All the articles published in 2021, and all except one in 2022 included data sharing statements. Further evaluation of the reviewed articles (Figure 3f) showed that 37% of the researchers most commonly shared their data associated with studies in the form of supplementary materials, and 18% of authors stated that data would be made available on request. In comparison, 9% of available data were either present in, the repository or both supplementary and in the article. Accordingly, more than two thirds of the published research indicates data sharing statements, which is a positive trend for understanding the MP pollution phenomenon and finding risk mitigation solutions.

However, there is still a significant proportion of research that is not fairly sharing their data. This is a concerning issue, as unshared data not only hinders scientific progress but also results in public and other funds being wasted. Without access to the underlying data, verifying research findings or conducting further analyses is difficult, which limits the potential impact of the research. Furthermore, the lack of quantitative data is also a hindrance to data-driven policy recommendations. Policymakers rely on reliable and robust data to make informed decisions, and without access to data, it is challenging to make evidence-based policy recommendations. This highlights the importance of data sharing and the need for researchers to make their data accessible and transparent to facilitate data-driven policymaking.

In summary, while there is a positive trend in data sharing within the reviewed articles under the Sri Lankan context, the issue of unshared data remains prevalent. This not only hinders scientific progress but also has implications for policymaking. It is important for researchers to make their data available and accessible to ensure transparency, reproducibility, and informed decision making. Policymakers and funders can also play a role in incentivizing data sharing by recommending researchers share their data as a condition for funding or publication.

Regulating MP Pollution in Sri Lanka

Research Recommendations in the Sri Lankan Context

As presented below in Figure 3, there are limited studies (11) published and hence there are limited recommendations available to reduce MP pollution or pollution risk specifically for Sri Lanka. Among published research papers focusing on Sri Lanka, only five (05) presented recommendations for MP pollution mitigation [39, 47, 64, 68, 69]. All the recommended aspects can be categorized into four: bridging research gaps, establishing needed infrastructure, knowledge dissimilation among the general public, and enhanced policy backing.

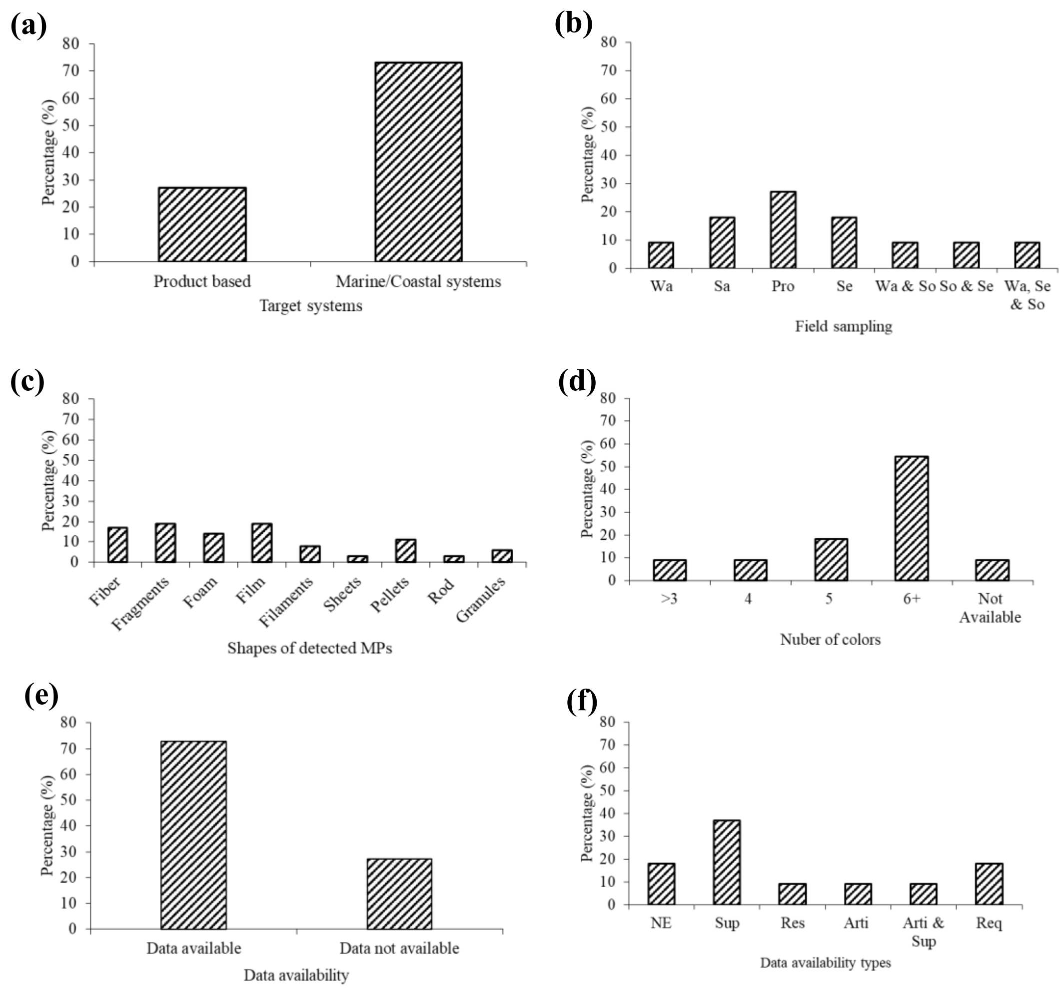

Figure 3. Simple statistics of MP research carried out in Sri Lanka; (a) Percentage of the studied system; (b) Percentage of field samples under investigation (Wa=Water, Sa=Sand, Pro=Product, Se=Sediments, So=Soil); (c) Percentage of shapes of detected MP; (d) Percentage of the color of detected MP; (e) Data availability of research studies; (f) Status of available data (NE=no evident, Sup=In supplementary materials, Res=Respiratory, Arti=available within the article, Req= Data will be made available on request)

Highlighted general research needs are an in-depth understanding of the chemical properties of MP, their weathering mechanisms, contaminant interactions with MP, microbial interactions and biofilm formation, ecotoxicological effects, MP transport in food webs, and technologically innovative remediation. In addition, two researchers recommended facility establishments such as sewage treatment facilities improvement and long term monitoring processes of plastic pollution in marine environments [62, 64]. The same publications have suggested awareness raising programs among the general public regarding MP pollution. Though the above recommendations can be considered as suggested policy instruments, these publications thoroughly discuss them through a political science lens.

Three (03) publications stated the importance of enforced policy support in their recommendations for MP risk reduction [39, 64, 70]. They suggested strengthening current policies and introducing new policies as a necessity in several aspects: adopting producer responsibility policies, limiting plastic waste and other plastic management policies at multi scales considering different stakeholders, and implementing environmental best management practices. However, a realistic public policy framework is needed to address all the major stakeholders (policy actors) through proper policy instruments to reach the policy goal of MP risk mitigation beyond the simple recommendations.

Current Sri Lankan Policies Relevant to Plastic Pollution

Sri Lankan policies still have not paid much attention to MP pollution. However, Sri Lanka has paid attention to macro plastic pollution. Even though MP and macro plastics are different, macro plastics could get converted into MP through decaying processes [71]. Accordingly, we consider the importance of macro plastic pollution regulation here.

Pollution by macro plastic and polythene materials has been under the consideration of national policies since 2006. After a few policy changes, in 2017, the Sri Lankan government took a prominent policy action to ban the manufacture, sale, offer for sale, offer free of charge, exhibition, or in-country use of prescribed items and actions to ensure the environmental safeguard from plastic pollution through several command and control policy instruments. The banned items include polythene or any polythene product of twenty (20) microns or below in thickness except prescribed uses (Gazette No: 2034/33); food wrappers (locally called lunch sheets) from polythene as a raw material (Gazette No: 2034/34); any bag of high density polyethylene (locally called sili sili bags) except garbage and textiles with prescribed dimensions (Gazette No: 2034/35); and food containers (locally called lunch boxes), plates, cups and spoons from expanded PS for in-country use (Gazette No: 2034/38). The prohibited items can be identified as the most common and widely used single-use plastics which are easily subjected to break. The prohibited actions are open burning of refuse or other combustible matters, including plastics (Gazette No: 2034/36) and event decorations from prescribed plastic materials (Gazette No: 2034/37). The plastic item ban was extended (Gazette No: 2211/51) to prohibit PET or PVC material for packing agrochemicals used for any process, trade, or industry; and any plastic item such as prescribed sachets, inflatable toys, and cotton buds with plastic stems in trade or industry. In addition to all these command and control instruments, Sri Lankan environmental policies imposed a communication and diffusion instrument; any manufactured plastic item shall be marked clearly by the Plastic Material Identification Standards specified in the schedule (Gazette no. 2211/50).

All these policy instruments are imposed on the broader policy objective of the national environmental act; protection and management of the environment [72]. However, the ability of these policy instruments to reach the policy objective and the extent of successful implementation are still not scientifically investigated. On the other hand, policy instruments other than command and control instruments are not defined to control macro plastic pollution. More effective market-based policy instruments are capable of reaching short-term plastic regulation, while knowledge-based policy instruments are capable of long-term plastic regulation and the national system is lacking from both types. Though the macro plastics regulation is beneficial for the MP regulation, particular attention to MP was not paid to environmental policies in Sri Lanka, possibly due to a lack of scientific evidence regarding MP pollution or their toxic impacts at the national scale. As the described in above sections, there is limited MP research carried out in Sri Lanka, and research also concentrated on the X-press pearl disaster.

Microplastic Regulation Lessons; from the Globe

Plastic regulation is challenging worldwide as it conflicts with national economic growth goals [73]. Despite that fact, many countries of the world are making policy efforts to reduce plastics considering the social and environmental threats of plastics. Policies can be identified as an effective tool in MP regulation and Hossain et al. (2023) predicted potential MP reduction in an extensive mariculture zone of China through policy interventions [74].

The European Union has had plastic regulation concerns for a longer time, such as single-use plastic and plastic carrier bags. For example, Germany has been trying to regulate plastic pollution through market-based policy instruments, i.e. tax, since the 1990s [75]. However, MP have been getting policy concerns recently, probably with growing scientific evidence of MP pollution and their negative impacts as well as pressure from environmental NGOs [76]. The Ministry of Environment and Climate Change of Canada declared MP below 5 mm as a toxic substance and, hence are regulating under the Canadian Environmental Protection Act of 1999. Though Canada did not completely ban MP, in 2018, they have banned MP in certain products; toiletries that contain microbeads. The United States passed an act in 2015 called the Microbeads Free Water Act targeting plastic microbeads in the manufacturing of certain personal care products. China also took steps to regulate MP with their ban on household chemical products containing plastic microbeads in 2022. Several countries in the African region imposed many policy instruments to regulate MP, mainly command and control. They include; production volume restrictions, restricting single-use plastics, promotion of compostable and biodegradable bags, tax breaks for producers who recycle or manufacture, reusable bags, and cleaning concepts such as “National Cleanup Day”. The African policy instruments are mostly targeting the prevention of waste generation, however, product designing and waste management are also not completely ignored [77]. Rwanda has effective plastic regulation policies among other African countries and they have diverse policy instruments such as; raising social awareness, developing an ecofriendly alternative to plastic materials, and imposing fines for illegally bringing in plastic materials [78]. The Philippines also focused on reducing plastic waste by regulating single-use plastic bags, however, the effectiveness of the policy instruments is questionable [79].

The most popular policy instrument among all the countries is restricting single-use plastic bags which can be decayed into MP. However, Nielsen et al., (2020) and Convery et al. (2007) pointed out the insufficient stakeholder consultation before applying that policy instrument demonstrating potential ineffectiveness in implementation [80, 81]. Most countries' plastic bans have not been effective because of the financial clout of plastic producers and other stakeholders; a lack of policy implementation; a short window of time between the announcement of the ban and its effective date; and a lack of alignment between national policies [78, 82] . Li (2022) pointed out the famous ban on microbeads, mostly in PCCPs by many countries regardless of the other types of MP [71]. However, in some countries, such as Japan, the major producers voluntarily agreed to avoid microbead usage in PCCPs.

Galarpe et al., (2021) highlighted the importance of research for source apportionment in MP pollution policy formulation under the context of the Philippines [79]. In contrast, more developed nations have already moved with source identification and imposing policies on the cosmetics industry. The MP in cosmetic products are in the spotlight and several environmental organizations are making voices against it. Therefore, many countries have imposed policy instruments on non-biodegradable or non-water soluble MP in cosmetics and hygienic products. The state of Illinois was the first country who ban MP in cosmetics [83]. There are two major policy instruments visible in cosmetic MP regulation and they are MP ban and phaseout agreements; Canada, China, France, Ireland, Italy, New Zealand, South Korea, Sweden, Taiwan, and the USA banned while Australia, Belgium, and South Africa are regulating through phase out agreements. Some countries are in the process of banning MP in cosmetics, such as Brazil, Denmark, Finland, Iceland, India, and Norway. However, still, only 7% of the UN countries and 15% of the EU countries moved forward to regulate MP pollution by cosmetics [76]. In addition to the above mentioned policy instruments, some other knowledge based instruments have been proposed to regulate cosmetic MP such as introducing natural and synthetic alternatives such as polyhydroxyalkanoate, cellulose, silica, and walnut powder [84], sometimes low cost alternatives compared to MP beads [85]. Anagnosti et al. (2021) explained the potential of voluntary agreements in cosmetic MP reduction which leads production companies and sales chains to voluntarily reduce the use of MP [76].

The microbeads, the MP in PCCPs can be considered as primary MP. Secondary MP are more widespread in the environment and create more disastrous effects that have lesser regulation attention [71, 86]. In addition to the MP pollution regulation, their decaying and secondary MP also should be regulated through strong policies.

In the context of human contamination of MP, the attention is growing further in the global context. The recent focus on food and agricultural lands related MP contaminations focus on food related impacts mitigations. With the reporting of MP transferring from wastewater to wastewater treatment plant sludge, the management of wastewater treatment plant sludge received the attention of policymakers in certain geographic regions. In particular, practices such as open dumping, added as a soil improvement and used as a crop fertilizer, lead to recontamination by MP and associated toxins [87]. The land application of sewage sludge is regulated and institutionalized in several European Union (EU) countries, where these management practices indirectly restrict soil recontamination [88].

There are many policies to regulate MP from many sources in many countries, indicating a positive global trend to reduce MP pollution and relevant negative impacts. The majority of the policies do not address all the stages of the plastics value chain or all the major stakeholders. Nielsen et al. (2020)

observed a global trend of MP policies imposed on the later end of the plastic cycle [80]. Furthermore, Usman et al. (2022) highlighted several challenges in implementing MP regulation policies across several countries such as; poor acceptance by stakeholders, monitoring challenges, especially in rural areas, reluctance to adopt by profit oriented private sector industries, high cost of plastic alternatives, and poor public awareness [89]. OECD (2021) highlighted that tires and textiles are significant sources of MP pollution that are typically left out of regulations due to assessment difficulties [17]. On the other hand, there are several policy frameworks suggested by organizations like UNEP (UNEP, 2019a; UNEP, 2019b; UNEP, 2019c), WHO (WHO, 2023), and IUCN (UNEP and IUCN, 2022) to support overcoming these challenges [90-94]. After three decades of dedicated research and successful policy approach in the removal of heavy metals from wastewater through diverse methods, it becomes evident that a similarly intensive and comprehensive approach is essential for addressing MP pollution [95-100]. This underscores the need for concerted actions and parallel policy strategies to effectively mitigate the impact of MP on our environment.

Microplastic Risk Mitigation; Policy Solutions for Sri Lanka

Considering the widespread nature of the negative externalities created by the MP on both humans and the environment, there is a need for a national level intervention for risk mitigation through policies. The major challenge of addressing MP pollution is knowledge gaps of the pollutant risk factors, pollutant behaviors, pollution pathways, pollution sources, and sinks. Moreover, misaligned financial and human resources as well as gaps in policy instrument definitions most likely have intensified the challenge. Even with current knowledge, policy solutions are suggested, drafted, and implemented by different countries of the Globe to mitigate MP risk reduction. However, many of these countries do not focus on the full life cycle of plastics on the full life cycle of plastics.

Considering all these facts, we would like to suggest potential policy solutions to manage the risk of MP in Sri Lanka as presented in Table 2. However, all these are potential policy options and need stakeholder consultation and policy effectiveness assessment before implementation.

Table 2. Potential policy solutions to regulate MP risk in Sri Lanka

The targeted event in the plastic cycle	Policy recommendation or suggested policy instrument	Regulation aims
Full life cycle information (Plastic related data availability)	Policies targeting data management systems and data sharing platforms.	Make detailed import, export, and production data available for stakeholders (i.e. recyclers and users know what constituents in plastic products, including additives etc.). This will ultimately be supportive of sound end of life management.
	Introduce research outcome data sharing recommendations and infrastructure development policy instruments.	Promote FAIR data availability, for decision making and further research on plastic pollution.

Design and production regulation (target group: prescribed industries that use plastic in their production)	Financial incentives/voluntary agreements for product designs/productions with plastic alternatives	Reduce plastics within the chain and promote alternatives
	Tax/ban/partially ban microbeads in cosmetic and personal care products	Prevent MP contamination of the environment
	Maintain mandatory production and raw material standards (ex: Certifications)	Reduce plastic waste due to low quality materials and processes
	Knowledge and technology transfer to plastic waste reduction in production processes	Reduce plastic wastes from the production processes and waste contamination with the environment
	Incentives (ex: subsidy or tax relief) for recycling within production plants	Reduce new plastic product formation and waste generation
	Incentives (ex: subsidy or tax relief) for establishing recycling of used plastics	Reduce new plastic product formation, waste generation, and waste contamination in the environment
	Financial penalty (fine) for improper plastic waste management	Reduce plastic waste generation and contamination of the environment
Packaging and distribution regulation: all the product packaging and distribution above prescribed weight/volume (target group: manufacturers and distributors	Regulate plastic packages for prescribed products (ex: tax, labeling)	Reduce plastic waste generation and contamination of the environment
	Subsidizing plastic alternative packages for prescribed products	Promote alternatives for plastics and reduce plastic waste
	Incentives for recycling plastic packages	Promote alternatives for plastics and reduce plastic waste
	Financial penalty (fine) for improper plastic waste management	Reduce plastic contamination in the environment

	Tax for cosmetic and personal care products containing microbeads	Prevent MP contamination of the environment
	Regulate single-use plastic bags (ex: prohibit the use of plastic bags on dry goods, regulate its use on wet goods)	Reduce plastic waste quantity and prevent contamination of the environment
Use regulations. (target group: general plastic users)	Taxing single-use plastics, i.e. plastic drinking straws, plastic cups, plastic plates, plastic spoons, and forks	Reduce plastic waste quantity and prevent contamination of the environment
	Incentives for recycling (ex: financial incentive for used pens when buying a new pen)	Reduce new plastic product formation, waste generation, and waste contamination in the environment
	Encourage research for plastic alternatives and their implications	Reduce plastic quantity
	Incentives for commercializing the research findings to regulate plastics	Reduce plastic quantity
	Awareness rising, knowledge sharing, and technology transfer at different levels; school children, the general public, retailers, manufacturers, etc.	Behavioral changes for plastic use reduction and plastic reuse
Other strategies	Consider plastic reduction efforts as a necessity in registering new prescribed industries/businesses, i.e. restaurants, shops, and fast food chains	Behavioral changes for plastic use reduction and plastic reuse
	Monitoring and financial resource mobilization strategies for effective implementation	Ensure implementation of the plastic reduction policies
	Declare MP as a toxic substance and define threshold limits/standards to be presence in the environment/portable water/food	Establish plastic thresholds for risk regulations

Conclusion

It is imperative for Sri Lanka to address the growing problem of MP pollution through evidence-based policies and effective management strategies. The recent X-Press Pearl incident has underscored the urgent need for action in Sri Lanka, where MP are prevalent in multiple land and water systems. However, there is a lack of comprehensive research and data on MP in the Sri Lankan context, hindering the formulation of effective policies and measures. Our study highlights the importance of data collection and research to inform policy-making and management efforts. By utilizing FAIR data on MP, policymakers can develop evidence-based policies that address the full life cycle of plastics, including production, use, and disposal. Furthermore, our policy suggestions offer a roadmap for addressing MP pollution at different stages of the plastic cycle, emphasizing the need for collaboration among stakeholders and the incorporation of local context into policy formulation. Looking ahead, future research should aim to replicate and expand upon our study by incorporating data from other countries and regions. By incorporating data from a broader geographical scope, researchers can gain a more comprehensive understanding of MP pollution and identify best practices for mitigation and management. Additionally, leveraging government research and data from other sources can further enhance the robustness and applicability of research findings. In summary, addressing MP pollution requires a multi-faceted approach that integrates scientific research, data collection, and policy development. By working together at the local, national, and global levels, we can mitigate the environmental and human health impacts of MP pollution and safeguard our planet for future generations.

Conflicts of Interest

There is no conflict of interest between authors.

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